

North Sea Energy 2023-2025

Offshore Energy Clusters: Stepping Stones towards a Sustainable, Resilient and Cost-Effective North Sea Energy System



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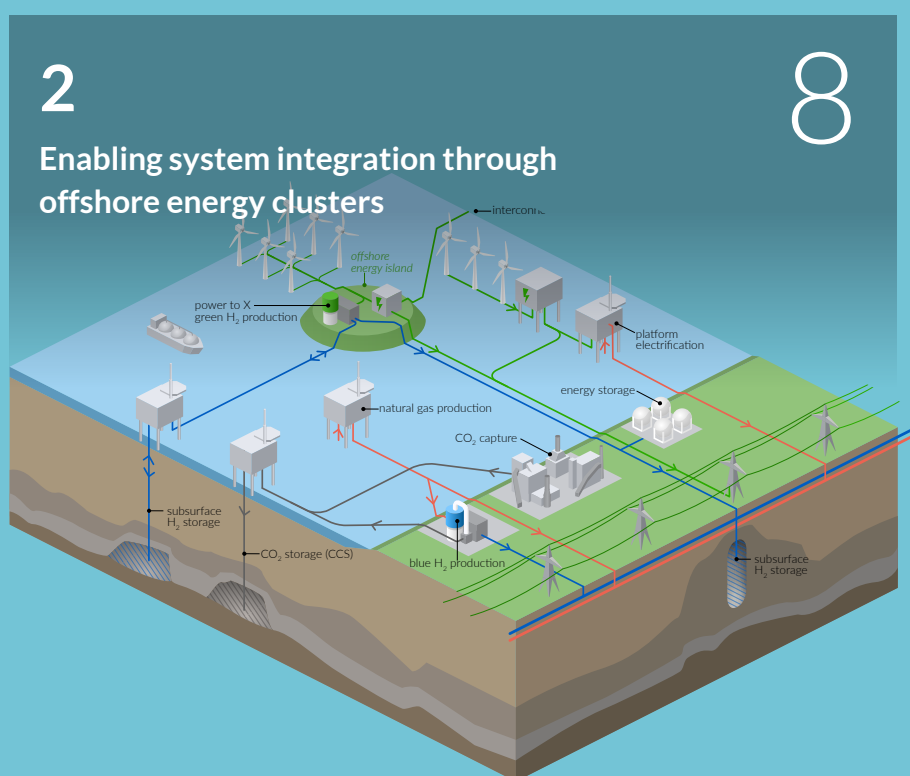
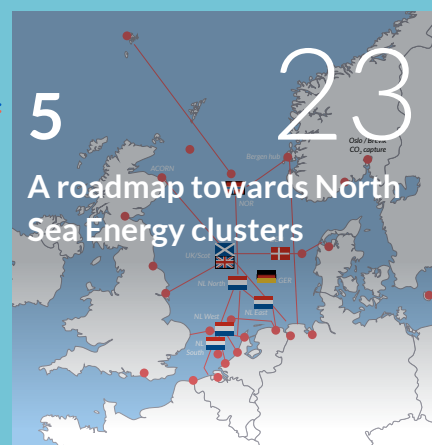
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1.

Introduction

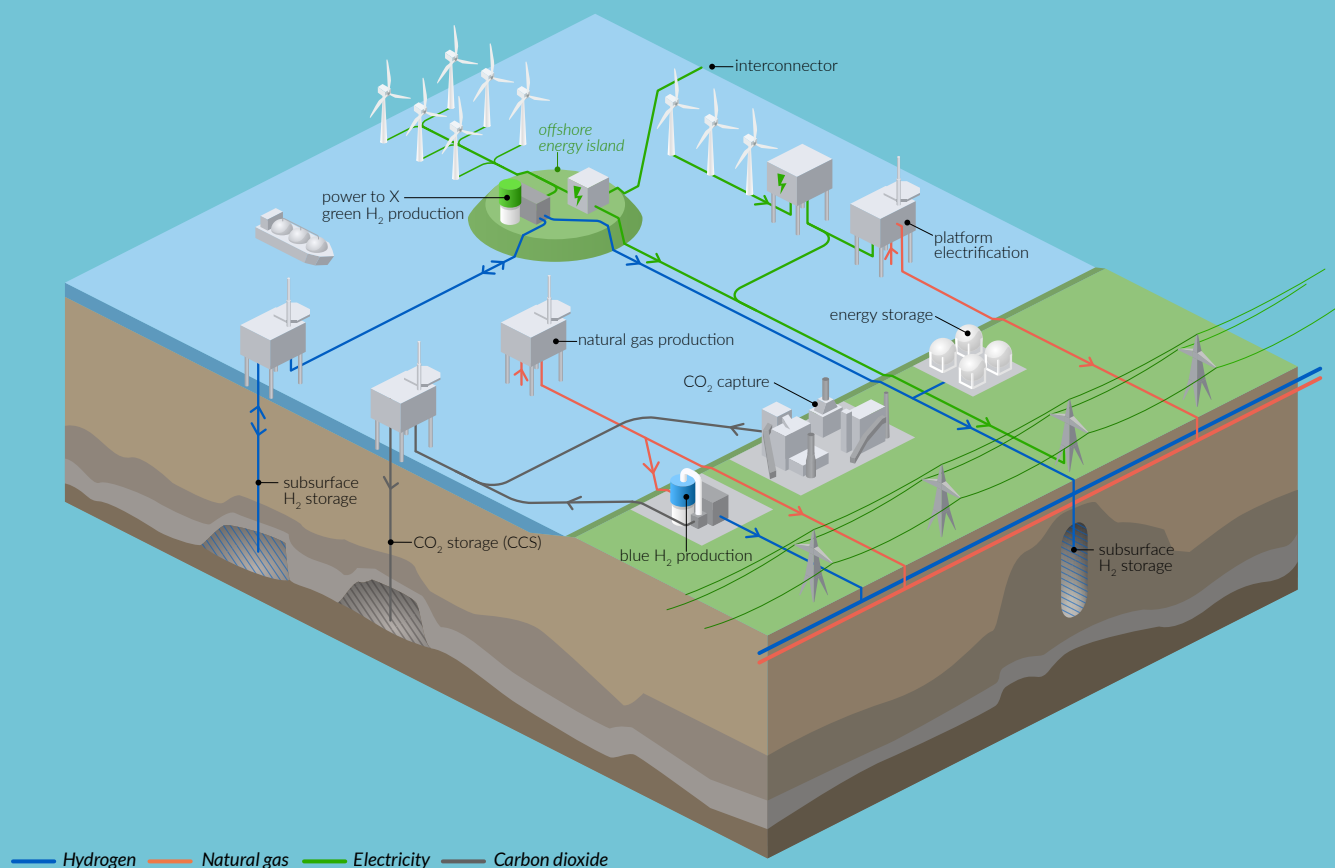
The North Sea is developing into an important region for Europe's energy transition, enabling the EU to achieve its climate targets of 50% CO₂ emission reduction by 2030 and carbon neutrality by 2050¹. The North Sea's shallow waters, favourable weather conditions and large industrial demand clusters enable the way forward for offshore wind expansion, where the North Sea countries have committed to the ambitious target of 120 GW of offshore wind by 2030 and 300 GW by 2050². In parallel, the CO₂ capture, transport and storage (CCS) industry is scaling-up, and new hydrogen production is emerging onshore, possibly followed by production offshore in the future. Lastly, the systematic phase-out of natural gas exploration and production activities is ongoing. Signs that the transition to a renewables-based energy system is materializing.

