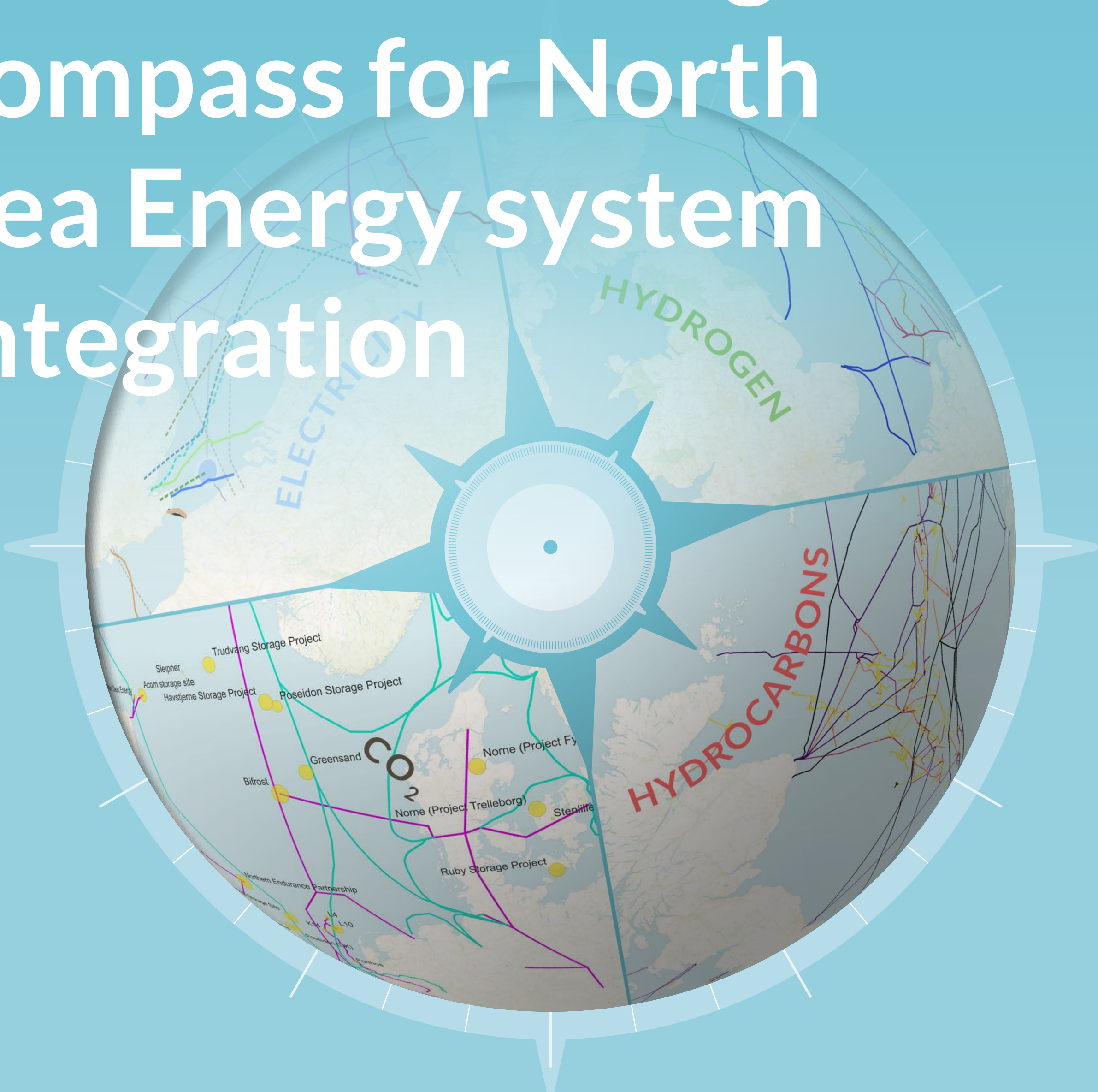
North Sea Energy
offshore system integration

D7.1 WHITE PAPER

North Sea Energy 2023-2025

Empowering & decarbonizing Europe: an international grid compass for North Sea Energy system integration



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North Sea Energy 2023-2025

Empowering & decarbonizing Europe: an international grid compass for North Sea Energy system integration

Towards an affordable, reliable and decarbonized energy system

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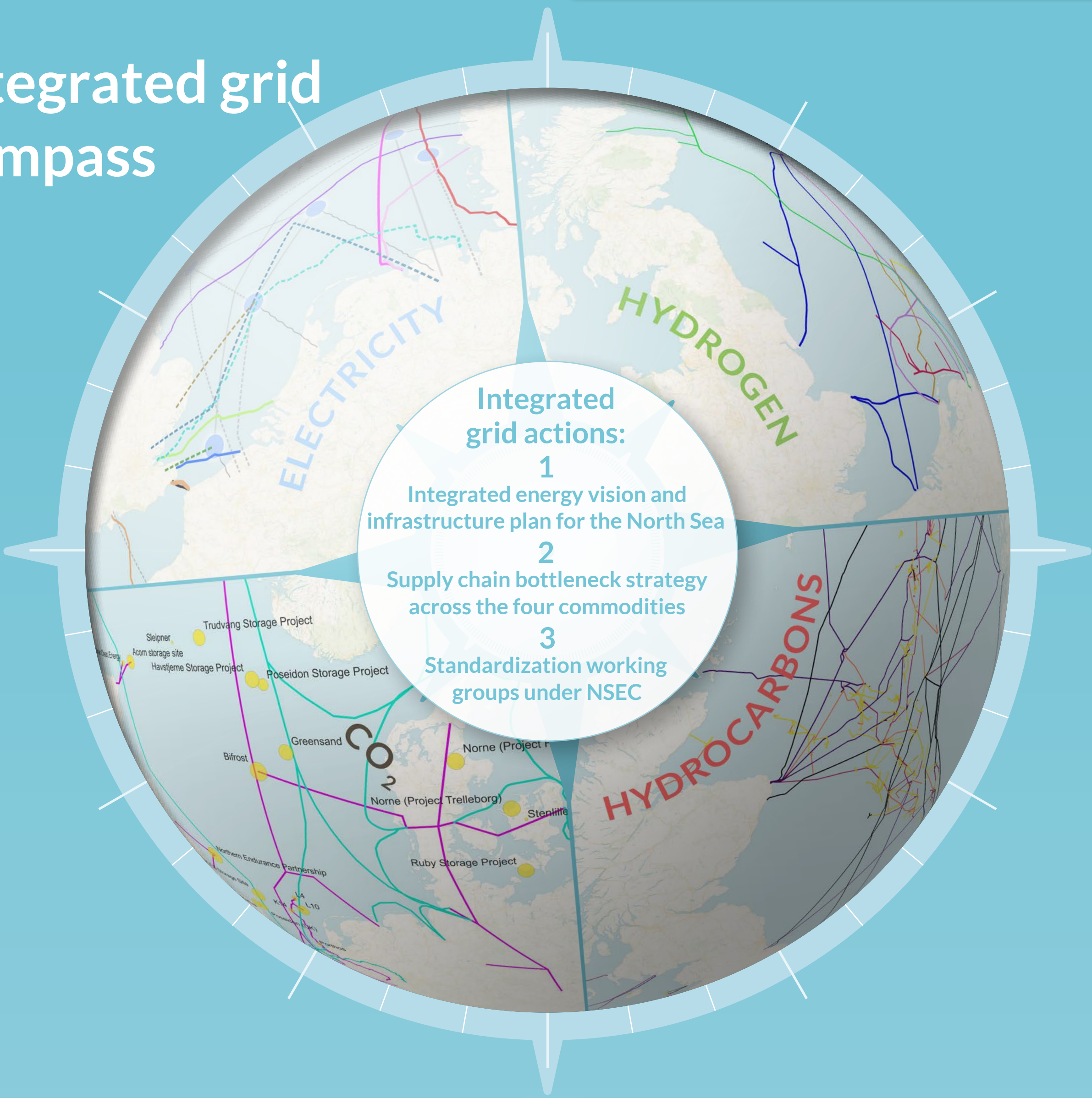
Electricity

- Extend European (HVDC) interconnectors and develop HVDC circuit breakers
- Develop a European supply chain and critical material plan
- Develop an offshore market design (bidding zones)
- Develop cost-sharing and financing guidelines for interconnectors

Hydrogen

- Create a long-term European H_2 grid and storage plan
- Develop legal, regulatory and market frameworks on offshore H_2
- Standardize and harmonize H_2 interoperability and quality

Integrated grid compass



CO_2

- Expand cross-border infra with a pan-North Sea body to coordinate efforts
- Develop regulatory frameworks and standards for transport and monitoring
- Develop trade and cooperation agreements (EU-UK)

Hydrocarbons

- Create a joint strategy on decommissioning efforts and timelines
- Improve data sharing on decommissioning
- Enable certification of pipeline re-use for CO_2 & H_2

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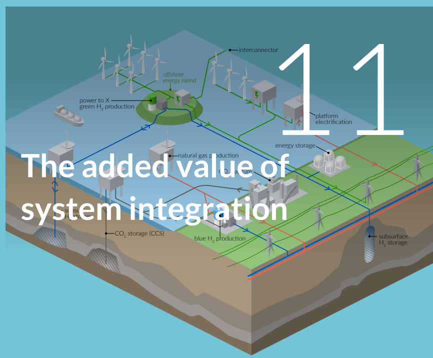
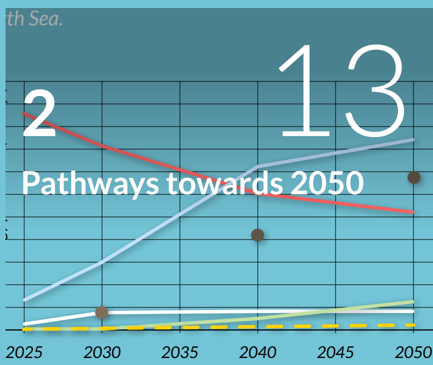




Commodity	Action	Sub-commodity	Action
Electricity	Extend international (HVDC) interconnections	Offshore wind	Appoint areas for further development
	Develop an international supply chain and critical material plan		Ensure parallel development of supply (industrial) demand & storage
	Develop offshore market design (bidding zones)		Close the business gap with relevant support mechanisms
	Develop cost-sharing and financing guidelines for interconnectors	Marine energy	Develop hybrid offshore tenders
			Accelerate scale-up with support schemes & demonstration areas
Hydrogen	Create long-term EU H_2 grid and storage plan	Green H_2	Create a development plan for offshore H_2 value chains
	Develop legal, regulatory and market frameworks on offshore H_2		Secure offtake and develop a market framework
		Blue H_2	Define timeline for transition period from blue-green H_2. Align blue H_2 with natural gas demand
	Standardize and harmonize H_2 interoperability (quality)		Provide investment security on blue H_2 assets
CCS	Expand cross-border infra with pan-North Sea body to coordinate efforts	CO_2	Resolve long-term cross-border liability and market alignment (EU-UK)
	Develop regulatory framework & standards for transport and monitoring		
	Develop trade and cooperation agreements (EU-UK)		Provide long-term market incentives
Natural gas	Create a joint strategy on decommissioning efforts and timelines	Natural Gas	Create a reliable long-term market outlook for production, import, storage, demand and decommissioning
	Improve data sharing on decommissioning		Enable platform electrification
	Enable certification of pipeline re-use for CO_2 & H_2		Reduce spatial impact of natural gas (decreased helicopter use)

1. The need for an international and integral vision on the North Sea Energy transition

The North Sea region has a significant low-carbon energy potential and is poised to become 'Europe's green power plant'[1]. Europe has committed to reduce its emissions by 55% by 2030 and achieve climate neutrality by 2050. This requires a substantial expansion of offshore wind capacity, alongside emerging technologies like floating solar, offshore hydrogen production, transport & storage and carbon capture & storage (CCS), as well as the systematic phase-out of gas exploration and production.

This expansion will be extremely challenging without an integrated and coordinated approach for the North Sea. The North Sea Energy (NSE) research program employs the concept of Offshore System Integration to identify options for reducing the costs, time, emissions, space and (human) capital required to realize the central role of the North Sea envisioned in the energy transition. Smart synergies are possible between offshore wind, marine energy, CCS, natural gas and hydrogen developments, presenting a unique opportunity for the North Sea countries to become and remain a pioneering region and innovation nucleus for global offshore energy solutions.

An integrated vision and roadmap are essential to unlock the North Sea's climate-neutral energy potential while optimizing its value for society and nature. Information is needed on the current role and future potential of energy supply, transportation, demand, conversion, and storage in the North Sea. Subsequently, short-term actions are required to enable the integration of the energy system. Such a roadmap can provide clarity and certainty to policymakers, project developers, and society.

North Sea Energy vison on system integration in the North Sea in 2050

The North Sea Energy consortium envisions the North Sea as a thriving energy region that has achieved carbon neutrality in 2050, perhaps even becoming a net negative carbon sink for Europe. Offshore energy system integration is seen as an enabler to accelerate low carbon and renewable energy options that provide reliable, low-cost energy sources for industry and other end-users on its coastline and in the hinterland. Strategic sector coupling allows deeper and faster reduction of CO_2 emissions, more efficient use of marine space and effective use of energy infrastructure for conversion, transport and storage of energy commodities. A well-integrated offshore energy system enhances energy security and resilience, reducing dependence on external energy sources and strengthening Europe's strategic autonomy. This secures livelihoods to millions of people and creates new sustainable jobs for the future. Offshore system integration can provide synergies with non-energy stakeholders to develop solutions that have positive impacts on nature and safety as well as contribute to sustainable food production and to the circular economy.

The North Sea Energy roadmap presented in this whitepaper outlines updated exploratory transition pathways for offshore wind, marine energy, hydrogen, CCS, and natural gas in an integrated assessment towards 2050[2]. These pathways are based on insights gathered during a participatory process with stakeholders both inside and outside the consortium and are aligned with national and European strategies, ambitions and targets.

In this phase of the North Sea Energy program, additional emphasis is placed on developing energy infrastructure visions towards 2050 for the four key energy commodities in the research program: electricity, hydrogen, CO_2 and natural gas.

Within the consortium, we have identified possible strategies to deal with challenges for system integration and have formulated actions on several main themes for all North Sea stakeholders. Additionally, we have identified sets of key actions for six offshore energy technologies and commodities (offshore wind, marine energy, offshore green hydrogen, blue hydrogen, offshore CO_2 transport and storage, and natural gas) to accelerate their development and strengthen their role in the offshore energy transition. By implementing these actions, stakeholders can take significant steps towards harnessing the energy potential of the North Sea while respecting the carrying capacity of our economy, society and nature.

1 Unlocking the North Sea as a Green Powerplant | North Sea Wind Power Hub
2 See https://northseaenergyroadmap.nl/pathways-towards-2050

The offshore energy transition on the North Sea

The transition to renewable and low-carbon energy sources in the EU

Energy independence has become a key topic after the invasion of Ukraine. The REPowerEU plan has been launched to decrease energy dependence on Russia by saving energy, diversifying sources and increasing the production of clean energy[3]. This energy independence on countries outside of Europe will go hand in hand with an increase of energy production and trade within the European countries in the coming years.

In the EU, the energy sector is responsible for an outstanding 75% of CO_2 emissions[4]. The transition from fossil fuels to renewable energy sources is therefore seen as a key driver for combatting climate change. Within the EU, 42.5% of the total electricity supply needs to be produced from renewable energy sources by 2030, with the goal of reaching a 100% by 2050.

Next to this, as outlined in the Draghi report, European industrial competitiveness could be increased by expanding its domestic renewable energy production[5]. The combination of decreasing CO_2 emissions, increasing energy independence and increasing European competitiveness, makes increasing the production of renewable energy one of the spearheads of EU policy.

Key focus on energy infrastructure in upcoming regulatory packages relevant for the North Sea energy infrastructure

The **European Grids Package** is to be proposed in Q1 2026 as part of the Affordable Energy Action Plan "Building on the actions of the Grid Action Plan adopted in 2023, the Commission will put forward a European Grid Package consisting of legislative proposals and nonlegislative measures to, among others, simplify the trans-European energy networks (TEN-E Regulation), ensure cross-border integrated planning and delivery of projects, especially on interconnectors, streamline permitting, enhance distribution grid planning, boost digitalisation and innovation as well as increase visibility of manufacturing supply needs. It will follow a top-down planning approach, integrating regional and EU interests and develop effective cost sharing mechanism (e.g. for cross-border projects), for an optimised energy system."