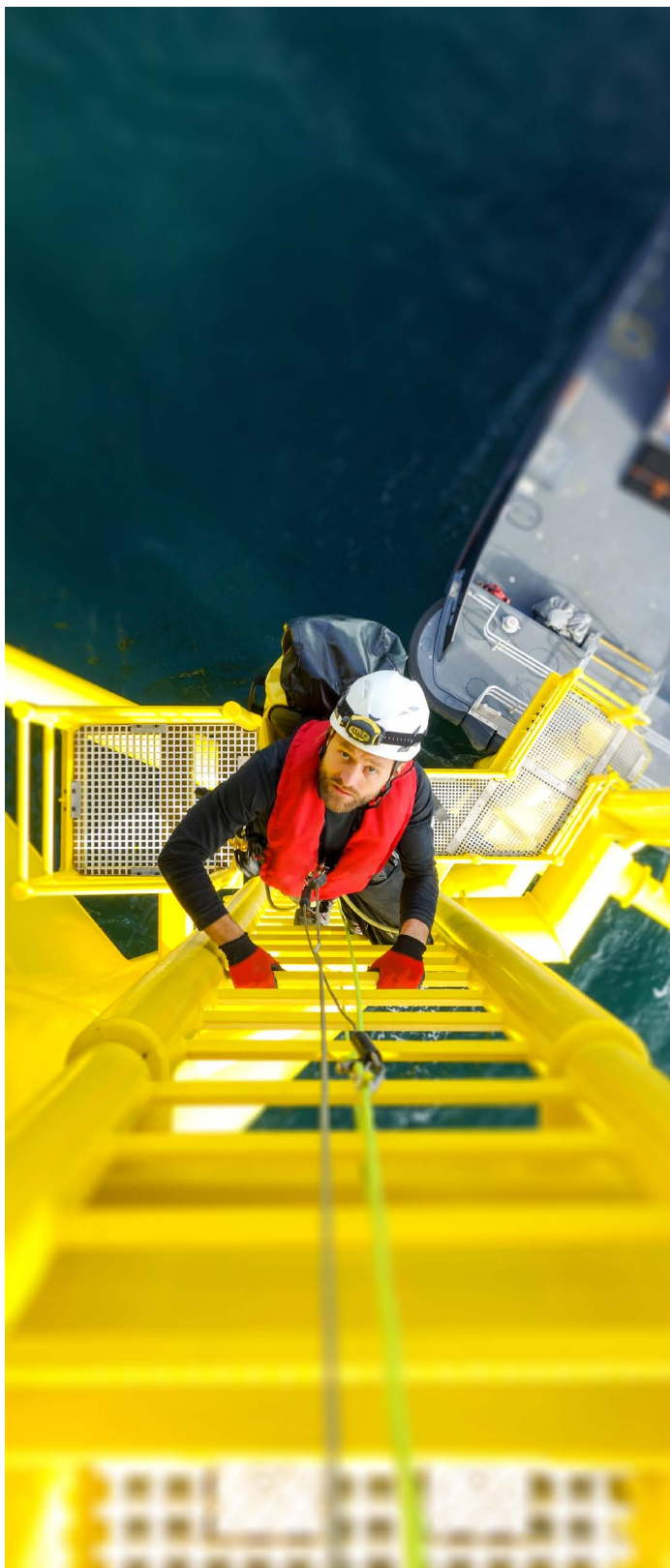
The rapid expansion of an offshore low-carbon energy system in the North Sea requires as well as enables an integrated

and cross-border approach. The North Sea Energy (NSE) program develops system integration concepts to enable smart synergies between various offshore low-carbon energy developments, aiming to reduce costs, time, emissions and the spatial impact of the energy transition. A graphical overview of the concept of offshore energy system integration is visualized in Figure 1.

Energy clusters are considered key enablers for effectively integrating renewable and low-carbon energy activities. An energy cluster is defined as an offshore area where the production, conversion and/or storage of energy commodities (electricity, natural gas, hydrogen) and CO₂ are co-located, and which is connected to other clusters and to the shores of the North Sea countries through transport corridors of cables and pipelines³. Energy clusters are therefore considered as search areas for system integration, enabling the co-location and connection of various energy-related activities. Such

Figure 1 System integration concepts in the North Sea





offshore system integration could enhance the effective use of the energy system, reduce (infrastructure) costs, strengthen energy system resilience, and reduce the spatial impact of the energy transition.

This whitepaper investigates the benefit of offshore energy clusters in enabling system integration (Chapter 2), drawing on research outcomes of the fifth phase of the NSE program (NSE5) and practical case studies (Chapter 3). It also incorporates an international perspective to highlight the importance of cross-country collaboration in the energy transition (Chapter 4). Finally, a roadmap is presented for facilitating the further roll-out of offshore energy clusters across the North Sea (Chapter 5).

Energy clusters enable more effective use of renewable energy sources, reduce (infrastructure) costs, strengthen energy system resilience, and reduce the spatial impact of the energy transition.

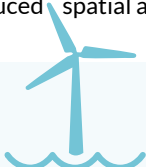
2.

Enabling system integration through offshore energy clusters

In this whitepaper, four added values of system integration are introduced: 1) improved utilization of intermittent renewable energy sources; 2) more cost-effective use of energy infrastructure; 3) reduced spatial and ecological impacts; and 4)

increased system resilience and energy independence. In this chapter, we explain these four added values, and in Chapter 3 and 4 we support them with key research results obtained in the NSE program.

1.



Clusters can increase the efficient use of renewable energy sources

Offshore energy clusters can increase the utilization rate of generated renewable electricity. As renewable capacity scales up, variability and intermittency issues pose significant challenges, with curtailment rates rising in the past few years⁴. This is especially relevant when grid infrastructure cannot keep up with growing offshore wind production capacities, or during periods when high renewable energy supply (significantly) exceeds demand. Energy clusters can facilitate the co-location of renewable energy sources with conversion and storage, where electrolysis and batteries can offer short-term flexibility, and hydrogen storage (offshore and/or onshore) can offer long-term seasonal system balancing⁵. This added flexibility not only alleviates the pressure on the electricity grid, but can also mitigate negative electricity prices and decrease overall system costs⁶. Together, these configurations offer flexibility and improve the balancing of supply and demand, reduce curtailment rates and increase the utilization of renewable energy sources.