CO_2 transport and storage regulatory package (2026)
"The Commission will start preparatory work on a possible future CO2 transport and storage regulatory package, which would consider issues such as market and cost structure, third-party access, CO_2 quality standards or investment incentives for new infrastructure."

The origins of energy production at the North Sea
In the 1960s, offshore production of natural gas, and later oil, marked the first offshore energy activities in the North Sea[6]. The area has developed into a crucial energy production region and has been critical for the supply of natural gas to mainland Europe. In the past two decades, the production of offshore hydrocarbons has been in decline and decommissioning efforts are intensifying. This warrants an orderly phase-out of infrastructure that is not needed anymore, but also provides opportunities for newcomers in the offshore energy transition, such as hydrogen and CO_2 transport and storage, where existing assets can be reused for new energy carriers.

The transition to renewable energy production at the North Sea

The decrease of hydrocarbon production offshore is partially offset by an increase in renewable energy sources. Offshore wind is expected to play a pivotal role in the future energy supply, accounting for approximately 30% of the total European electricity production by 2050[7]. In February 2025, the EU published an action plan on affordable renewable energy, highlighting the important role for offshore energy infrastructure[8]. It is foreseen that the North Sea will fulfil a crucial role in the European energy system, due to its shallow waters and existing energy infrastructure.

The energy carriers in a renewable energy system on the North Sea

The future renewable energy system will be associated with different energy carriers than the fossil-based system of the past decades. Due to the intermittent nature of renewable energy sources, flexibility is essential in the future energy system. Interconnected infrastructure, smart conversion and energy storage play a crucial role in achieving this. Hydrogen production using electrolysis is expected to play a major role here, with separate targets and infrastructure plans already developed and approved. Until 2050, natural gas will continue to be an important part of the energy supply, most likely combined with carbon capture and storage providing multiple

3 REPowerEU
4 Renewable energy targets - European Commission
5 The Draghi report on EU competitiveness
6 The North Sea Oil History
7 Offshore wind energy in Europe
8 Affordable Energy - European Commission

options for low-carbon hydrogen production. Currently there is a high import dependency on natural gas. This dependency is expected to remain for the near term but can be reduced and diversified with increased hydrogen import capacity. This also provides a balanced mix for hydrogen supply.

All in all we need to find the right balance in the offshore energy domain for the main four interlinked commodities: electricity, hydrogen, CO_2 and natural gas. In the coming decades, their role within the energy transition will change. Understanding how each commodity interacts with the others will help in timing infrastructure, supply, storage and demand developments appropriately.

We need to find the right balance in the offshore energy domain for the four main interlinked commodities.

The added value of system integration

Managing multi-use spatial challenges in the North Sea

Since the North Sea is one of the busiest seas in the world, it faces significant spatial challenges due to the multi-use of the area. Although this whitepaper focuses mainly on the 'energy system' of the North Sea, the 'total system' also includes, amongst others, fisheries, shipping routes, military activities and protected marine areas. The North Sea fulfills various functions and the ecological, societal and economic values of this area can result in conflicts among various stakeholders. Looking for synergies between the functions and adequately managing these interests, possibly prioritizing them and reaching consensus on the various functions, are crucial for smooth collaboration and alignment but can be highly complex.

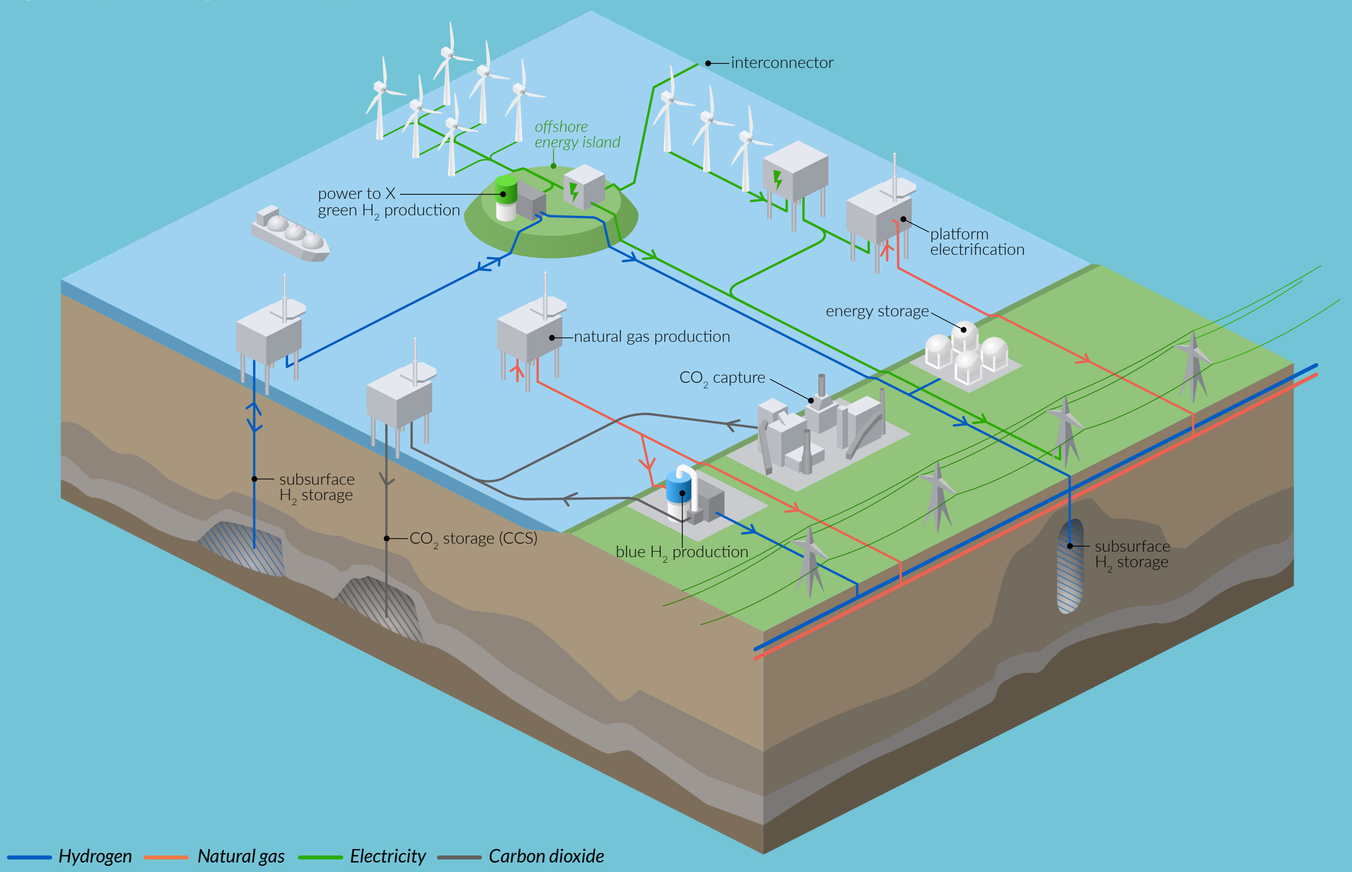
Enhancing cross-border energy cooperation in the North Sea region

The North Sea is surrounded by nine countries, each with their own targets, legislation and infrastructure plans. When looking at the energy system from a cross-border perspective, various sources and demand clusters could be coupled, thereby increasing the efficiency of energy infrastructure and driving down costs. This not only applies to the infrastructure and asset deployment, but also international agreements, legislation and standardization.

The interaction between the four energy commodities

The further development of the energy commodities is largely dependent on the others. For example, in order to re-use existing oil and gas infrastructure (such as wells, pipelines,

Figure 1 System integration concepts in the North Sea[9]



9 System Integration Concepts – North Sea Energy

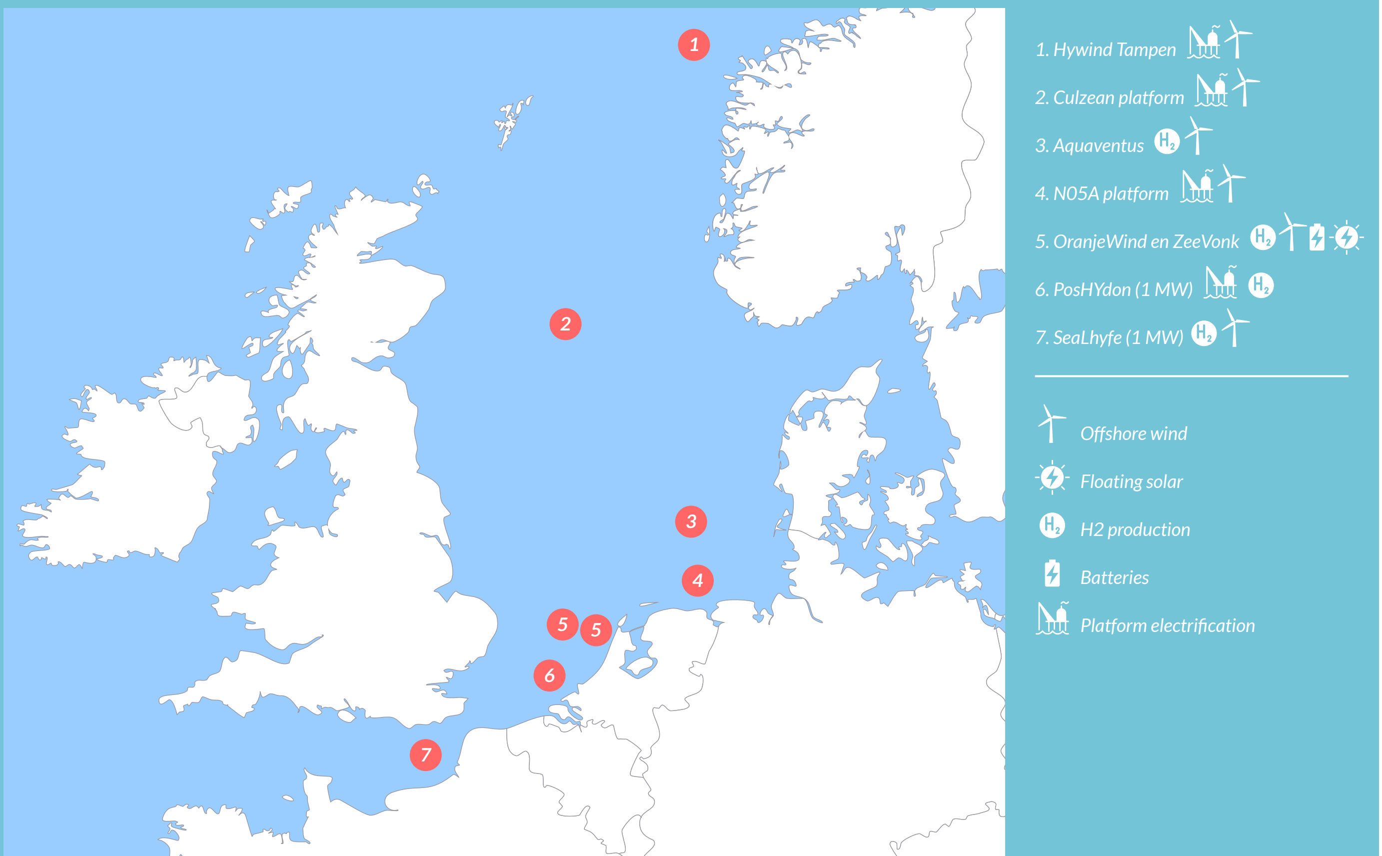
platforms or subsea structures for instalment) for transport and storage of CO_2 or hydrogen, it should be clear where this is technically possible and when decommissioning is planned. Next to this, due to its intermittent behaviour the value of offshore wind will rely on energy flexibility in the system such as (offshore) hydrogen conversion and or storage solutions. This suggests that a cross-commodity view is beneficial for further development plans.

System integration as a solution

Many of the above-mentioned challenges can be tackled by taking a system perspective on the North Sea energy system. The North Sea Energy program is based on the concept of offshore system integration, involving the strategic coupling of all dominant low-carbon energy developments in the North Sea, including offshore wind deployment, CCS, energy hubs & islands and energy interconnections, hydrogen infrastructure, energy storage, and more. This system integration concept couples there sectors by integrating infrastructure, services and logistics, and making multifunctional use of space. From the energy perspective, this suggests to not individually consider the energy carriers, commodities and infrastructure assets, but regard them as part of one holistic and integrated energy system. By approaching the North Sea as an integrated system, the costs of the energy transition can be reduced, security of supply can be enhanced, the spatial claim and impact on nature can be mitigated, and energy system development times can be decreased.

An example of an integrated North Sea energy system is depicted in *Figure 1*. Various (pilot) projects focusing on combining different energy commodities are already being deployed on the North Sea, as illustrated in *Figure 2*.

Figure 2 Graphical overview of system integration projects that are currently being developed on the North Sea, where various energy commodity functions are combined



2. Pathways towards 2050

This whitepaper examines key trends foreseen for electricity, hydrogen, CO_2 and natural gas in the North Sea region in the coming decades. The scenarios that form the basis of the 2050 pathways are TYNDP Distributed Energy (DE) scenario and Global Ambition (GA) scenario from ENTSO-E and ENTSOG for all North Sea countries, enriched with more focus using the II3050 National scenario for the Netherlands[10].

The scenario studies are complemented with insights from detailed regional or national studies on for example offshore hydrogen production and CCS. It is important to note that this approach explores and sketches one future scenario for the North Sea region that is also categorized as ambitious for the North Sea region. This approach is taken to identify what infrastructure for the North Sea would be required and to identify bottlenecks and resolving actions for making this ambitious scenario reality.

The trends of these potential pathways are explained per energy commodity below. *Figure 3* gives a graphical overview of the included countries and the applied scenarios. *Figure 4* provides the possible pathways for the offshore commodities, based on the scenario outcomes and additional sources.

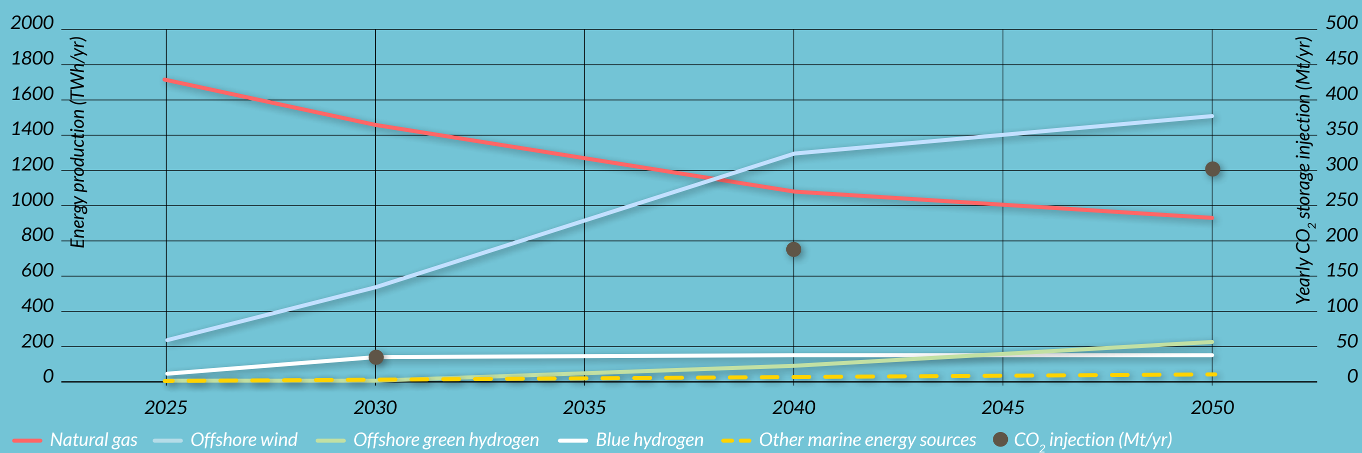
10 See for more details: dossier chapters, N. Dooley, R. van Zoelen and M. Vos, "International North Sea Collaboration: from buzzword to concrete actions," North Sea Energy, 2025, and S. Blom, J. van Stralen, L. Eblé, I. Magan and S. Hers, "Public Value Assessment of Offshore System Integration," North Sea Energy, 2025

Figure 3 Map of the North Sea countries and the applied scenarios[11]

Countries included in TYNDP scenarios *Focus countries NSE*
Dutch focus with NAT & DEC scenarios II3050

11 Europe | MapChart

Figure 4 Indicative pathways for the offshore energy commodities for all North Sea countries, combining various sources[12]. A full explanation on the developed pathways can be read in the Dossiers file – 1 The potential for energy system integration on the North Sea.



12 Pathway sources: natural gas → country specific pathways, offshore wind → average of the modelled scenarios & ONDP Sea Basin report, offshore green hydrogen → NSWPH - Pathway 2.0, blue hydrogen à average of the calculated DE & GA scenarios, other marine energy sources → North Sea Energy, yearly CO_2 injection in the North Sea → Xodus report. Further details are provided in extensive Dossiers per energy commodity and can be downloaded at http://www.north-sea-energy.eu/reports

A rapid expansion of offshore wind and a steady growth of other marine energy sources

The North Sea countries have committed to an ambitious target of 120 GW by 2030 and at least 300 GW of offshore wind by 2050. Offshore wind shows a in such a pathway a very rapid increase and steep growth towards 2050. The steepest growth occurs between 2030-2040, which is required to meet the ambitious European targets. This means that the yearly production of the North Sea countries will increase almost tenfold towards 2050 yielding approximately 1500 TWh/yr.

Figure 4 also depicts a trendline on electricity production from other marine energy sources, such as floating solar, wave and tidal energy. Their share in the offshore energy system will start having a more significant role on a longer timescale. The EU Strategy on Offshore Renewable Energy envisions about 40GW of ocean technologies. The development of ocean technologies – such as solar, wave and tidal energy – has progressed steadily over the past few years, reaching a near commercial ready technology status for niche market applications. Floating PV systems gain track with demonstration projects being planned towards the two-digit MW scale. The first large growth phase from 2030 (8GW) onwards will result in almost 20 GW of installed capacity at the end of that decade. For the year 2050, the capacity is expected to reach 30 GW, corresponding to 75% of the EU target of 40 GW by 2050 for ocean energy technologies. Additional information on the offshore electricity expansion pathways can be read in Dossier 1 – Electricity.

A gradual decrease in natural gas production

The natural gas production of the North Sea countries has been steadily declining for a few years now with only marginal new developments. This trend is expected to decrease further until 2030, after which it will eventually decrease to approximately 50% of the current production. However, this is greatly dependent on new policies that might be developed in the coming years to decrease energy import dependence. The recently approved Sector Agreement on Gas Extraction in the Netherlands for example emphasizes the continued role of natural gas as a transition fuel until at least 2045, to reduce import dependency and ensure energy security[13]. It is expected that the Netherlands and Denmark will completely phase out their natural gas production by 2050, the UK is expected to produce only 5% of her current production in 2050, whereas Norway is anticipated here to continue natural gas production until the 2050s, with only a minor decline (from 1300 TWh in 2023 to 900 TWh in 2050). Next to the depletion and thereby phase-out of current oil and gas fields, platform electrification could result in a reduction in emission intensity of extraction activities. However, it should still be investigated where this is technically and economically feasible for new developments on the North Sea. A deeper analysis on potential pathways of natural gas can be found in Dossier 4 – Natural gas.

The interaction between green and blue hydrogen

Blue hydrogen and offshore green hydrogen production currently represents only a minor fraction of the energy commodities. For blue hydrogen, a shift towards implementation phase is expected in the next few years. Blue hydrogen is produced and used as an energy commodity as long as there is still oil and gas production and is thereby expected to be deployed at least until 2050 and is expected to phase out with natural gas production.

Green hydrogen is expected to be developed at a somewhat slower pace, as this technology is commercially still emerging. Various studies confirm that offshore conversion of electricity for hydrogen production could yield system benefits mainly by providing flexibility to the system and saving cost of both offshore and onshore electricity transmission. Depending

The ambitions for the North Sea countries require a tenfold increase of offshore wind production to 1500TWh/yr towards 2050.

13 Sectorakkoord gaswinning in de energietransitie

on their assumptions different studies show a wide range of estimates for the offshore installed capacity for offshore hydrogen from zero to around 100 GWe or even higher for study outliers (see *Figure 5*). The recently published Offshore Network Development Plan (ONDP) states 34 GW[14], equaling roughly 10% of installed wind capacity. The NSWPH system study indicates approximately 20% of offshore wind is directly converted to hydrogen via offshore electrolysis. Following these paths the offshore hydrogen production grows in our indicative scenario to around 225 TWh/yr in 2050. After the 2040s, the blue and green hydrogen pathways could converge and have comparable production around 2045 where blue hydrogen flattens towards 150 TWh/yr and offshore green hydrogen continuous its growth path in parallel with offshore wind deployment. A full analysis on the green and blue hydrogen trends can be read in Dossier 2 – Hydrogen.

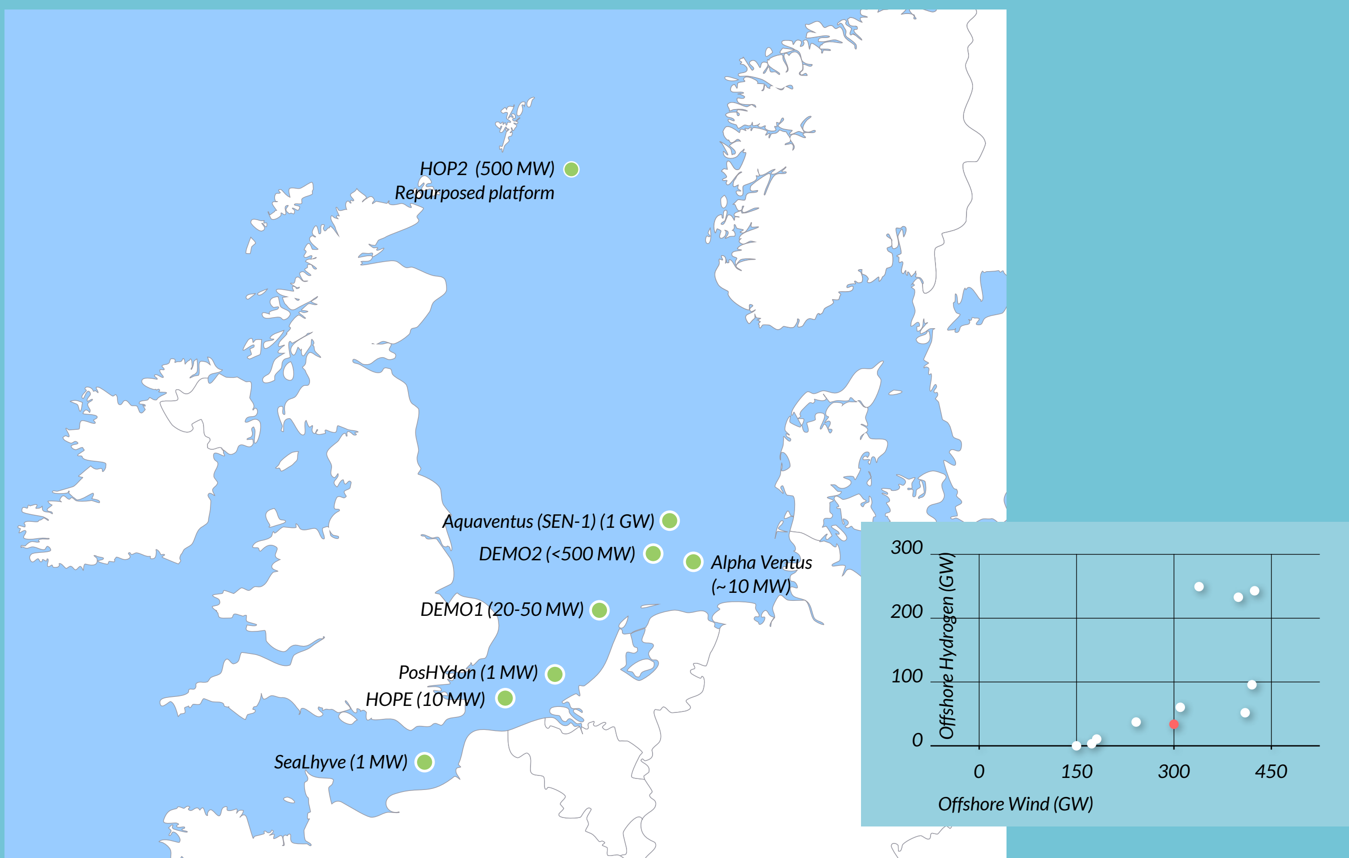
14 https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/ONDP2024/web_entso-e_ONDP_PanEU_240226.pdf

A gradual increase of CO_2 storage

Currently, there are only two operational CCS sites in Europe, both in Norway. In the coming years, various early commercial projects are expected to start, after which a significant increase in capacity is expected in the coming decades. In the near future, CCS will mostly be used for CO_2 capturing from industrial production activities. However, in the long-term, CCS could have a role in achieving negative emissions when used with biomass. The EU has the ambition to capture 50 Mt of CO_2 by 2030, 280 Mt by 2040 and 450 Mt by 2050[15]. Even though there is not a direct number stated for the North Sea, this region is expected to host the majority of the storage sites. The depletion and abandonment of gas fields in the coming years will allow for an increase in storage capacity. Next to this, storage in aquifers is likely to be deployed as well. A further explanation on CO_2 pathways can be read in Dossier 3 – CO_2.

15 In focus: Industrial carbon management

Figure 5 Offshore hydrogen projects and outlook in the North Sea. This figure shows (forthcoming) pilot and demonstration projects for offshore hydrogen production in the North Sea region. Graph bottom right indicates the relationship between installed offshore wind capacity and offshore hydrogen (in GWe) in future scenario studies.



3.
Commodity and grid action agenda

To fully deploy a renewable and low-carbon energy system which uses system integration as an implementation strategy for the energy transition on the North Sea, an action agenda is proposed that addresses the current key challenges. *Figure 6* contains the action agenda with commodity specific and grid actions that are required for a timely development of the offshore integrated energy system. Per commodity these actions are elaborated upon in the following sections. We conclude with an overview of general thematic actions that relate to the integration of multiple commodities.

Figure 6 Action agenda for offshore system integration with commodity specific and grid actions

	Grid actions	Commodity	Commodity actions
Electricity	Extend international (HVDC) interconnections	Offshore wind	Appoint areas for further development
	Develop an European supply chain and critical material plan		Ensure parallel development of supply, (industrial) demand & storage
	Develop offshore market design (bidding zones)		Close the business gap with relevant support mechanisms
	Develop cost-sharing and financing guidelines for interconnectors	Marine energy	Develop hybrid offshore tenders
			Accelerate scale-up with support schemes & demonstration areas
Hydrogen	Create long-term European H_2 grid and storage plan	Green H_2	Create a development plan for offshore H_2 value chains
	Develop legal, regulatory and market frameworks on offshore H_2		Secure offtake and develop a market framework
		Blue H_2	Define timeline for transition period from blue-green H_2. Align blue H_2 with natural gas demand
	Standardize and harmonize H_2 interoperability (quality)		Provide investment security on blue H_2 assets
CCS	Expand cross-border infra with pan-North Sea body to coordinate efforts	CO_2	Resolve long-term cross-border liability and market alignment (EU-UK)
	Develop regulatory framework & standards for transport and monitoring		
	Develop trade and cooperation agreements (EU-UK)		Provide long-term market incentives
Natural gas	Create a joint strategy on decommissioning efforts and timelines	Natural Gas	Create a reliable long-term market outlook for production, import, storage, demand and decommissioning
	Improve data sharing on decommissioning		Enable platform electrification
	Enable certification of pipeline re-use for CO_2 & H_2		Reduce spatial impact of natural gas (decreased helicopter use)

Targets & planning *Standardization & regulation* *Market development* *Technology development*

Electricity

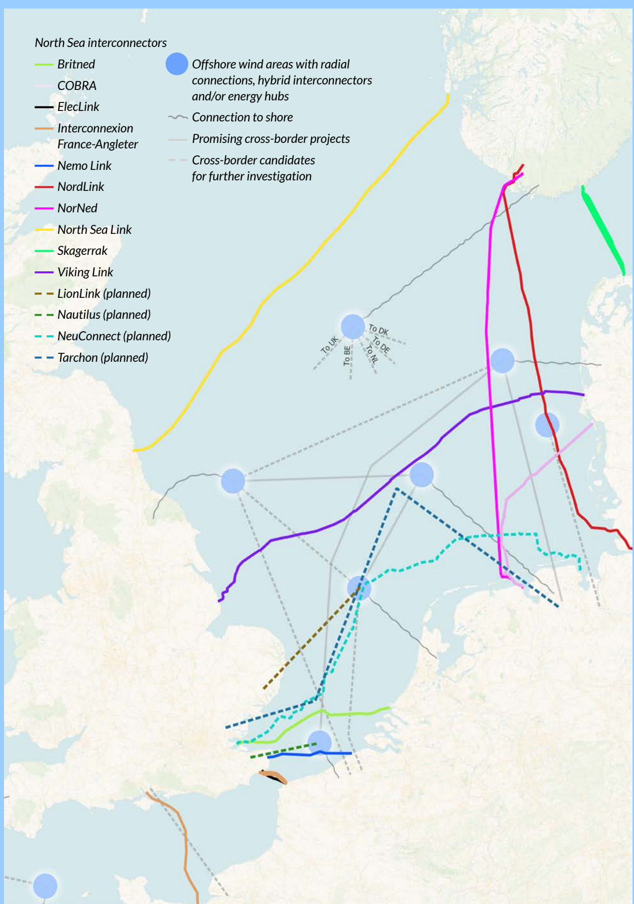
Grid actions: towards an internationally connected network

For the offshore electricity grid, several actions are required that focus on a European connected network with the following timeline:

2030: Focus on radial connections and the first offshore hybrid elements to achieve faster deployment speeds
2040: Development of the first interlinked offshore clusters, with further increases towards 2050
2050: Continued expansion of offshore wind capacity and other marine energy sources, with a focus on reinforcing existing transmission corridors

Figure 7 The North Sea electricity grid envisioned in the North Sea Energy program, with both existing and planned interconnectors.

Disclaimer: maps are a representation of announced and envisioned plans and projects in the public domain and therefore subject to frequent updates and may not always reflect the most recent information. For more detailed spatial information and updates see: North Sea Energy Atlas



A visualization of the envisioned electricity grid can be seen in *Figure 7*. A full explanation on the electricity grid vision and actions towards 2050 can be read in Dossier 1 – Electricity. On the short term, adequate technology innovations are required to efficiently transport large amounts of offshore wind energy over long distances. For this, new technologies like HVDC circuit breakers and hybrid interconnectors are essential. Standardization is also crucial for ensuring interoperability between various systems and countries. Additionally, pilot projects are vital for testing and demonstrating these solutions in real-world applications at scale. Together, this builds towards an internationally connected electricity grid.

Strengthening the offshore electricity network will require significant investments, estimated at over €50 billion by 2030, €150 billion by 2040, and an additional €60 billion by 2050[16]. It should be avoided that the countries with the most renewable energy production capacity have to bear all infrastructure costs. The European Commission, under the new TEN-E Regulation, will develop guidelines for a cost-benefit sharing system to facilitate international collaboration. Additionally, market conditions need to support hybrid interconnections between countries. Agreement should be reached on how offshore bidding zones will be developed and which agreements will be made between countries (specifically the UK, Norway and the EU). Appropriate regulatory frameworks should be developed in parallel. Especially the development of hybrid interconnectors and energy hubs requires a supportive regulatory framework. This includes clear guidelines for risk bearing, cost allocation, revenue sharing, and operational responsibilities among the various involved parties.