2.



Clusters can increase the cost-effective utilization of energy infrastructure

Converting electricity to hydrogen offshore and transporting it via pipelines to shore can reduce the need for costly new electrical infrastructure, which is typically more expensive than pipelines, especially for locations further offshore⁷. The co-location of renewable energy generation and hydrogen production in offshore energy clusters can thereby optimize grid utilization and reduce overall transmission system costs^{8,9}.

Secondly, a further expansion of international interconnectors can strengthen the complementarity between various North Sea countries and integrate larger amounts of renewables¹⁰. Due to varying weather profiles and regional imbalances, interconnectors can make use of national complementarities and improve the matching of supply and demand, thereby increasing the optimal use of the grid. This increases the effective use of the energy infrastructure assets and the overall use of renewable energy, therefore improving the cost-effectiveness of the energy system from a system-level perspective¹¹.

Thirdly, the potential re-use of existing natural gas infrastructure may provide opportunities for offshore hydrogen production and transport, provided that the coordinated phase-out of natural gas and build-up of (offshore) hydrogen production assets are properly aligned in time, space, and capacity. Several studies have already suggested the feasibility or system cost-effectiveness of repurposing existing platforms and pipelines^{12,13}, however, technical and non-technical challenges still exist this is currently not being deployed yet.

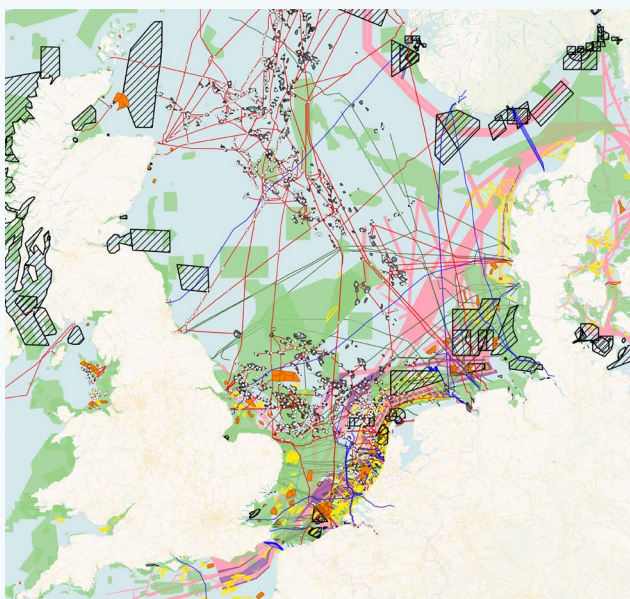




3.

Clusters can reduce the spatial impact of the energy transition

Proper integration and coordination of energy assets and infrastructure can significantly reduce the required space for the energy transition¹⁴. System integration is essential to minimize the spatial impact of the offshore energy transition in the North Sea, which is already one of the busiest seas in the world¹⁵. The North Sea is not merely an energy system; it is a complete system that entails marine protected areas, fishery, sand extraction, shipping routes, military activities, and oil/gas and renewable energy production. As offshore energy assets and infrastructure continue to expand in a context of growing spatial pressure of other use functions, competition for the limited space will intensify. By fostering synergies between sectors and co-locating several activities in offshore energy clusters, the multi-use of space can be enabled and the overall spatial impact can be decreased. When this is further supported by properly deploying the re-use of natural gas infrastructure, additional new infrastructure can be avoided, lowering the spatial impact.



4.



Clusters can increase energy independence & infrastructure resilience

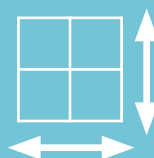
An interconnected North Sea energy system with energy clusters can increase Europe's energy independence and improve system resilience¹⁶. The combination of renewable electricity generation, hydrogen production, domestic natural gas production and CCS reduces the reliance on imported fossil fuels, and mitigates supply chain vulnerabilities by the diversification of resources while keeping climate targets within reach. A diverse mix of energy sources increases redundancy and enhances energy security¹⁷. Next to this, the use of parallel transmission systems, such as HVDC cables, legacy natural gas pipelines and hydrogen pipelines, strengthens infrastructure resilience.



1. Efficient use of renewable energy sources



2. Cost-effective utilization of energy infrastructure



3. Reduced spatial impact of the energy transition



4. Energy independence & infrastructure resilience

3.

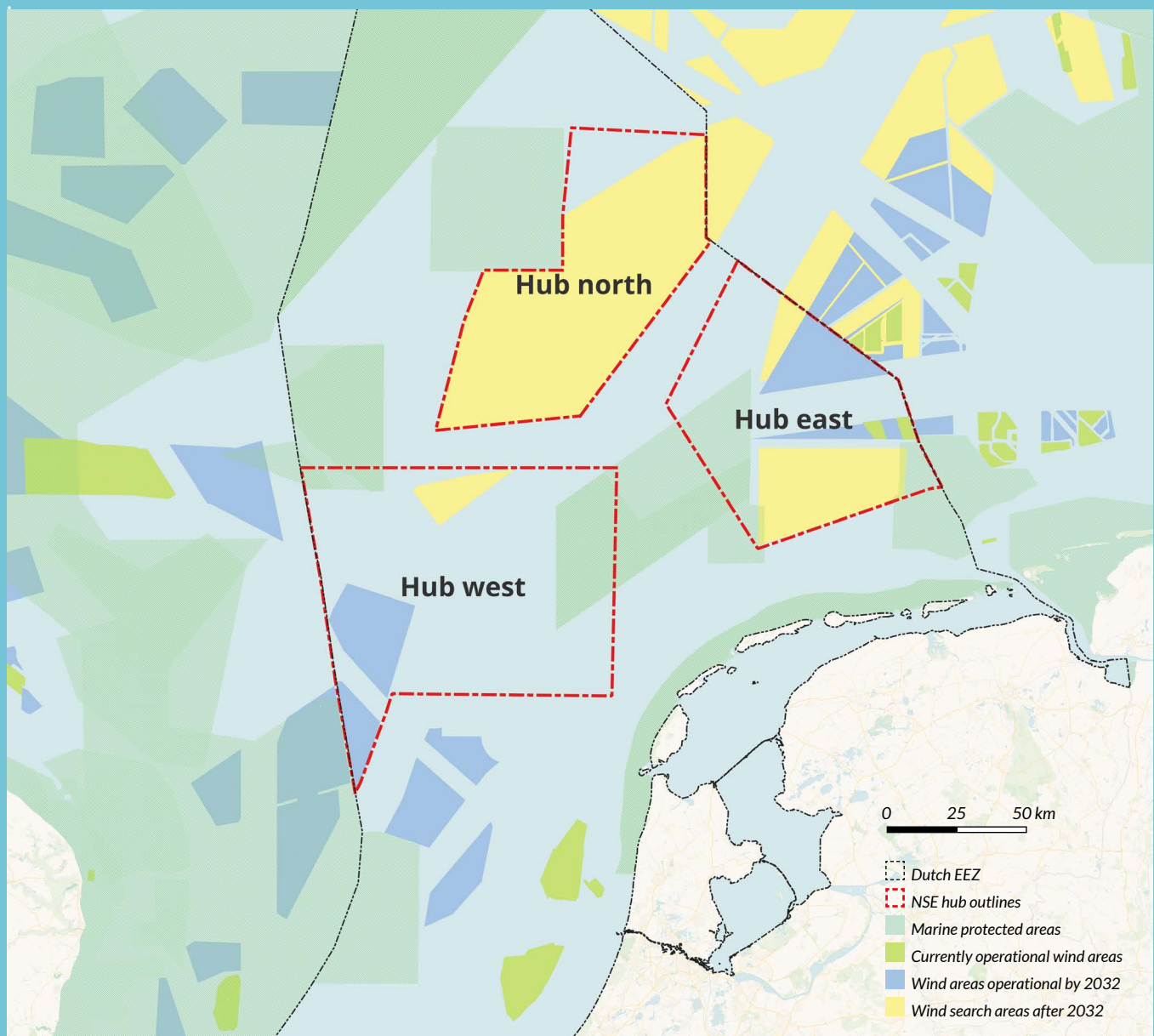
Case study: Dutch offshore energy clusters