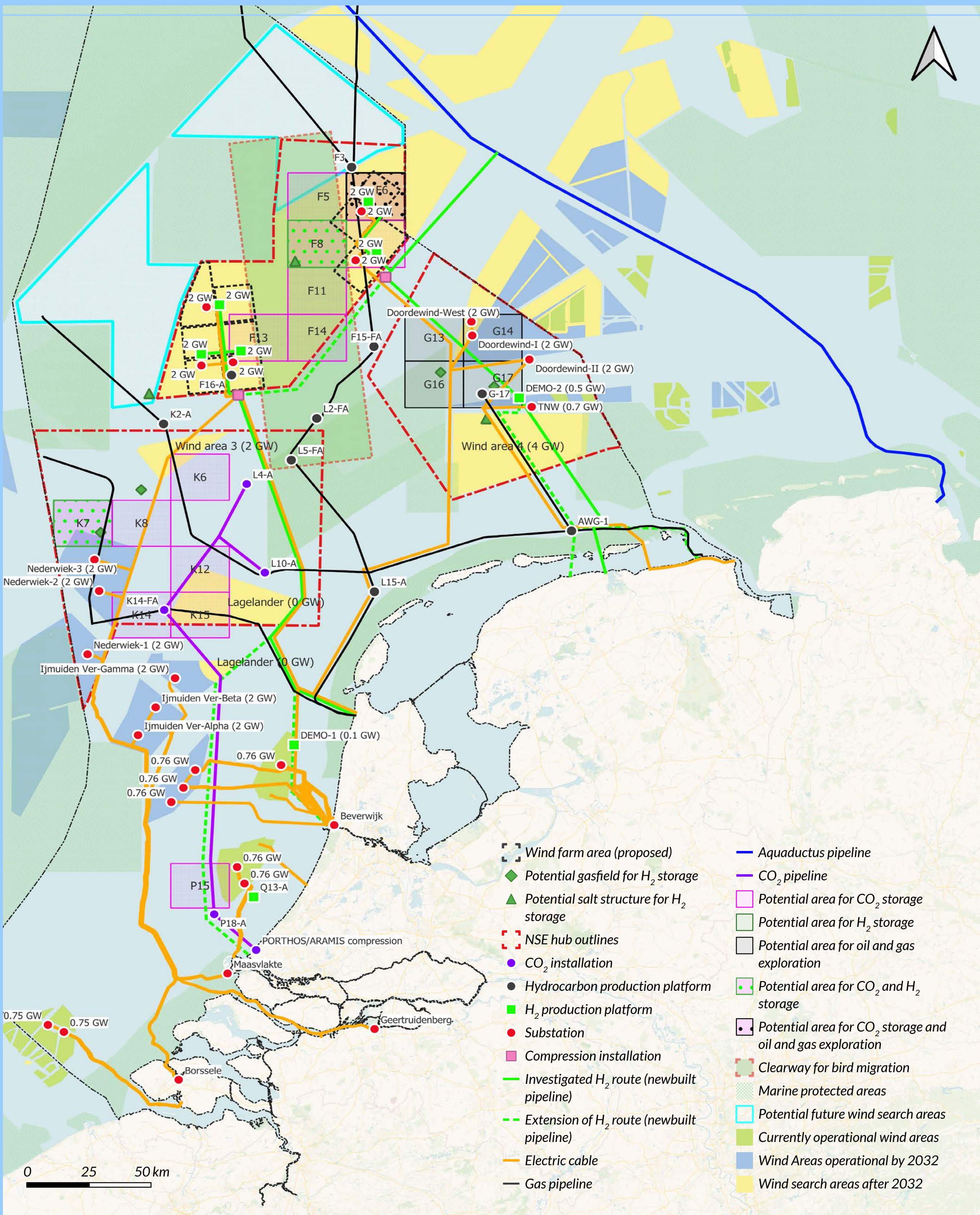
To fully deploy an offshore electricity network, drastic amounts of (scarce) materials are needed (for further information see D4.5 Material Flow Analysis[17]). To avoid supply chain disruptions and shortages within certain countries, an international supply chain and critical material plan should be drafted that addresses these issues and investigates where bottlenecks could arise. The supply chain not only relates to materials, but also sufficient capacity of human capital, port availability and vessels (for further information see D2.3 Human Capital Agenda[18] & D6.3 Logistics[19]). All are crucial for the massive expansion of the electricity grid. Smart solutions should be investigated where various grid and project plannings are aligned to optimally schedule further deployment.

16 ENTSO-E TYNDP 2024 Sea-Basin ONDP Report – Northern Seas Offshore Grids
17 M. Kamps and R. Elbing, "Material Flow Analysis and Criticality Assessment," North Sea Energy, 2025.
18 N. Reijmers and O. de Vreede, "Human Capital agenda for offshore energy system integration," North Sea Energy, 2025
19 V. Uritsky, J. Mohanan Nair, "Logistics", North Sea Energy, 2025

Figure 8 Vision of the North Sea in 2050 with blueprints of the 3 NSE hubs according to the ambitious NSE5-NAT scenario with 70 GW offshore wind and 20 GW offshore hydrogen production, and transport infrastructure of electricity and hydrogen (all new built in this scenario). More information can be found in D1.3[22].

Disclaimer: maps are a representation of announced and envisioned plans and projects in the public domain and therefore subject to frequent updates and may not always reflect the most recent information. For more detailed spatial information and updates see: North Sea Energy Atlas

22 R. Groenenberg, J. Fatou Gomez, F. Janssen, H. Yousefi, G. Jayashankar and A. Martin Gil, "Storylines and blueprints for the integration of three NSE hubs in the future energy system of The Netherlands and the North Sea," North Sea Energy, 2025



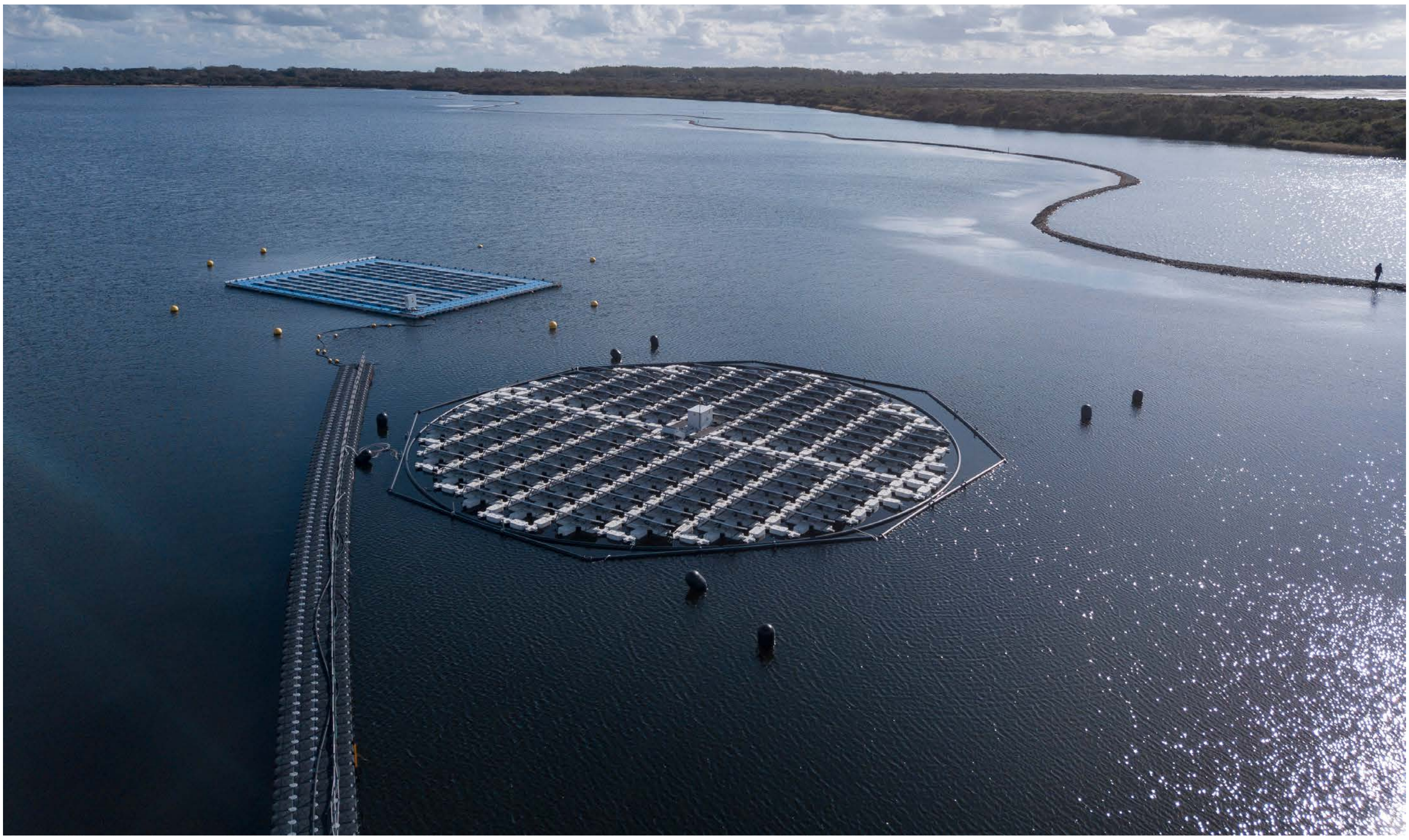
Commodity specific actions: ensure the parallel development of energy flexibility and an offtake market for offshore wind, and ensure the further development of other marine energy sources

To achieve the ambitious offshore wind targets, designating areas and coordinating marine-spatial planning are essential. This process should initiate early stakeholder discussions and planning processes to meet the 2030-2040 goals. It is important that the planning not only includes offshore wind, but also focuses on existing oil and gas production, hydrogen production, energy storage, and carbon capture and storage (CCS). Examples on approaches followed in the North Sea Energy program for the Dutch offshore can be found in D1.3[20] (see *Figure 8*) and strategies for the multi-use functions of the North Sea area are available in D6.4[21] Offshore Multi-use in the North Sea area.

20 R. Groenenberg, J. Fatou Gomez, F. Janssen, H. Yousefi, G. Jayashankar and A. Martin Gil, "Storylines and blueprints for the integration of three NSE hubs in the future energy system of The Netherlands and the North Sea," North Sea Energy, 2025

21 A. Satish, M. de Respinis, J. Breuer, O. Khatraoui and P. Marcus, "White paper – multifunctional spatial use at the North sea and the implications of future energy infrastructure," North Sea Energy, 2025

The future of offshore wind will partly be determined by the development of sufficient electricity demand and flexibility solutions.



The future of offshore wind will partly be determined by the parallel successful development of sufficient (onshore) electricity demand and flexibility solutions (for further information see D3.2 Business models for value chains for new offshore energy concepts[23] & D3.3 Business case assessment for the offshore value chain[24]).

A key point in here is the electrification of large industrial demand clusters, either through process electrification or indirect electrification through power-to-X solutions. Large investments on storage, (industrial) flexible demand and energy conversion are also required, which means that the alignment of offshore wind, infrastructure and flexibility solutions is critical. This concerns both short-term electricity storage (batteries), as well as long-term energy storage in the form of hydrogen (derivatives). For an optimally integrated energy system, the parallel development of supply, (flexible) demand, conversion, transport and energy storage is crucial.

From a societal value point of view it is crucial to avoid stagnation on the offshore wind deployment and close the business gap with relevant support mechanisms to bridge the current rise in costs and uncertainty in stable revenues. As the other offshore energy solutions offshore wind requires substantial upfront capital investment, making project de-risking and access to lower-cost financing critical to their viability.

Besides offshore wind, the scale-up of other offshore renewable energy sources such as floating solar, wave and tidal energy, is widely recognized as a critical part of the renewable energy system. For this, rapid scale-up and replication is needed, together with adequate planning and support schemes to increase the learning potential for these technologies. For floating solar it is important that sufficient demonstration projects are deployed, with preferably a focus on recycled materials to reduce the impact on critical raw materials.

Because of the synergistic effects between offshore wind and other marine energy sources, the deployment of the latter should beneficially coincide with the quick development of offshore wind. This could be achieved through integrated offshore tenders that allocate certain areas to multiple energy sources, resulting in a reduced variability of energy supply and an optimal use of the available infrastructure. Where possible, regulatory barriers that hamper the co-use of wind areas should be removed. An option would be to include the efficient use of space and offshore infrastructure as part of the evaluation criteria for offshore demonstration and deployment areas.

23 R. van Zoelen, S. Mahfoozi,. D. Boer, N. Dooley, "Business models for value chains for new offshore energy concepts", North Sea Energy, 2025
24 R. van Zoelen, D. Boer, S. Mahfoozi, "Business case assessment for the offshore value chain", North Sea Energy, 2025

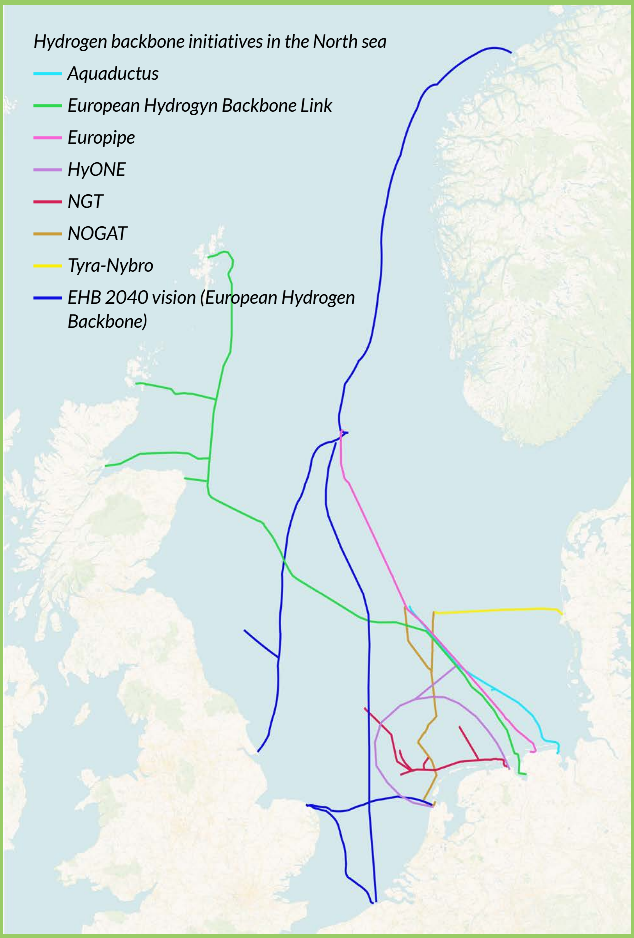
Hydrogen

Grid actions: a European infrastructure plan including standardization and the development of market and legal frameworks

An overview of all the offshore hydrogen grid project can be seen in *Figure 9*. A full explanation on the hydrogen grid vision and actions towards 2050 can be read in Dossier 2 - Hydrogen. On the short term, a coherent international plan on offshore hydrogen production, infrastructure and storage should be created. The new NSEC ambitions to start a dedicated support group on green hydrogen are already a good starting point[25]. It should be clear where new infrastructure will be developed, which parts of legacy infrastructure could be re-used and the offshore storage potential should be identified. Further research is required on the technical and economic feasibility of reusing the subsea infrastructure. For this potential re-use, adequate planning is required, since natural gas will still have a role on the North Sea in the coming decades.

Figure 9 The planned hydrogen backbone initiatives in the North Sea.

Disclaimer: maps are a representation of announced and envisioned plans and projects in the public domain and therefore subject to frequent updates and may not always reflect the most recent information. For more detailed spatial information and updates see: North Sea Energy Atlas



Strengthening international collaboration among governments is crucial to align strategic planning and decision-making for a fully meshed hydrogen grid. For this, it is advised that a centralized European working group or even institution can drive hydrogen infrastructure developments and incentivize cross-border investments, for example ENNOH, in close connect with the GNSBI to coordinate spatial planning[26]. Standardization and harmonization between countries are necessary to maximize the full learning potential and speed of deployment and allows for interoperability in the region and optimally make use of the offshore grid. Lastly, due to the immaturity of the technology, an international portfolio of demonstration projects is required to test the integration of hydrogen in the grid with sufficient cross-border knowledge sharing to fast-track the development and deployment.

Offshore hydrogen deployment requires intensive alignment between offshore TSOs for electricity and hydrogen as offshore hydrogen typically provides intertwined costs and value across the typically drawn sectoral borders. Integrated TSOs as found in Denmark (Energinet) and the United Kingdom (National Energy System Operator) have the benefit of the integrated perspective on grid development for both electricity and hydrogen. It its absence in other countries intensive alignment needs to be strived for.
Cross-country coordination (e.g. ENNOH+UK+NO) should be maximised as soon as possible to identify and progress possible valuable interconnectors and cooperate on the suggested actions above.