To identify and assess the opportunities for system integration at the North Sea, cluster designs have been developed in the NSE5 program for three areas in the Dutch North Sea: Cluster West, Cluster North and Cluster East (see *Figure 2*)¹.

This chapter briefly explains the wider context and design approach, summarizes the key characteristics of the designs, and highlights key results of NSE5 research that underline the added values of offshore energy clusters for the Dutch energy

¹ The research in NSE5 has been carried out in the period beginning 2023 to mid-2025. Although the project continuously strived for the most updated information, policy developments after May 2025 could not be incorporated in the reporting. These developments will be addressed in NSE6.

*Figure 2 Map of the southern North Sea with the Dutch Continental Shelf (dotted line) and outlines of three offshore clusters (red polygons), in context with operational windfarms (dark green), planned windfarm areas (dark blue), search areas for developing windfarms (yellow), and nature areas (light green)*⁸.



system from an asset and infrastructure perspective, and from a broader societal perspective. More information can be found in the NSE5 reports^{8, 18}.

3.1 Design approach

The development of energy clusters in the North Sea requires a spatially explicit design approach. It is centered around creating blueprints that map the phased development of offshore energy clusters, incorporating scenario-based targets for the energy commodities. It contains detailed layouts for wind, hydrogen, natural gas, and CO₂ infrastructure, while balancing technical, ecological, and spatial considerations. This subchapter briefly explains this design approach, consisting of the development of storylines and the spatial explicit mapping of energy clusters.

Formulating storylines and design scenarios for offshore energy clusters

Energy cluster designs are based on translating policies and targets into storylines (narratives) that can serve as basis for design scenarios that are explicit in time and space. These scenarios should not be considered as the future, but as possible pathways for the energy system to develop. Even when certain targets and ambitions are reformulated throughout the years, the storylines still show how different assumptions impact the design of the future energy system. The offshore energy cluster designs are based on European and Dutch energy and climate targets, entailing CO₂ reduction targets, offshore wind targets, CO₂ storage potentials, etc. Additionally, it is assumed that policy targets must be achieved without violating the ecological carrying capacity of the North Sea, as outlined in the North Sea agreement¹⁹. In the NSE5

research, the storylines are based on two energy system scenarios developed by the Dutch grid operators; the National Leadership (abbreviated “NAT”) and the Decentralized Initiative (abbreviated “DEC”) scenarios²⁰. A brief overview of the characteristics of the two scenarios is outlined in *Figure 3*. Within these scenarios, supply and demand volumes are quantified for electricity, hydrogen, natural gas and CO₂ for future reference years: 2030, 2035, 2040 and 2050.

In the NAT storyline, the Netherlands aims for an energetically efficient energy system by focusing on self-sufficiency, with strong electrification and limited activity reduction of the industrial sector. This storyline meets the ambition of the Dutch government for 70 GW of offshore wind capacity in 2050 to support the high level of electrification, and foresees a large role for offshore hydrogen production²¹. Originally, the Dutch target aimed for 50 GW of offshore wind capacity in 2040²². However, this would assume a drastic increase of offshore wind production in the next fifteen years. While working on the cluster designs in NSE5, we realized that this ambition was not realistic, hence decided to include 37 GW offshore wind to be installed in our NAT storyline in 2040. Shortly after completion of NSE5, the “Wind Infrastructuur Plan Noordzee (WIN)”²³ was published by the Dutch government, which confirmed that 50GW offshore wind in 2040 is no longer realistic mainly due to slower than expected demand through electrification of industry and grid roll-out limits offshore and onshore. In the Netherlands, onshore grid capacity is limited at 40GW, suggesting that further offshore wind expansion can only be accommodated by sufficient flexibility solutions (such as offshore hydrogen). The WIN now proposes to aim for a capacity between 30-40GW, with further

Figure 3 Key characteristics of the 2 development scenarios for the future energy system of The Netherlands that form the basis for the cluster designs²⁰.

Collective Technology Choices and Management by Government

- Very high level of renewable generation (offshore wind)
- Strong electrification
- Industry stays in NL
- H₂ for industry, power generation, and long-term storage
- H₂ and Carbon for synthetic fuels

NAT

National Leadership



Market-driven, Individual Solutions

- High level of renewable generation
- Strong electrification
- Reduction in energy-intensive industry
- Certain industries leave NL
- H₂ only in industry
- Energy hubs (decentralized)

DEC

Decentralised Initiatives



growth post-2040 depending on the growth of the hydrogen value chain, the development of offshore hydrogen production, and the availability of space offshore. For more information on the WIN plan, see the textbox below.

The DEC storyline also strives for self-sufficiency, however, it assumes a strong activity reduction of energy-intensive industries. Next to this, hydrogen will mainly be used in the industrial sector. A smaller role for offshore hydrogen production and offshore wind is foreseen (45GW in 2050), resulting in smaller offshore energy clusters and a more modest utilization of the offshore space.

Spatial explicit blueprints with embedded ecological principles

From the storylines, spatial explicit designs over time are proposed that provide insights into the location and timing of installation of assets and infrastructure for electricity, hydrogen and CO₂, and the decommissioning of assets and infrastructure in relation to phase-out of natural gas. The resulting cluster designs (blueprints) specify the locations and capacities of wind farms, electrolyzers, CO₂ and hydrogen storage platforms, natural gas facilities, as well as the connecting cables and pipelines. The cluster designs are tested by calculating electricity and hydrogen production volumes

Highlight: Wind Infrastructure Plan North Sea

In June 2025, the Dutch Ministry for Climate and Green Growth published its “Windenergie Infrastructuur Plan Noordzee (WIN)” (Wind Energy Infrastructure Plan for the North Sea), addressing key choices that have to be made to facilitate and deploy the required infrastructure for offshore wind expansion. An emphasis is put on a phased and adaptive approach towards achieving the Dutch wind and offshore hydrogen ambitions.