25 The North Sea as Europe's Green Energy Hub
26 Welcome | ENNOH

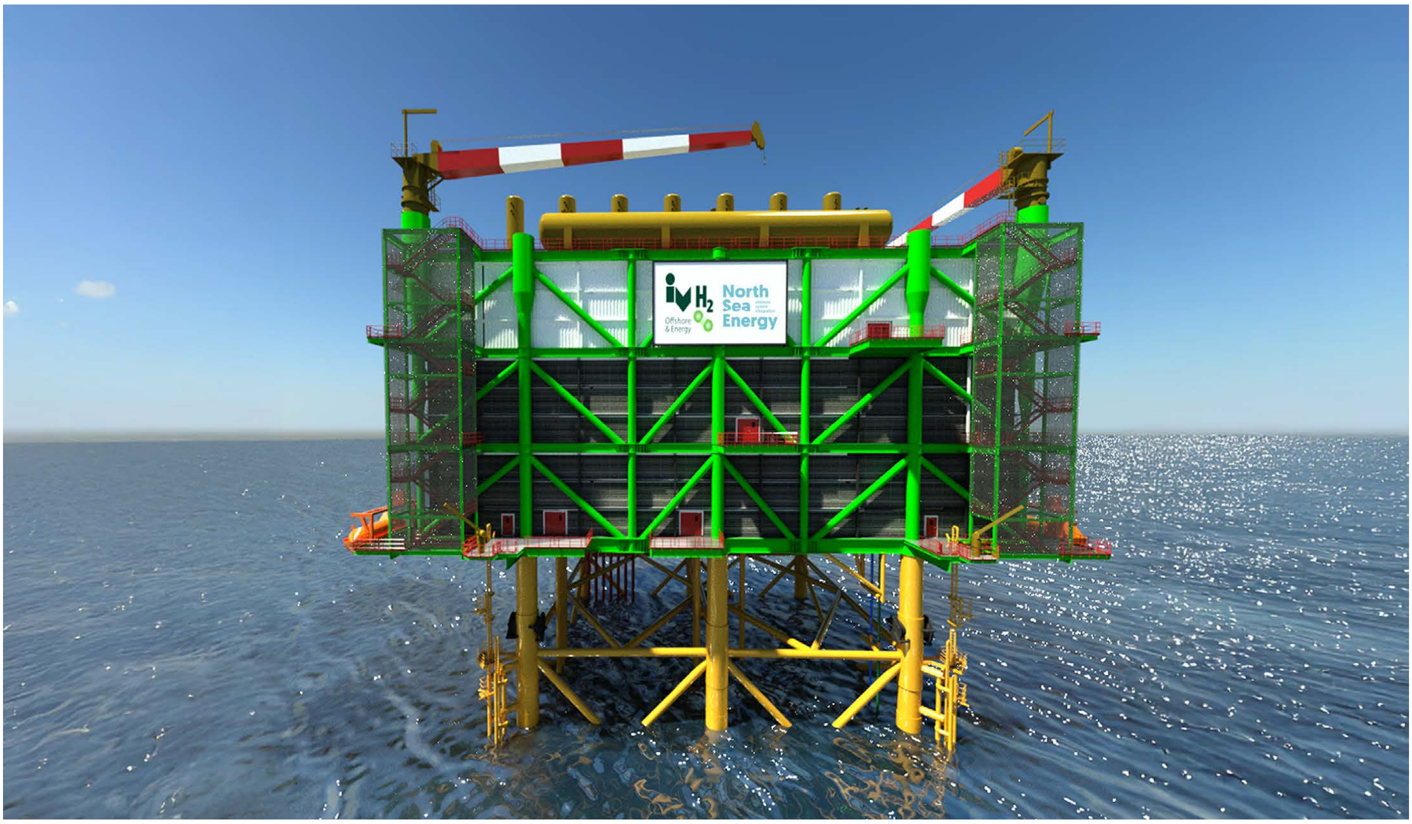
Commodity specific actions: create a long-term roadmap on the interaction between blue and green hydrogen

Offshore green hydrogen production is still in its early stages, but the region is globally leading with several pilot projects currently ongoing or planned in the North Sea area. To develop a full value chain, more pilot projects are needed to advance technologies like electrolysis on platforms, hydrogen transport through pipelines, and storage in compressed vessels or underground structures. Rapid development is essential to meet targets, requiring stakeholder coordination, deployment plans, harmonized regulations, and long-term planning across sectors and borders. A full value chain roadmap should be developed to provide clarity in the coming years.

A very important aspect of the value chain is ensuring sufficient demand, since security of demand and a clear market framework are crucial for a closing business case. Associated investment risks on hydrogen can be further read in D3.2 Business models for value chains for new offshore energy concepts[27]. In the coming years it is advised that uncertainties are removed as much as possible, together with attracting sufficient investments. This could be done through contracts for difference or double tender schemes (for example the H2Global Foundation[28]). Integrated tenders with subsidization across various commodities could be beneficial for the parallel development of hydrogen with for example offshore wind.

Even though the hydrogen commodity actions can apply to both green and blue hydrogen, it is important that blue hydrogen is supported in another way on the short term. Blue hydrogen is considered a transition technology towards green hydrogen, peaking production in the 2030s, after which it will not expand further. Since it is considered as a transition option, long-term clarity should be created on how long it will be deployed. Otherwise, it would be very difficult to attract sufficient investments. Next to this, it should become clear how the blue hydrogen demand relates to the overall natural gas demand, since a significant decrease for this is foreseen in the coming decades. In summary, a clear roadmap on blue and green hydrogen production is required, with a specific roadmap for offshore developments.

27 R. van Zoelen, S. Mahfoozi,. D. Boer, N. Dooley, "Business models for value chains for new offshore energy concepts", North Sea Energy, 2025
28 H2GlobalStiftung-What we do



CO_2

Grid actions: expand cross-border infrastructure & facilitate EU-UK cooperation

To ensure the continued growth and expansion of CCS in the North Sea, a series of strategic actions are crucial. These steps aim to establish an international CCS backbone, utilizing both existing and new infrastructure for long-term CO_2 storage. A visualization of the envisioned hydrogen grid can be seen in *Figure 10*. A full explanation on the CO_2 grid vision and actions towards 2050 can be read in Dossier 3 - CO_2.

In the short term, it is essential to focus on infrastructure planning by identifying suitable fields and locations for CO_2 storage. The strategy should describe at what point in time and under which conditions CO_2 storage is available, how much storage is needed, how much CO_2 can be imported from other regions and what the role of CCS will be in achieving negative emissions. This should be done by taking a broad perspective on other offshore activities that are being pursued, such as offshore wind and hydrogen storage and by conducting pre-competitive assessment of storage readiness levels. There can be potential overlap in wind and CCS areas, which can pose a risk for sufficient development. Conducting spatial modeling for route optimization and network architecture will enhance international CCS synergies. On a technology level, facilitating the re-use of existing infrastructure for CCS applications and continuing research on the behavior and impact of CO_2 impurities on the storage backbone are key steps. Secondly, it is important that a supportive regulatory framework is designed to allow for cross-border collaboration, transport, and monitoring, amongst others, to initiate the development of trade and cooperation agreements between the UK and the EU.

On a medium term, it would be highly beneficial if the system design and international planning are coordinated by a pan-North Sea body to align the efforts, with sufficient mandate to make decisions (for further recommendations see D7.3 International North Sea Collaboration[29]). This organization can also facilitate the sharing of technology and best practices among North Sea countries which will improve efficiency and

Figure 10 The envisioned North Sea CO_2 grid, consisting of planned CCS projects, shipping routes and pipeline routes for transportation.

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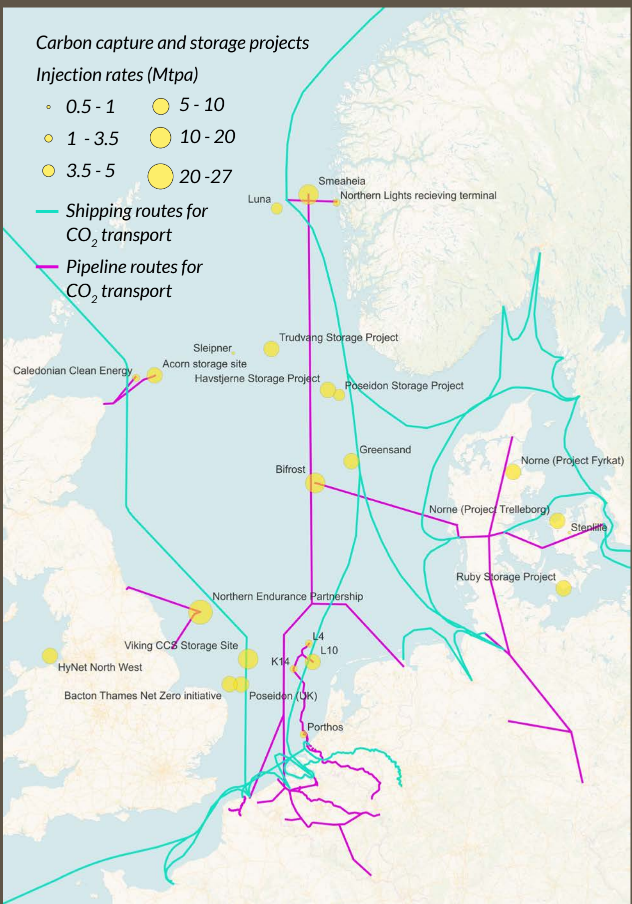


29 N. Dooley, R. van Zoelen and M. Vos, "International North Sea Collaboration: from buzzword to concrete actions," North Sea Energy, 2025

In the short term, it is essential to focus on cross-border CCS infrastructure planning.

speed of deployment. Next to this, North Sea-wide agreements should be made on nature-inclusive design and the mitigation of negative environmental impacts. Cross-border CO_2 infrastructure will have to be expanded, most likely supported by mechanisms such as the Innovation Fund and CEF[30].

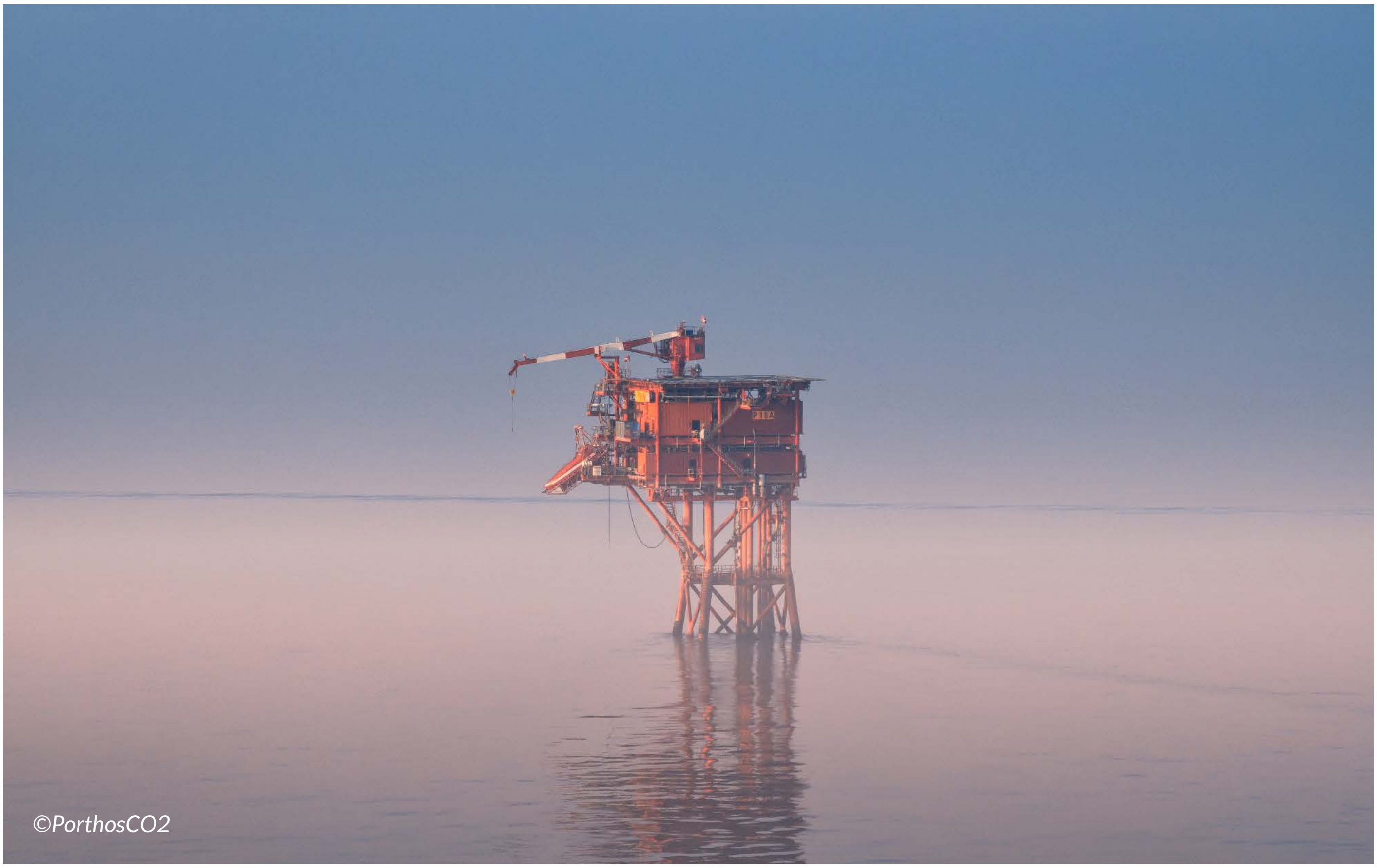
Commodity specific actions: provide long-term market incentives

The primary business case for CCS lies within the EU and UK Emission Trading Schemes (ETS), which recognize CO_2 that is being captured and safely stored as 'not emitted'. However, the issue of long-term liability remains a challenge, particularly for cross-border international CO_2 projects.

Due to a lack of clear CCS policy and long-term targets, investors are hesitant on the economic viability of CCS. Next to this, CCS business models are very different to what offshore operators of hydrocarbon reservoirs are experienced with. The CCS business model is not a 'high risk, high reward' model, but requires capital intensive long-term investments in repurposing or new assets for CO_2 transport and storage with a rather limited reward model. Developing a CCS network requires extensive involvement and dependency on additional parties in the value chain (e.g., collaborative model with suppliers of CO_2), long permitting and project timelines further complicating the investment climate. Actions towards derisking initial investments and getting a grip of the permitting timelines combined with and a long-term outlook would be beneficial to mobilize private capital in developing CCS projects.

An important aspect in providing market clarity, is to ensure a pre-competitive storage appraisal for the CO_2 storage portfolio. This appraisal involves assessing potential storage sites before they are commercially developed, which helps in identifying viable storage locations and their capacities in time to avoid stagnation in the deployment of CCS over the next decades. A holistic strategy should be drafted to clarify which storage capacities are available when and where, to ensure sufficient storage potential for CCS projects and avoid delays.

30 https://cinea.ec.europa.eu/programmes/connecting-europe-facility_en



Natural gas

Grid actions: the development of a decommissioning strategy

Key actions to the natural gas grid relate of preparing parts of the existing infrastructure for re-use for hydrogen and CO_2. In the short term, it should become clear which pipelines can be re-used. Proper certification should be put in place, together with implementing robust safety measures and conducting dynamic lifetime assessments for reused pipelines. More effort is needed to increase decommissioning efficiencies, which can optimize costs and needed activities.

It is also important to strengthen security monitoring of the existing natural gas network on external threats. Often, adequate monitoring equipment is included in new pipelines, however, this is also extremely relevant to include in existing infrastructure. Next to this, to facilitate centralized grid planning in the North Sea basin, (international) data should be shared on which pipelines can be reused and which parts will be decommissioned when.

In the medium-term, a cross-country strategy should be created on the strategy of decommissioning and re-use of existing infrastructure, applying to both platforms as well as pipelines. Extending their lifetime can reduce the overall system costs. The current unclarity adds uncertainty for investors and asset owners in planning their investments (e.g. relating to CO_2 and hydrogen). This strategy should focus on the timelines for decommissioning assets and infrastructure to enable timely decisions about potential reuse or co-use. Additionally, a strategy to evaluate and implement re-routing requirements for natural gas infrastructure for CO_2 and hydrogen reuse is necessary. For this, it is also important to map supply chain issues to investigate when decommissioning peaks, for example related to vessel capacity. A visualization of the envisioned natural gas grid can be seen in *Figure 11*. A full explanation on the natural gas grid vision and actions towards 2050 can be read in Dossier 4 – Natural gas.

Figure 11 The North Sea natural gas grid in the North Sea Energy program, with pipelines of various diameters.