The WIN plan indicates that the ambition of installing 50 GW of offshore wind by 2040 is unlikely to be achieved. The lower than expected speed of industrial electrification and slow ramp-up of onshore hydrogen production and industrial end-use greatly impact the need for further offshore wind expansion. Additionally, there is considerable uncertainty regarding the timely development of hydrogen infrastructure (both pipelines and storage), as well as the viability of the business case for offshore hydrogen production (demonstration) projects. This has resulted in the formulation of a minimum target for offshore wind of 30 GW in 2040, with annual decisions from 2027 on how to expand further.

Likewise, any future decisions regarding the roll-out of offshore hydrogen infrastructure will also follow this phased-approach, subject to ongoing market and demand developments. For the moment, the two offshore hydrogen demonstration projects have been paused for at least the next five years. Most likely, between 2-26 GW of electrolyzer capacity will be necessary towards 2040, however, no target is set for offshore hydrogen production.

The WIN plan addresses the expansion of international interconnectors as a key topic, both for electricity and hydrogen. Creating a better connected North Sea energy system can support the European electricity market, make more optimal use of renewable energy sources, increase flexibility and increase energy security and system resilience. The WIN plan announces plans for a further roll-out of hybrid interconnectors, with an emphasis on designing new legislation to facilitate this. Cost-benefit analyses will be made in the coming years to decide on the most viable new interconnectors.

Planning of offshore wind expansion until 2040, with timelines for decision-making ²⁴

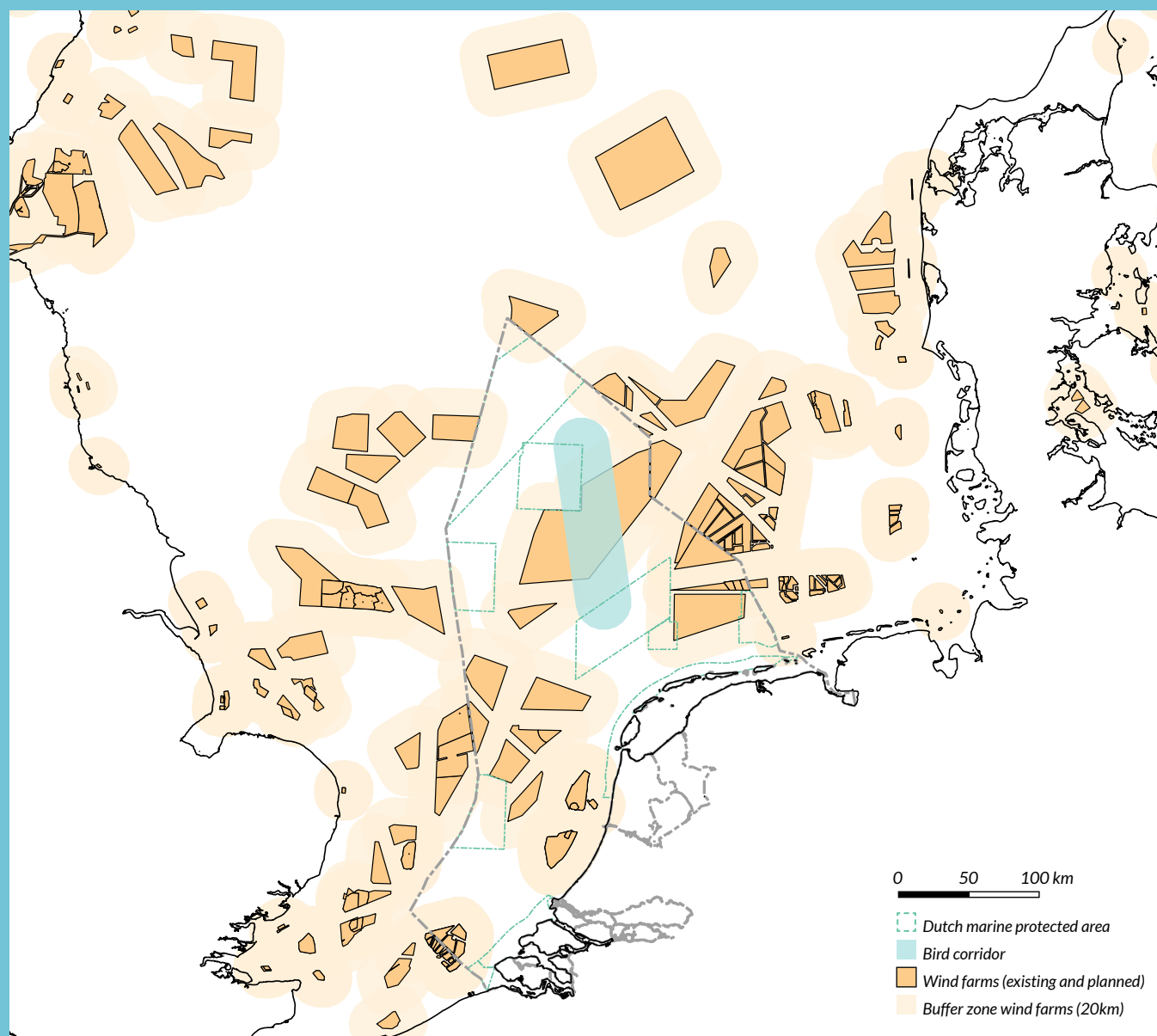
Realization	Minimum capacity expansion	Maximum capacity expansion	Final decision in year
Now until 2032	Roadmap 21 GW		Already decided
2033	Doordewind II, 2 GW		Already decided
2036	0 GW	2 GW	2026
2037	2 GW	4 GW	2027
2038	2 GW	4 GW	2028
2039	2 GW	4 GW	2029
2040	2 GW	4 GW	2030
Total	30 GW	40 GW	

for a given (climate) year and volumes to be transported to shore to match expected demand, to assess whether or not the designed infrastructure is able to meet these requirements, and what role storage can play in sustaining a more stable flow to shore and optimal use of infrastructure.

In the cluster design process, nature-inclusive design (NID) takes a central place. NID aims to integrate measures to

mitigate and compensate for adverse effects of installing (additional) energy assets and infrastructure on the ecosystem. In the NSE5 program, requirements for preserving, if not strengthening, the ecological value are incorporated in collaboration with ecology experts⁹. An example of how nature-inclusivity influences the design is the addition of a corridor to allow birds to migrate from near-coastal shallow-water areas to more distal areas (see Figure 4).

Figure 4 Map of the proposed bird corridor for Cluster North, in relation to Dutch marine protected areas and planned wind farms. This 20-km zone around wind farms is a disturbance area that could act as a barrier for certain species⁹.



3.2 Cluster design descriptions

For the two storylines, spatial explicit designs (blueprints) of three offshore energy clusters are defined. Table 1 describes their key characteristics, whereas *Figure 5* visualizes the designs on a map of the Dutch part of the North Sea for the two storylines. A brief description for each offshore energy cluster is given below.

Cluster West is concentrating on offshore wind with no hydrogen production. Offshore wind will expand towards 8GW in 2050, while natural gas production will be phased out towards 2050. Storage potential is available for CO₂ and hydrogen in depleted gas fields.

Cluster East is also concentrated on offshore wind production, albeit with a small amount of hydrogen production from DEMO-2 (0.5 GW). Offshore wind capacity will increase to 11.3 GW in 2050. There is hydrogen storage potential in small gas fields and salt structures, as well as CO₂ storage potential in larger gas fields. At the time of NSE5, DEMO-2 was foreseen to be operational by 2033, however, in its Letter to Parliament of July 2025 the Dutch government announced that further

preparations for the 2 demonstration projects will be paused for a period of 5 years²⁵.

Cluster North is considered a truly integrated energy cluster, with an equal size of offshore wind and electrolyzer capacity. In the NAT scenario, 20 GW of offshore wind will be realized in this cluster in 2050, of which 10 GW is connected to electrolyzers for (non-dedicated) hydrogen production. The electrolyzers are connected to substations that are also connected to shore via bi-directional electricity cables, hence at times of low wind and high solar, they can still produce hydrogen with electricity from shore. In the DEC scenario, 14 GW of offshore wind will be operational in this cluster in 2050, of which 7 GW is connected to electrolyzers via substations that are also bi-directionally connected to shore. Hydrogen is transported to shore with re-used (NOGAT, NGT) and new-built pipelines. The techno-economic viability of re-use through the NOGAT and NGT pipelines and its overall attractiveness compared to fully new-built infrastructure is subject of ongoing studies by Gasunie, the future network operator of the hydrogen grid²⁶.

In the NSE5 cluster designs, the possibility of re-use was explored and compared to fully new-built from (primarily) a technical perspective. In and around this cluster, there is hydrogen storage potential in salt structures (license block F8) and gas fields (license blocks G16, G17). Next to this, there is CO₂ storage potential in gas fields and aquifers. For Cluster North, specific nature-inclusive design considerations are incorporated, by implementing, amongst others, no-fishing zones, establishing bird corridors (see *Figure 4*) and creating multi-purpose zones.

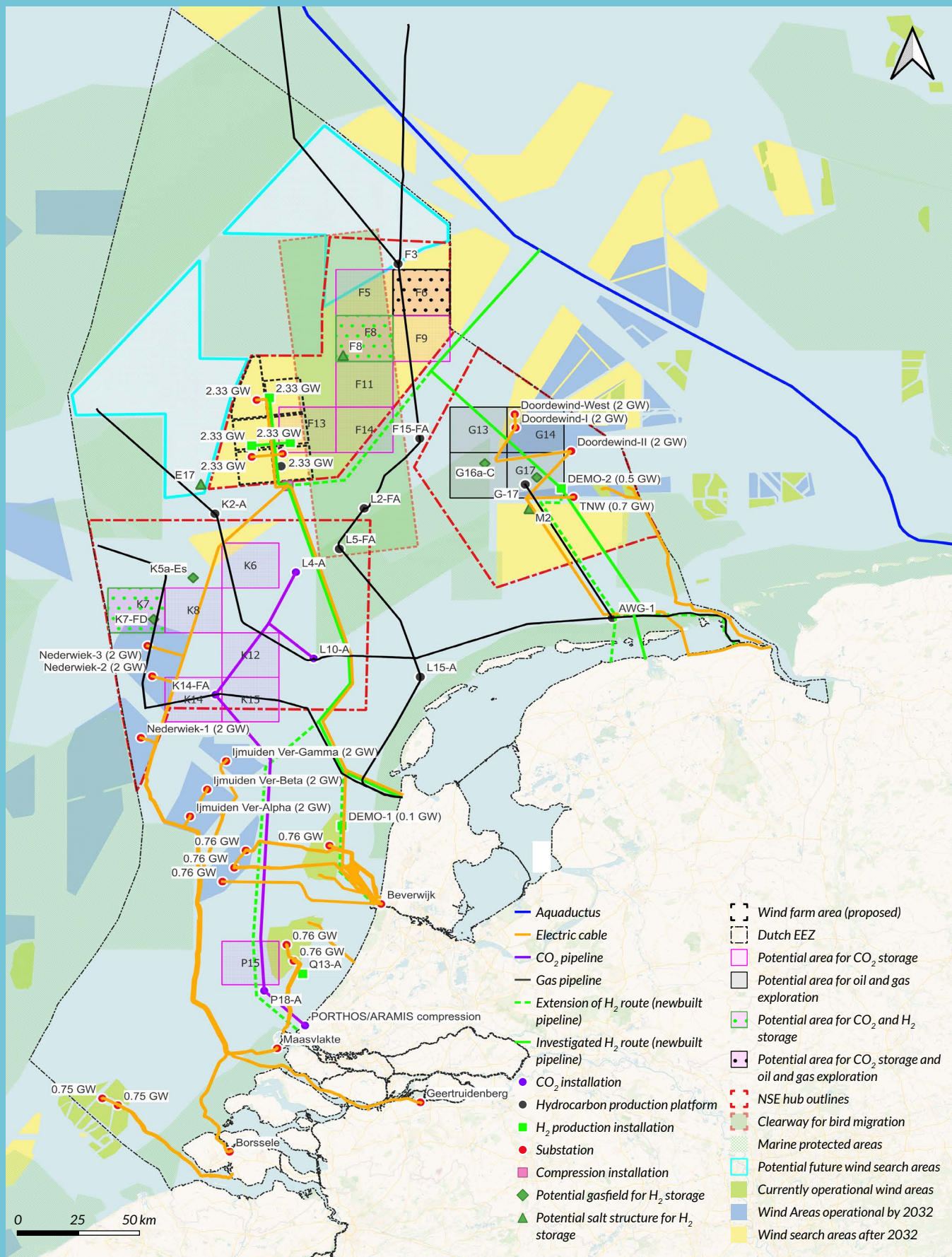
Specific nature-inclusive design considerations are incorporated in the designs to preserve the ecological carrying capacity of the cluster areas.