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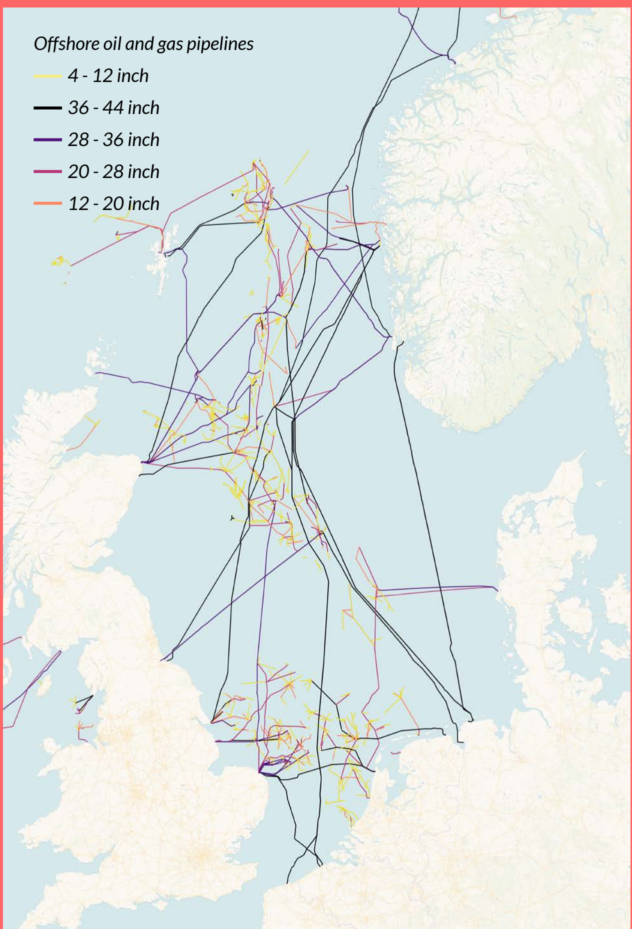


Key actions for the natural gas grid relate to preparing parts of the existing infrastructure for re-use for hydrogen and CO_2.

Commodity specific actions: create a long-term natural gas strategy and enable platform electrification

As long as hydrocarbon assets are still active within the North Sea, electrifying them decreases the consumption of gas offshore and with it the emission footprint of natural gas production and transport (i.e. GHG and NOx). Several projects are already being put in place internationally but also in the Netherlands, such as ENI Q13a-A platform, NAM AWG-1 and ONE-DYAS N05 platform. An updated international plan is required on the short term to investigate where platform electrification is technically and economically feasible for new developments and where possible also for existing production assets, which is for example dependent on the availability of close-proximity wind farms and other offshore marine energy potential.

There has been significant uncertainty on the future production and consumption of natural gas in the North Sea countries. A long-term strategy should be developed, defining country-level outlook for the production, import, storage and consumption of natural gas is needed to remove the volatility currently surrounding the role of natural gas in the energy mix. It is highly important that this strategy is reliable and will not change in the coming years, to decrease uncertainty for operators and investors. This strategy is especially relevant since the production timeline will impact import dependency and the decommissioning possibilities of the natural gas assets, which is a required input for the further development of CCS and hydrogen.

To foresee an integrated energy system where natural gas and other subsurface activities co-exists next to renewable energy sources, its spatial impact should be reduced wherever possible. An important aspect here is the area required for helicopter use and reduced spatial footprint for exploration, installation and monitoring options and more research & innovation is required on how this could be tackled.

4.
System integration actions for the North Sea

The future transitions of the four offshore energy commodities and their technologies cannot be seen in isolation; they are highly entangled. By taking an integrated perspective, problems can be tackled together, paving the way for sufficient market development, efficient infrastructure planning and reduced decarbonization costs. Integrated areas need to be appointed that combine various commodities, together with an internationally interconnected transportation system.

Integrated grid actions

The North Sea is, and will be, a very crowded region, as visualized in the grid vision for the four energy commodities in *Figure 12* . This figure provides an overview of the North Sea energy grid, containing both existing and to be developed infrastructure for the four commodities. The timely development of this integrated energy grid is crucial for a renewable energy system, which is why three specific integrated grid actions are proposed.

Integrated grid action 1: Develop an integrated energy vision for the North Sea

An extensive infrastructure plan should be developed on how the four energy grids will be integrated in the future. The infrastructure forms the basis for further development and clarity is needed on the short term. This integrated vision should focus on various aspects. First of all, marine spatial planning needs to be included where nature-inclusive design is included from the beginning, with early stakeholder engagement. Secondly, to extend infrastructure from a national to an international aspect, cost-benefit-sharing agreements should be made, specifically on energy infrastructure interconnections. Thirdly, the strategy should include a way to deal with physical and cyber security. Together, this should result in long-term clarity on which infrastructure will be available when.

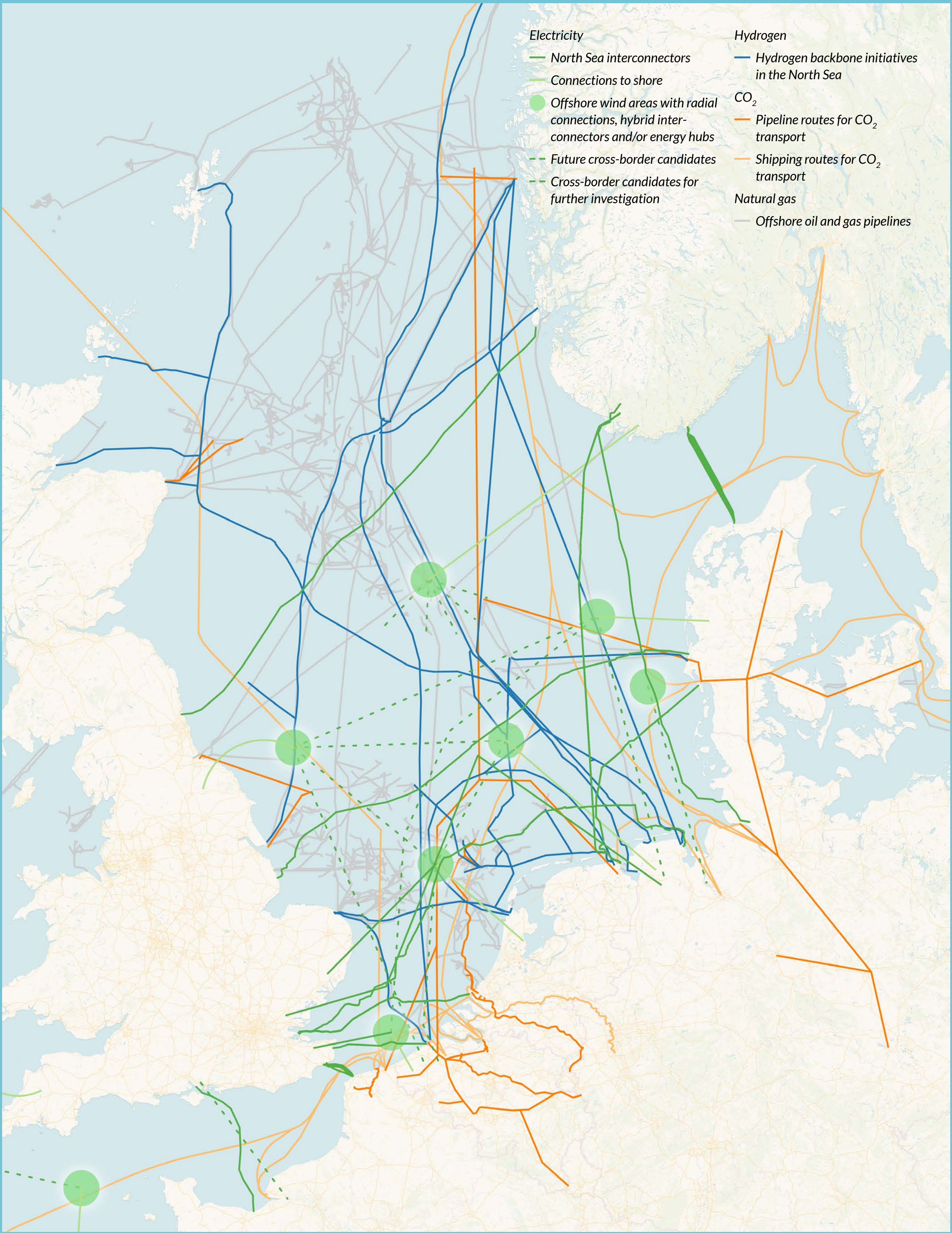
Integrated grid action 2: Establish standardization working groups under The North Seas Energy Cooperation

Various international collaboration initiatives already exist, as is researched in depth in the D7.3 International North Sea Collaboration report[31]. A graphical overview of the types of these initiatives is given in *Figure 13*. For smooth cross-country grid development, it would be beneficial if standardization working groups are started within the NSEC as well. In the coming decades, energy trade between North Sea countries will increase, highlighting the importance of cross-country interoperability of the energy infrastructure.

31 N. Dooley, R. van Zoelen and M. Vos, "International North Sea Collaboration: from buzzword to concrete actions," North Sea Energy, 2025

Figure 12 Overview of the grid visions for energy infrastructure development for the North Sea basin for electricity, hydrogen, CO_2 and natural gas.

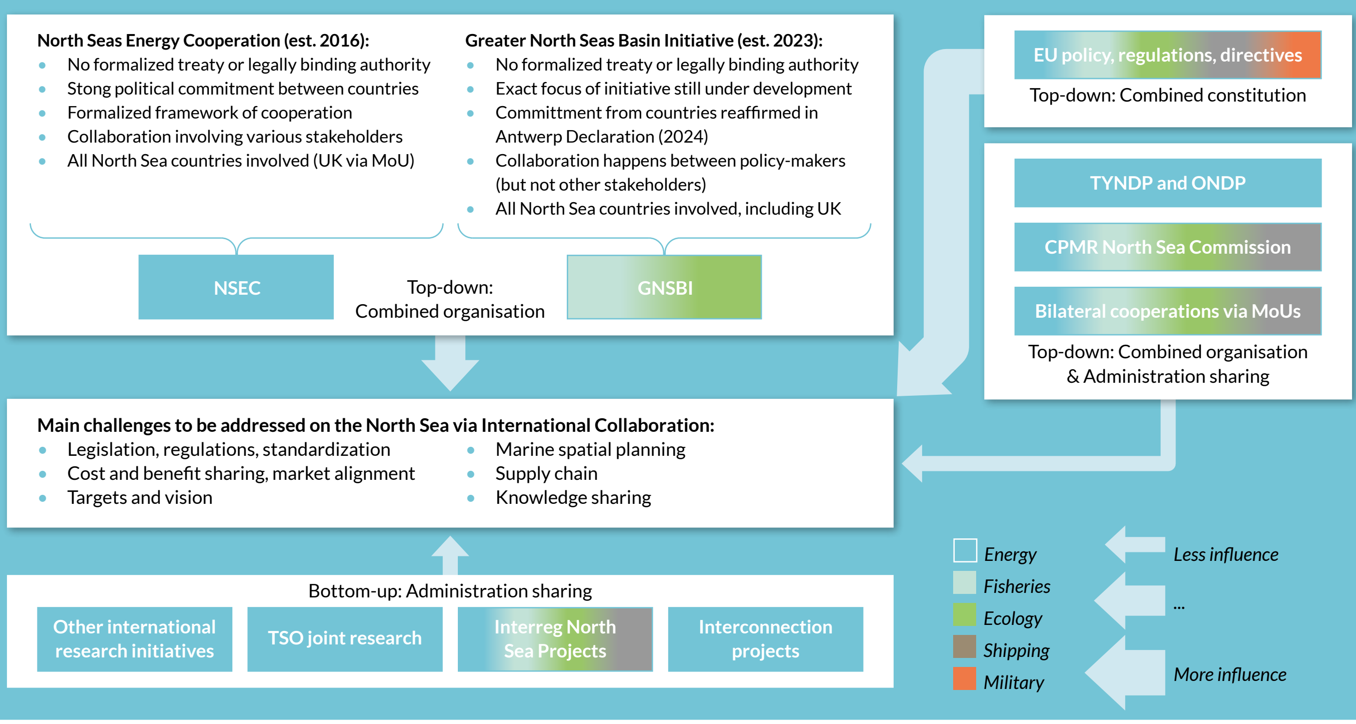
Disclaimer: maps are a representation of announced and envisioned plans and projects in the public domain and therefore subject to frequent updates and may not always reflect the most recent information. For more detailed spatial information and updates see: North Sea Energy Atlas



Integrated grid action 3: Create a strategy on future supply chain bottlenecks

Since the coming decade will be very busy in terms of decommissioning and new grid instalments, integration between the four commodities is key again. All grids will require human capital, materials, O&M vessels, port capacity, etc. Next to this, critical and strategic raw materials might not always be available. A strategy on supply chain including installation and decommissioning bottlenecks should be created that covers all energy commodities and investigates where their respective timelines overlap and potential challenges arise. It is advised that a joint campaign strategy and tendering processes are developed, to clarify timelines and see where bottlenecks might arise. In line with the NSEC advice, it would be beneficial if a digital transparency tool is developed to increase the data availability and strengthen the supply chain. This should not only focus on offshore wind tenders, but projects on all commodities.

Figure 13 Current collaboration initiatives related to the North Sea[30].

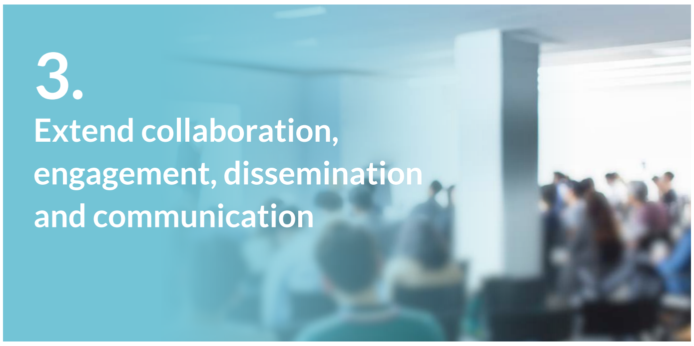


Thematic actions

Next to the integrated grid actions, eight thematic actions have been identified that are required for a smooth system integration, transcending the four energy commodities. Even though a large number of actions is required, it is crucial to implement them all on the short term, as the time to act is now.

1. Governance: set clear international, spatial and integral goals

2. Governance of the transition: coordinate regulatory frameworks and standardization



3. Extend collaboration, engagement, dissemination and communication

4. Provide economic stimuli for sufficient market development of a renewable and low-carbon offshore energy system

5. Minimize negative impacts and seek positive impacts on the ecosystem

6. Create a clear human capital agenda & strategy on supply chain bottlenecks

7. Technological innovation: focus on knowledge dissemination in pilot and demonstration projects

8. Strengthening energy security & defending energy infrastructure

NSE Spotlight on the Multi-use of Space: achieving effective offshore multi-use in the North Sea requires holistic regulation and coordination

The NSE whitepaper on the multi-use of offshore space in the North Sea demonstrates that multi-use of space in the offshore environment is highly complex, due to increased protein, energy and nature spatial claims in the future. The figure below provides an overview of the current uses of the North Sea. Synergistic effects and effective multi-use are crucial to fulfil all these various functions. For this, it is encouraged to strive for synchronized international regulations to incorporate the multi-use of space in planning processes. It could be especially relevant if all North Sea countries incorporate multi-use of space in legislation where it provides net-positive impacts.