Table 1 Key characteristics of the three Dutch clusters⁸

		Cluster West	Cluster East	Cluster North NAT	Cluster North DEC
Key description (with ratio wind: electrolyzer capacity)		Offshore wind cluster, phased out natural gas, hydrogen and CO ₂ storage, potentially offshore solar Ratio 100:0	Offshore wind cluster, with some hydrogen production hydrogen and CO ₂ storage Ratio 96:4	Offshore wind and hydrogen cluster, hydrogen and CO ₂ storage Ratio 50:50	Offshore wind and hydrogen cluster, hydrogen and CO ₂ storage Ratio 50:50
	wind	2030: 2 GW 2040: 6 GW 2050: 8 GW	2030: 0.6 GW 2040: 7.3 GW 2050: 11.3 GW	2040: 10 GW 2050: 20 GW	2040: 6 GW 2050: 14 GW
	solar	55 MWp			
	transport	HVDC cables to Borssele, Maasvlakte & Geertruidenberg Interconnection with UK (LionLink 1.8GW)	HVDC cables to Eemshaven	HVDC cables via Dodewaard	HVDC cables via Dodewaard
	production	20-50 MW P2G 2033 (DEMO-1)	0.5 GW P2G > 2038 (DEMO-2)	5 GW 2040, 10 GW 2050	3 GW 2040, 7 GW 2050
	transport	-	-	Re-used NOGAT & new	Re-used NOGAT & new
	storage	Gas fields	Gas fields and salt structures	Salt structures and gas fields	Salt structures and gas fields
	CCS	6-14 MT 2030, 22 MT 2040	Storage potential in larger gas fields	Storage potential in aquifers	Storage potential in aquifers
	Natural gas	3.5 bcm/yr 2030, 2.5 bcm/yr 2040, <0.5 bcm/yr 2050	0.2 bcm/yr 2030, 0.9 bcm/yr 2040, 0.4 bcm/yr 2050	0.1 bcm/yr 2030, 0.4 bcm/yr 2040, 0.3 bcm/yr 2050	0.1 bcm/yr 2030, 0.4 bcm/yr 2040, 0.3 bcm/yr 2050

Figure 5 Vision of the North Sea in 2050 with blueprints of the three NSE clusters according to the DEC scenario. In the DEC scenario, 45GW of offshore wind capacity is installed in 2050, of which 33GW in the 3 clusters. Offshore hydrogen production capacity in DEC amounts to ~8GW, and is (almost) entirely located in the southwest of cluster North.



3.3 The benefits of offshore energy clusters for The Netherlands

Offshore energy clusters can offer techno-economic benefits, spatial planning advantages, and benefits for the energy system and society at large. Achieving an optimal design while balancing the interests of diverse stakeholders remains a complex challenge though. By enabling the integration of multiple technologies and energy commodities, offshore energy clusters can add value, provided that they are designed through coherent spatial planning with appropriate stakeholder processes. Through the NSE5 research, four distinct benefits were explored.

The integration of offshore wind and electrolysis can increase the efficient use of renewable energy sources and reduce curtailment rates

The integration of offshore electrolysis with offshore wind partly absorbs the intermittency of offshore wind, resulting in a more efficient use of renewable energy sources and lower curtailment rates for the offshore wind farms⁸. The flexibility provided by offshore electrolysis dampens some of the wind power fluctuations, and through this more of the generated electricity (in the form of hydrogen) can be landed, thereby making more effective use of the energy infrastructure. The presence of offshore electrolysis results in a 8-14% increase of

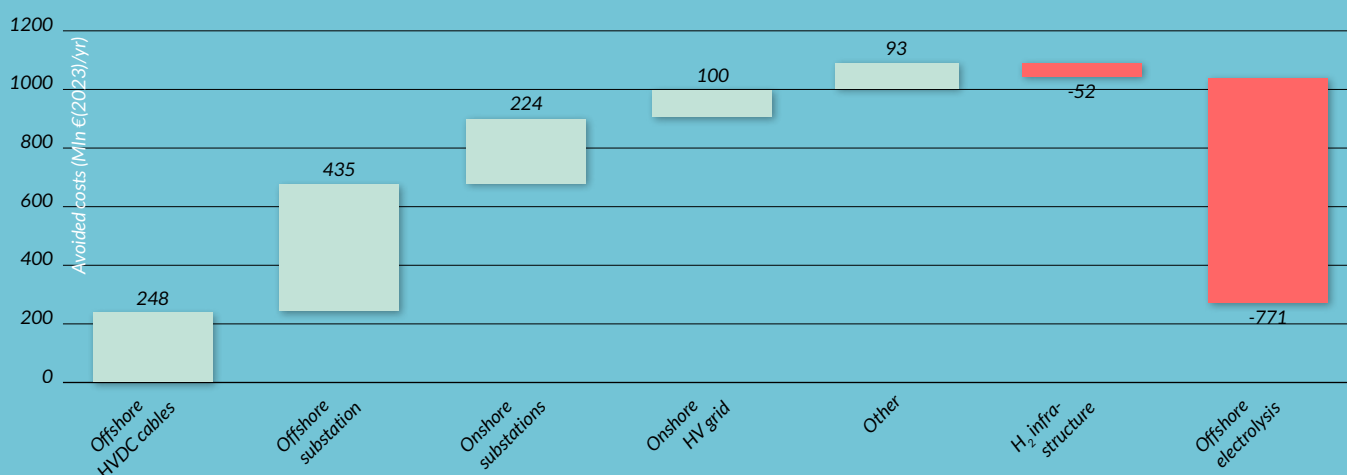
offshore wind full load hours, resulting in decreased offshore wind curtailment (15-44 TWh less curtailment compared to a scenario without offshore electrolysis), thereby increasing the effective use of renewable energy sources¹⁸. Even though the role of offshore electrolysis in the future energy system is highly uncertain², market simulations clearly show there is potential for offshore hydrogen production in all scenarios, especially for areas far offshore¹⁸. This is due to the fact that pipelines are generally cheaper than cables for transport of energy over long distances²⁷. For the northernmost regions (in and around cluster North), any wind capacity is always accompanied by hydrogen production, showing the clear benefit of having an integrated system.

Offshore electrolysis can increase the cost-effective use of energy infrastructure

The integration of offshore electrolysis increases the cost-effective use of the available offshore infrastructure. In all modelled scenarios where offshore wind capacities expand beyond 40 GW towards 2050, offshore electrolysis plays a significant role, demonstrating its cost-effectiveness compared to a system without it. This is primarily because offshore electrolysis reduces the need for additional electricity cables to bring the generated wind energy to shore¹⁸. In general, the investments for the required offshore electrolysis capacity, and infrastructure to transport the hydrogen to shore are expected

2 At the moment, planned offshore hydrogen demonstration projects have been paused, and a decision on their development will be made in the Climate and Energy Note (Klimaat- en Energienota) at the end of 2025.