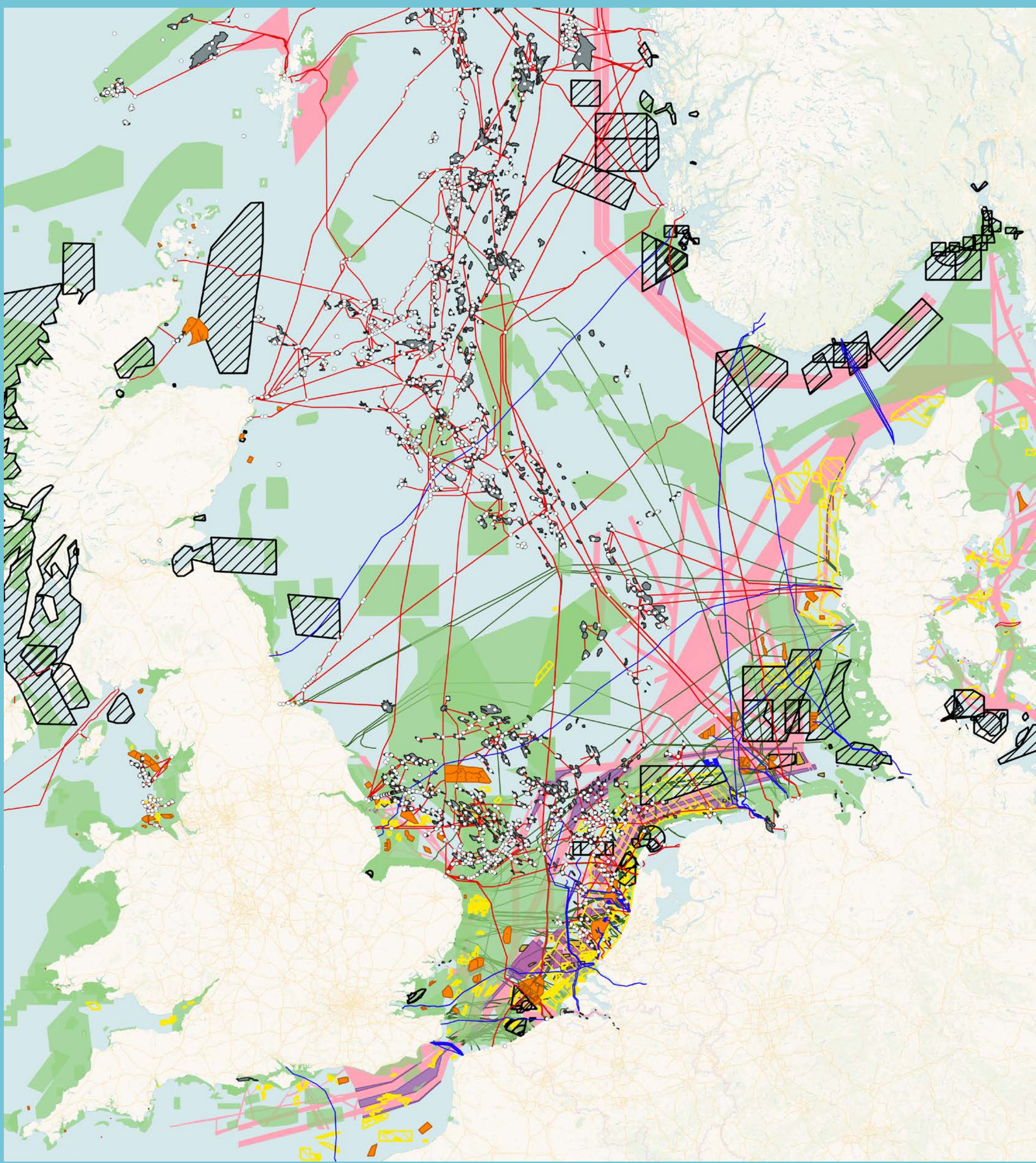


Figure 14 A graphical overview of the current uses of the North Sea. For further information: D6.4 A. Satish, M. de Respinis, J. Breuer, O. Khatraoui and P. Marcus, "White paper – multifunctional spatial use at the North sea and the implications of future energy infrastructure," North Sea Energy, 2025

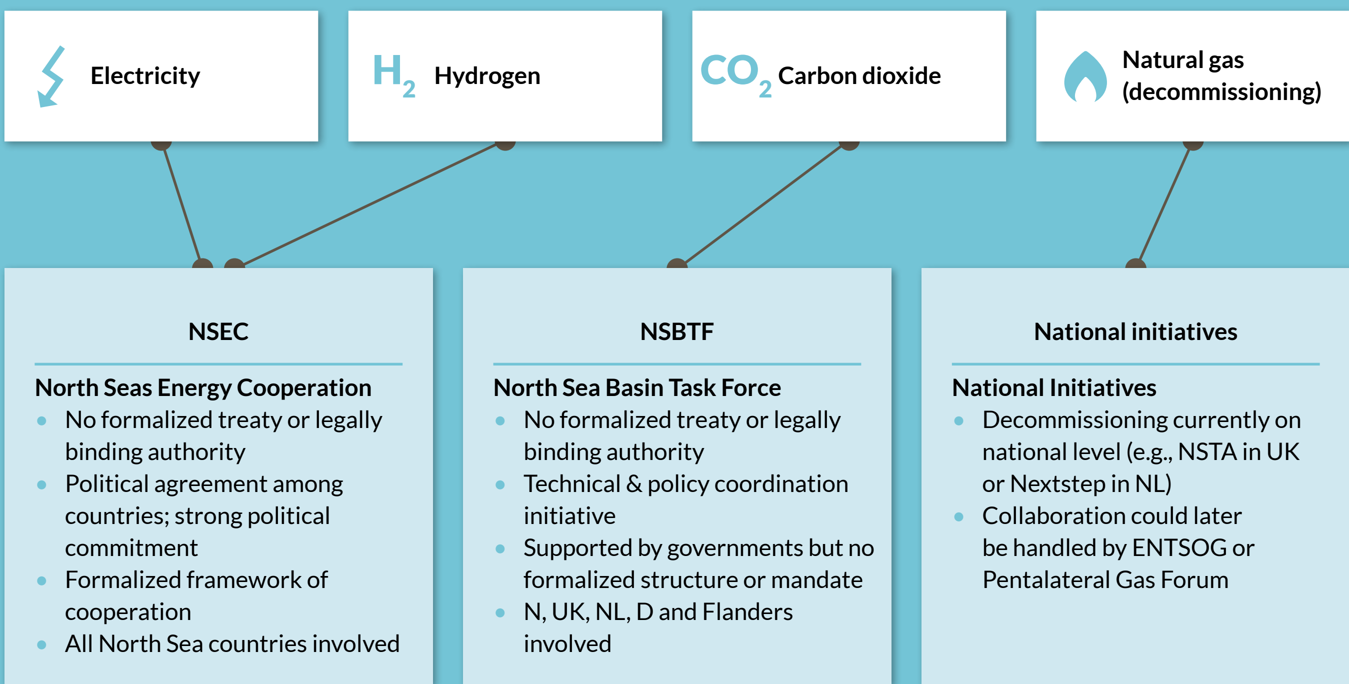
1. Governance: set clear international, spatial and integral goals

In the past years, ambitious targets have been formulated on offshore wind and total hydrogen production. Targets specifically on offshore hydrogen production, transport and storage are lacking, despite its major foreseen role in combination with offshore wind. Next to this, policies and targets on CCS, together with blue hydrogen, have not been developed yet. Lastly, even though the majority of the North Sea countries has pledged to decrease its natural gas production or indicate a long term perspective, no targets or

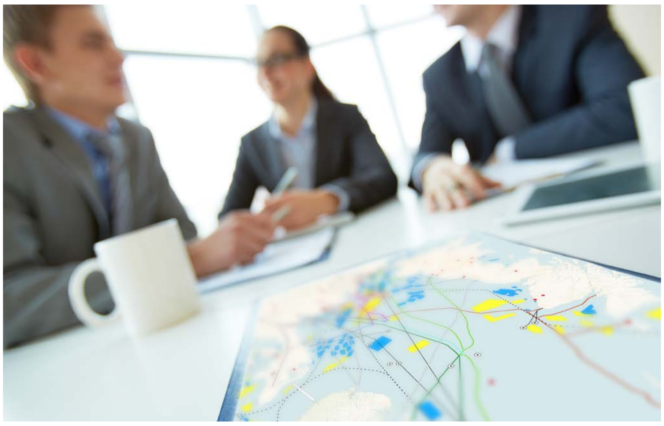
NSE Spotlight on International Collaboration: A fully integrated cross-sector and cross-border governance is needed to ensure an interconnected energy system

The NSE whitepaper on International Collaboration, investigated current collaboration initiatives over various sectors and governance levels within the North Sea region. The figure below provides an overview of the most important initiatives, spread out over the four energy commodities. Even though various initiatives already exist, it is recommended to expand the cross-border and cross-sector approach in the coming decades, to fully deploy an integrated energy system. The governance framework is currently fragmented and a macro-regional EU strategy should be formed that takes a fully integrated approach.

Figure 15 A graphical overview of the current collaboration initiatives in the North Sea region over the various energy commodities. For further information: D7.3 N. Dooley, R. van Zoelen and M. Vos, "International North Sea Collaboration: from buzzword to concrete actions," North Sea Energy, 2025



outlooks on actual demand or import have been set. This means that a clear pathway for the North Sea energy system has not been developed at this moment, obstructing a clear vision and way forward.



The development of an integrated strategy is needed to guide public and private strategies, and decrease the spatial impact of the transition. It is advised that this vision is as spatially explicit as possible, in order to align stakeholders' perspectives and minimize negative impacts. Next to this, the targets and strategies should focus on infrastructure planning in an international context, to provide long-term pathways for the commodity developments. This should also ensure an energy independent and cost-competitive Europe.

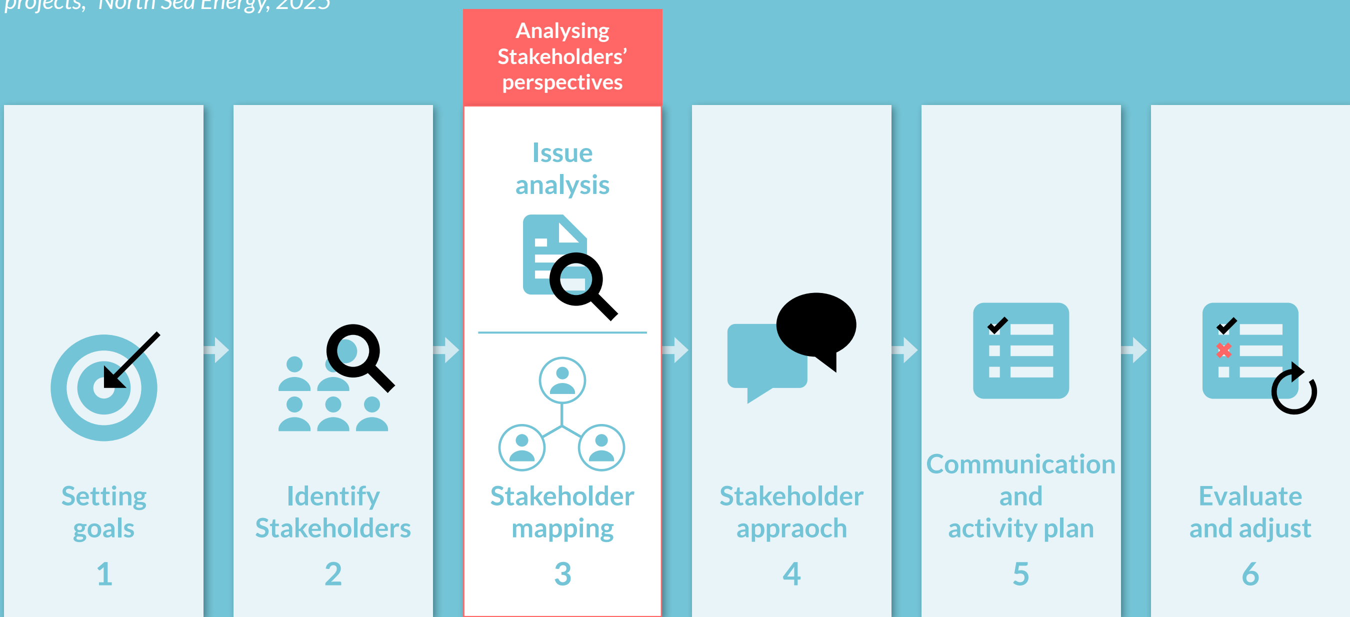
2. Governance of the transition: coordinate regulatory frameworks and standardization

Proper governance of the transition is required to smooth deployments and create investment certainties. Integration can be hampered by inconsistent national regulations or the absence of standardization. To align spatial planning and increase permitting processes, a proper governance structure is required for quick and adaptive decision-making across

NSE Spotlight on Stakeholder Engagement Strategies: a step-by-step approach

The NSE whitepaper on a Stakeholder Engagement Strategy in Offshore Energy Projects has highlighted how to create a strategy to engage with the large group of stakeholders that is involved in the development of the offshore renewable energy system (as visible in the figure below). Effective stakeholder engagement is crucial to realize the North Sea's potential and will help with identifying risks and opportunities, promoting transparency and accelerate progress.

Figure 16 A graphical summary of the developed stakeholder engagement strategy steps. For further information: D2.2 J. van der Vliet, G. Wurpel, A. Jørgensen and I. de Klerk, "Whitepaper: best practices in stakeholder engagement for offshore energy projects," North Sea Energy, 2025



the North Sea Countries. Several initiatives are already running, such as the OSPAR Commission, North Sea Basin Task Force, Greater North Sea Basin Initiative and North Seas Energy Cooperation. It is recommend to implement a fully integrated (cross-sector and cross-border – including non-EU countries) approach to marine spatial planning; one with complete political buy-in from all member countries to enable effective and accelerated decision making, a formal governance structure, permanent funding streams, and legal backing[32].

3. Extend collaboration, engagement, dissemination and communication

Besides adequate collaboration between countries, broader stakeholder engagement and collaboration are crucial for a successful rollout of the offshore energy system. Due to the multi-faceted approach and intertwinement of the various commodities and sectors, it is essential to engage with stakeholders spanning all actors from the public, private and civil society. Early engagement can help in faster decision-making and avoid potential delays. In D2.2 Stakeholder Engagement Strategy in Offshore Energy Projects[33], the key stakeholder groups for offshore system integration have been

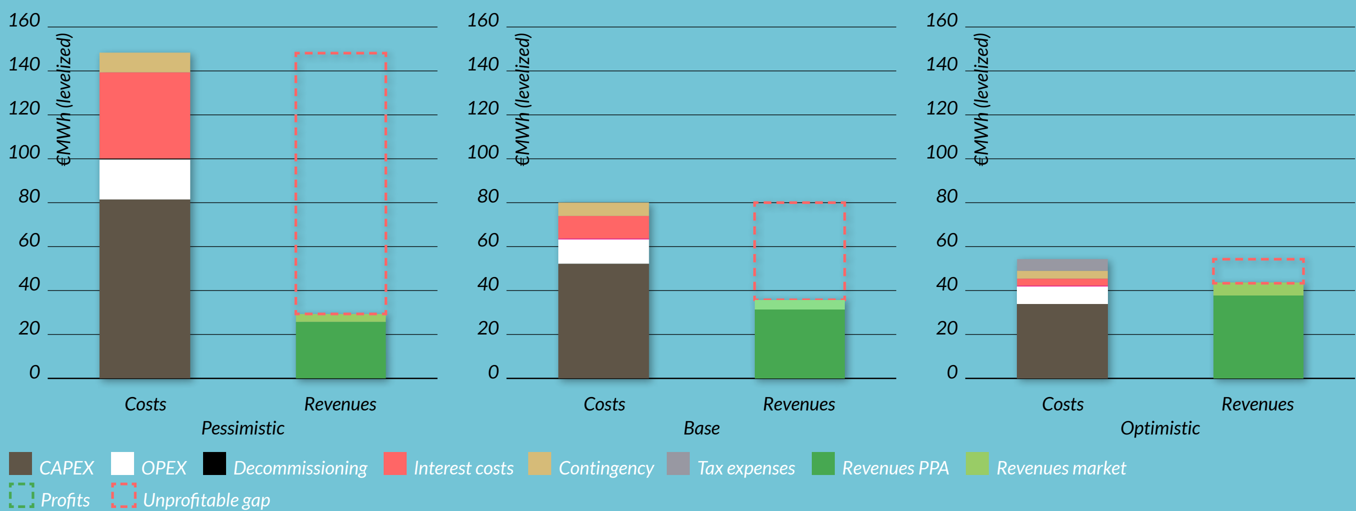
32 N. Dooley, R. van Zoelen and M. Vos, "International North Sea Collaboration: from buzzword to concrete actions," North Sea Energy, 2025

33 J. van der Vliet, G. Wurpel, A. Jørgensen and I. de Klerk, "Whitepaper: best practices in stakeholder engagement for offshore energy projects," North Sea Energy, 2025

NSE Spotlight on the Business Case Assessment for the Offshore Value Chain: business cases across the offshore energy value chains are under increasing pressure

While system-level modelling points clearly toward optimal pathways for societal decarbonization, current market structures and incentive schemes do not consistently support private project developers in pursuing those same outcomes. This misalignment threatens to delay investment, increase public costs, and constrain the potential of the North Sea as a renewable energy backbone for Europe. It is therefore recommended that thoughtful actions are taken to support the offshore value chains. An example of the unprofitable gap in offshore wind developments is visualized in the figure below.

Figure 17 The levelized costs and revenues of offshore wind for three scenarios, where the unprofitable gap is clearly visible. For further information: D3.3 R. van Zoelen, D. Boer, S. Mahfoozi, "Business case assessment for the offshore value chain", North Sea Energy, 2025



identified, together with a general strategy on how to engage them.

For organizations that are directly involved in the development of the energy system, international collaboration and knowledge sharing should be improved. Due to the quick technological developments and complicated spatial planning, smooth knowledge sharing is of the utmost importance. This can be strengthened by the establishment of a dissemination platform.

NSE Spotlight on Nature Inclusive Design: nature-inclusive spatial design can decrease the disturbance on various species

Nature-inclusive spatial design focuses on avoiding and reducing negative impacts on the environment. Within a nature-inclusive design approach, it was found that disturbance on various ecological groups was less, compared to a standard design. Even though several knowledge gaps still exist, it is always advisable to include ecological impacts in the spatial planning process and follow a precautionary principle. The figure below provides a proposed bird corridor for Hub North, together with buffer zones for wind farms.

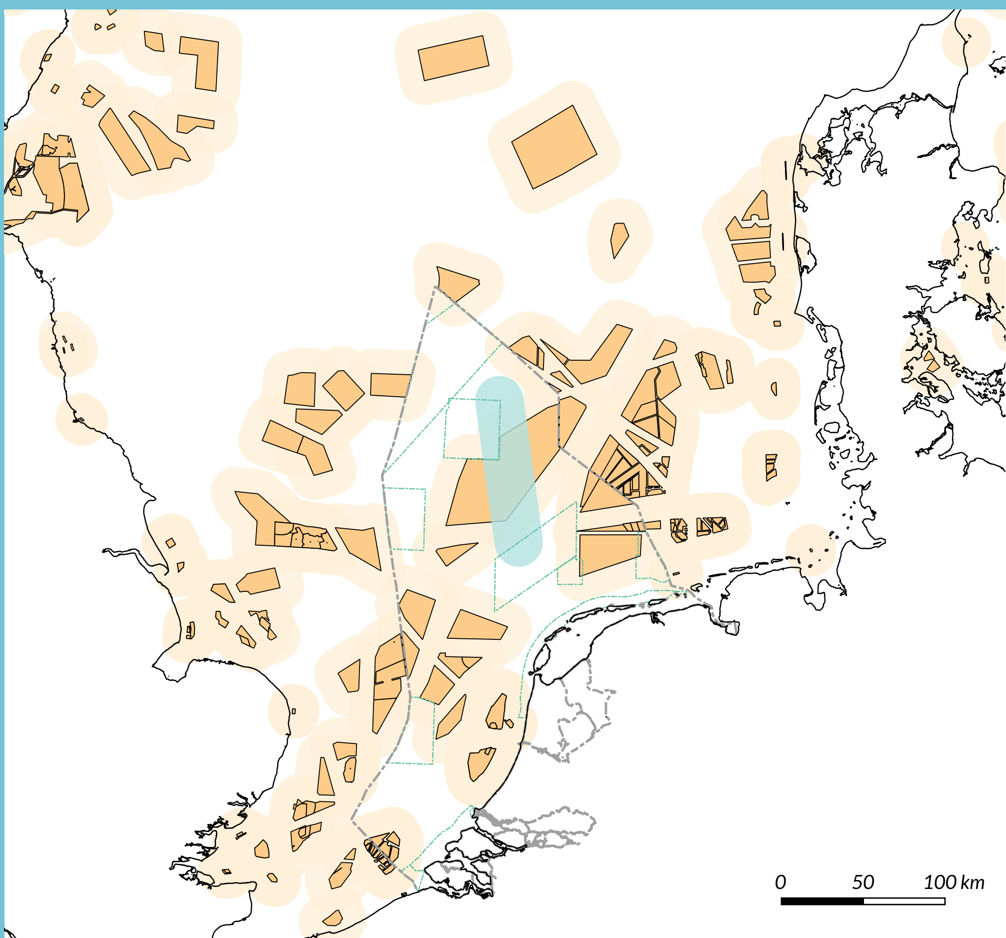


Figure 18 Map of the proposed bird corridor for Hub North, in relation to Dutch marine protected areas and wind farms. For further information: D4.1 A. Jørgensen, I. de Klerk, L. van der Heijden, A. Emmanouil, I. Gerritsma, J. Rienstra, S. Versteeg, B. Schoon, C. Dinjens and D. Smeets, "Designing Nature-Inclusive Energy Hubs | Whitepaper on General Recommendations and Outcomes for Hub North," North Sea Energy, 2025

Dutch marine protected area
Bird corridor
Wind farms (existing and planned)
Buffer zone wind farms (20km)

4. Provide economic stimuli for sufficient market development of a renewable and low-carbon offshore energy system

Currently, the offshore system integration is hampered by the lack of long-term certainty in terms of offtakers, infrastructure development and uncertain business cases. For example, the development of offshore wind needs to run in parallel with electricity demand, the green hydrogen market needs to be de-risked for investors (on demand, supply and infrastructure side) and CCS needs support until the price of emission allowances can close the business case gap. Comparing the public value with the business case assessment, it was seen that current market structures do not always incentivize project developers in pursuing societal optimal decisions indicating market failure. It is advisable that various support mechanisms be put in place in the coming decade that serve a level playing field across the North Sea basin. D3.4 provides recommendations on how projects can be incentivized to towards system optimal investment and operation.

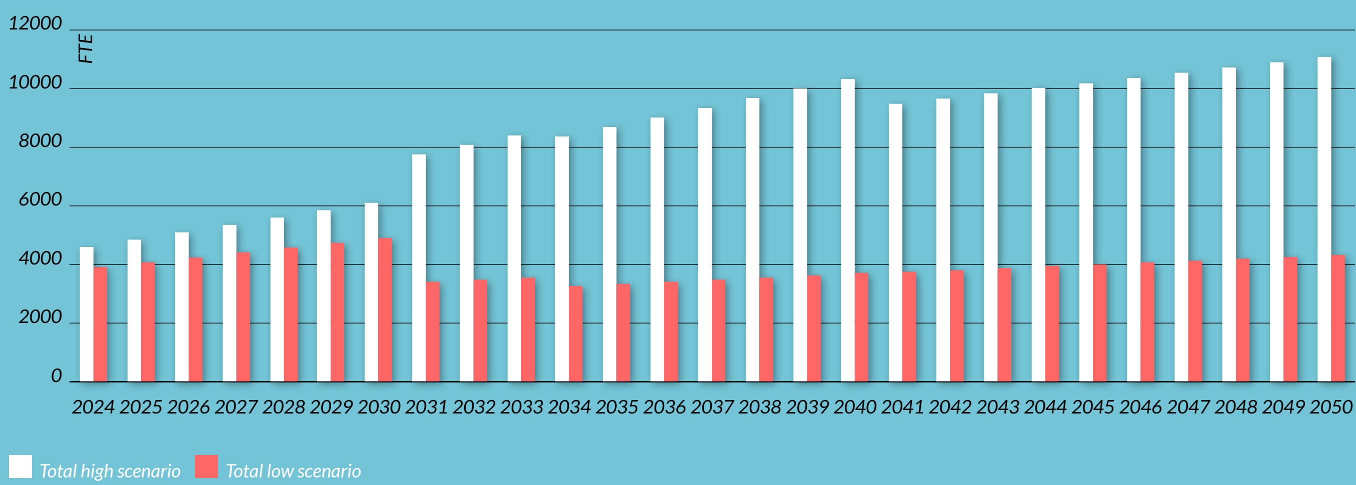
5. Minimize negative impacts and seek positive impacts on the ecosystem

The North Sea is an ecologically sensitive area, with various protected species and important marine ecosystems. It is important to minimize the impact of disruptive activities and actively pursue positive impacts on the environment, while developing our future energy system. This requires the embodiment of ecological principles into the design of this energy system, so-called nature-inclusive design, instead of only considering it as a separate aspect. A robust research

NSE Spotlight on Human Capital: a growing workforce need for the offshore energy system

A human capital "Framework" was created, which is meant to recognize and facilitate management of human capital transitions that are needed for the period 2025-2030. It focuses on human capital capacity, workforce skills and standards, and human capital offshore data monitoring. Several workforce bottlenecks and opportunities have been identified, together with skills-mapping over various areas, as visualized in the figure below. The graph below depicts the expected Dutch FTE growth in the coming decades to deploy the offshore renewable energy system.

Figure 19 Estimation of total employment per year for the Netherlands for two NSE scenarios. For further information: D2.3 N. Reijmers and O. de Vreede, "Human Capital agenda for offshore energy system integration," North Sea Energy, 2025



and monitoring program must be established to study the environmental and ecological impacts of new offshore energy systems. The Dutch Assessment Framework for nature-protecting and nature-enhancing measures at the North Sea can act as a starting point here[34]. Furthermore, better funding and financing options must be extended to projects with lower ecological impacts or positive environmental externalities. Further recommendations can be read in D4.1 report on nature inclusive design[35].

34 Noordzeeoverleg publiceert Afwegingskader voor natuurvriendelijk bouwen op de Noordzee | Noordzeeoverleg

35 A. Jørgensen, I. de Klerk, L. van der Heijden, A. Emmanouil, I. Gerritsma, J. Rienstra, S. Versteeg, B. Schoon, C. Dinjens and D. Smeets, "Designing Nature-Inclusive Energy Hubs | Whitepaper on General Recommendations and Outcomes for Hub North," North Sea Energy, 2025

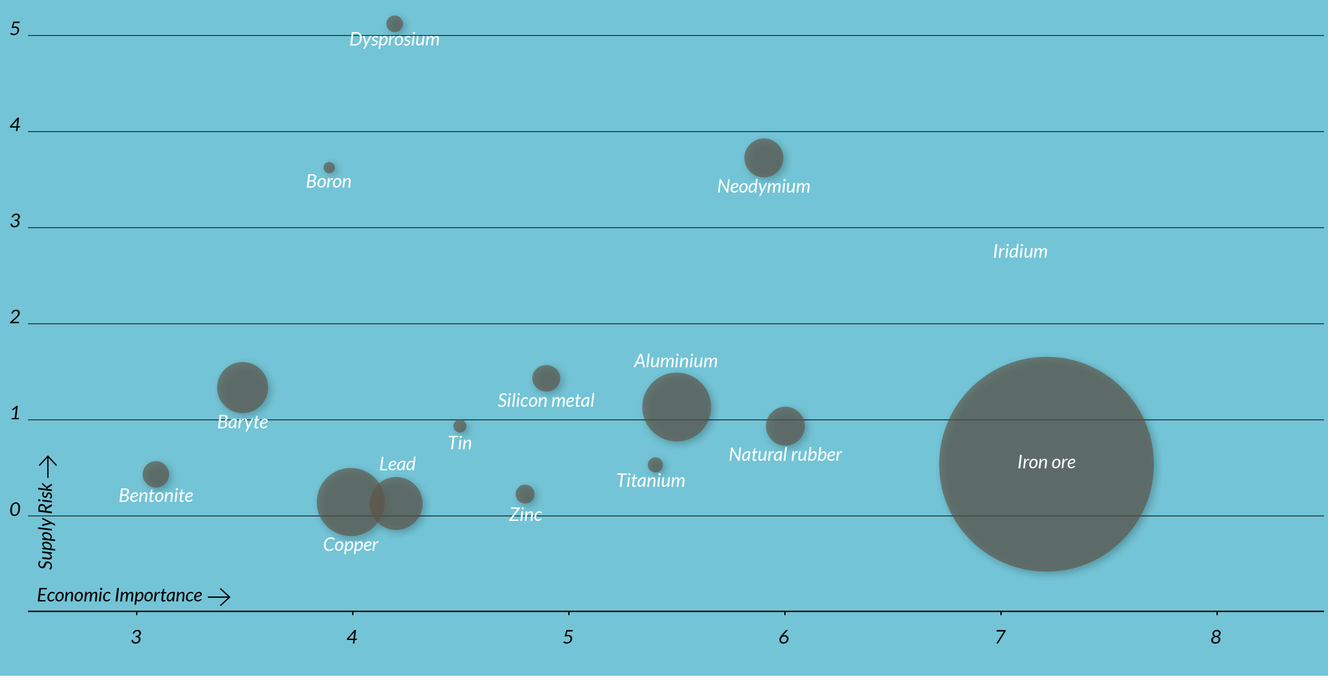
6. Create a clear human capital agenda & strategy on supply chain bottlenecks

One of the central pillars of making this energy transition succeed is the availability of a skilled and motivated workforce. The growth of the offshore renewable energy sector will create many new jobs, while the declining fossil fuel production poses a difficult situation for the experienced oil and gas workers. Significant efforts are needed to transition these workers to a decarbonized energy sector, by providing proper training to work on hydrogen, CCS and electricity, and by integrating ecological principles. Secondly, the offshore renewable energy sector should become more attractive to the workforce of

NSE Spotlight on Material Flow Analysis: the renewable energy system will come with significant increased demand for critical raw materials

Through the increased installments of offshore wind, floating PV, hydrogen production and CCS, significant rises in critical raw materials are expected in the coming decades, posing significant risks. It is recommended to regularly assess risk, vulnerabilities and dependencies associated with supply disruptions, geopolitical factors, and market fluctuations to inform decision-making. Additionally, it is recommended to develop and build out strategic partnerships with a diverse range of key suppliers across various countries, and to explore partnership with emerging producers of low-CRM energy technologies. The figure below depicts an overview of the critical raw materials with the most significant risks.

Figure 20 Bubble graph of critical raw materials, depicting the supply risk, economic importance and inflow to the North Sea area in the period 2025-2050 (bubble size). For further information: D4.5 M. Kamps and R. Elbing, "Material Flow Analysis and Criticality Assessment," North Sea Energy, 2025



the future. While currently being perceived as 'far away', it is often not on people's top of mind when searching for job opportunities. More effort needs to be made to communicate the excellent long-term job opportunities in the offshore energy sector. Lastly, automation and digitization can lessen the pressure on the required workforce. Labor reducing technologies such as autonomous vehicles, unmanned monitoring systems, logistic optimization models and predictive maintenance with AI can effectively decrease the pressure on the required workforce. It is strongly advised that the implementation of these technologies is progressed. Further recommendations can be read in the D2.3 Human Capital report.

The upscaling of the renewable energy system goes hand in hand with the sufficient availability of materials. It is important that adequate resources become available in Europe, that recycling technologies are developed further and that the key bottlenecks on the supply chain are identified in time. Further recommendations can be read in D4.5 Material Flow Analysis.

7. Technological innovation: focus on knowledge dissemination in pilot and demonstration projects

Offshore energy technologies mentioned in this report are in different phases of maturity. Part of the discussed energy technologies are still in an early stage of (scale-up) development. Onshore electrolyzer innovation processes currently focus on the scale-up from the 100s of MW to GW scale. Learnings must be translated to the offshore electrolyzer development, which requires more piloting due to its different environment and role in the energy system. Many scale-up pilot and demonstration projects for offshore hydrogen have already been announced, focusing on both the implementation on new and existing platforms, as well as the integration with wind turbines. Secondly, more research is required that focused on technologies that favor the multi-use of space, such as batteries within wind farms, platforms that combine oil & gas activities with CCS, etc. A great learning potential can be achieved by combining the knowledge of all European demonstration projects, paving the way towards standardization and de-risking the technologies. Currently, the North Sea region lacks an integrated approach to share best practices and innovation learnings for various offshore system integration concepts. A North Sea offshore demonstration Flagship program could align national and regional innovation programs, setting clear goals for technology improvement, scale-up, and deployment. The NSEC framework or European Technology & Innovation Platforms could serve as starting points for this program.

8. Strengthening energy security & defending energy infrastructure

Since the war in Ukraine, security threats of critical offshore energy infrastructure became realistic, resulting in energy security and safety becoming a major theme in Europe. It is strongly advised that the security and resilience of the future offshore energy system are properly assessed, together with the development of multi-use sensor networks for monitoring environmental, operational and security conditions in the North Sea. This also relates to building a robust cybersecure network of both the assets as well as the international interconnections. In the next phase of the NSE program, this topic will be more intensively addressed.

Besides monitoring and cybersecurity, it is important that the system itself is resilient. This relates to the diversification of the energy sources, the interconnectivity levels between countries and sources, and the amount of storage and storage locations for the various energy carriers. For this, adequate onshore and offshore system planning is required.

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