Figure 6 Decomposition of avoided system costs of offshore hydrogen production in 2050 (in million €/year, 2023 prices)³



3 To complement the technical research and investigate the societal benefits of offshore energy clusters, three energy system scenarios are used, developed by TNO. One scenario (ADAPT) assumes high hydrogen and wind deployment, continued use of fossil fuels and rapid expansion of CCS, reflecting the same pathway as NAT. Another scenario assumes an ambitious change of the energy system with large-scale adoption of renewables (TRANSFORM). The third scenario is a variant of this, but with decreased industrial activity in the chemical sector (comparable to DEC). Together, they span in broad range of potential pathways for the future energy system.

to remain lower than the investments required for installing additional electricity infrastructure (substations, cables). *Figure 5* depicts a decomposition of the avoided and incurred system costs by deploying offshore electrolysis. The blue parts (avoided costs) outweigh the orange parts (incurred costs), indicating that offshore hydrogen production is beneficial for society from a (system) cost perspective, resulting in a net gain of 30 – 350 million euros annually¹⁸.

Choosing an optimal operational strategy of offshore electrolyzers can enhance the efficiency of power delivery to shore. By flexibly adjusting the electrolyzer's load in offshore energy clusters (rather than maintaining a fixed 50% minimum load), it can absorb excess wind power during peak production, allowing the cable to shore to operate at full capacity more frequently, with simulations showing up to 1000 additional hours of stable power delivery to shore⁸. The addition of hydrogen storage (in salt structures or depleted gas fields) to the offshore energy system can enhance this stable power delivery effect even more and enable a nearly-constant flow of hydrogen to shore, further smoothing out wind power fluctuations⁸. Lastly, when part of the existing infrastructure is re-used for hydrogen transport, additional infrastructure costs can be saved, increasing the overall cost-effectiveness of the energy system.

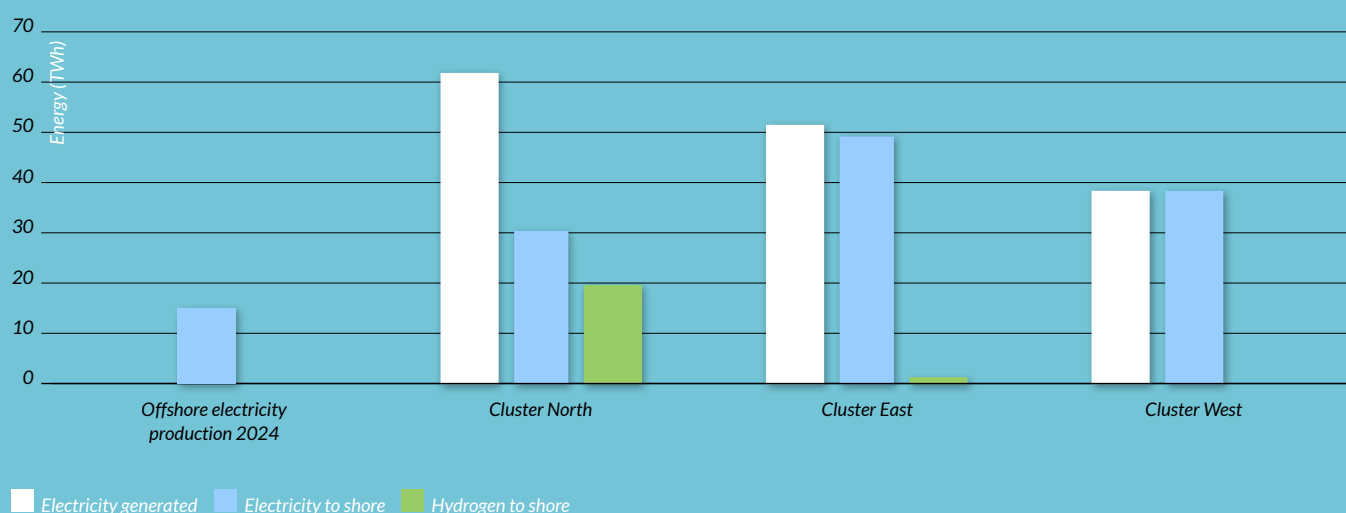
Offshore energy clusters can decrease the spatial impact of the energy transition

The integration of multiple offshore energy commodities can

decrease the required spatial impact of the energy transition. First of all, the offshore presence of energy production and conversion provides spatial benefits by reducing the onshore required space for hydrogen production. By moving offshore, the use of roughly 480 hectares onshore can be avoided¹⁸. Secondly, integrating several energy functions enables the more efficient use of space. For example, the co-location of offshore wind with hydrogen production, and potentially hydrogen or CO₂ storage, results in a smaller spatial impact than installing individual assets. When existing oil and gas infrastructure is re-used for hydrogen and CO₂ transport, this reduces the spatial impact even more.

With the proposed designs, the three clusters together can produce a significant share of the electricity demand towards 2050, thereby alleviating the need for additional onshore electricity production, conversion and transport assets. *Figure 6* visualizes the share of electricity production in one of the various simulated scenarios for the three offshore clusters. The three clusters would in this case supply 42% of the yearly electricity demand and 21% of the hydrogen demand in the Netherlands in 2050¹⁶. This scale of offshore wind production (~152 TWh/yr) requires an area of roughly 5900 km², clearly emphasizing how the vast scale of offshore electricity and hydrogen production offshore can alleviate the pressure on land but also places a significant spatial pressure on the already very busy North Sea²⁸.

Figure 7 Energy flows (TWh/yr) of the NSE5-DEC scenario in 2050, separated for the three clusters, compared to the current offshore electricity production.



4.

The North Sea international energy system

The North Sea will be a key region in the energy transition, with offshore wind accounting for approximately 30% of the total European electricity production by 2050²⁹. Since the North Sea is surrounded by nine European countries, a high need for international collaboration is foreseen. Looking at the strengths of every country, making smart use of existing infrastructure, and developing market and regulatory frameworks that facilitate European collaboration can decrease energy dependence on countries outside of Europe and increase the effective use of the available infrastructure. This chapter describes development pathways for the offshore energy system in the North Sea basin and what is required to facilitate these developments. It highlights the added value of an interconnected integral energy system, which increases energy security and energy system resilience. The outcomes are based on the research conducted in NSE5³⁰.

4.1 Pathways towards 2050

To analyse the development of the future energy system and investigate the role of each individual country, the NSE5 research considers two scenarios: the Distributed Energy (DE) and Global Ambition (GA) scenarios developed by ENTSO-E and ENTSO-G³¹. The GA scenario (also called the 'high' scenario) envisions high decarbonization through large-scale infrastructure, international cooperation, and rapid deployment of offshore wind, hydrogen, and CCS. The DE scenario (or 'low' scenario) emphasizes local initiatives and decentralized energy solutions, with high European autonomy and generally a smaller role for hydrogen. These scenarios form

the basis for the development of the indicative pathways for the production of key energy commodities and CO₂ storage, which have been visualised for the North Sea basin towards 2050 in Figure 7. Figure 8 provides a qualitative scale of the development and contribution of an energy commodity within every North Sea country. The scale is relative and in relation to the other countries. The transition to renewable energy sources is clearly visible, with a decrease of natural gas, and a drastic increase of offshore wind production. The developments per energy commodity are described below.

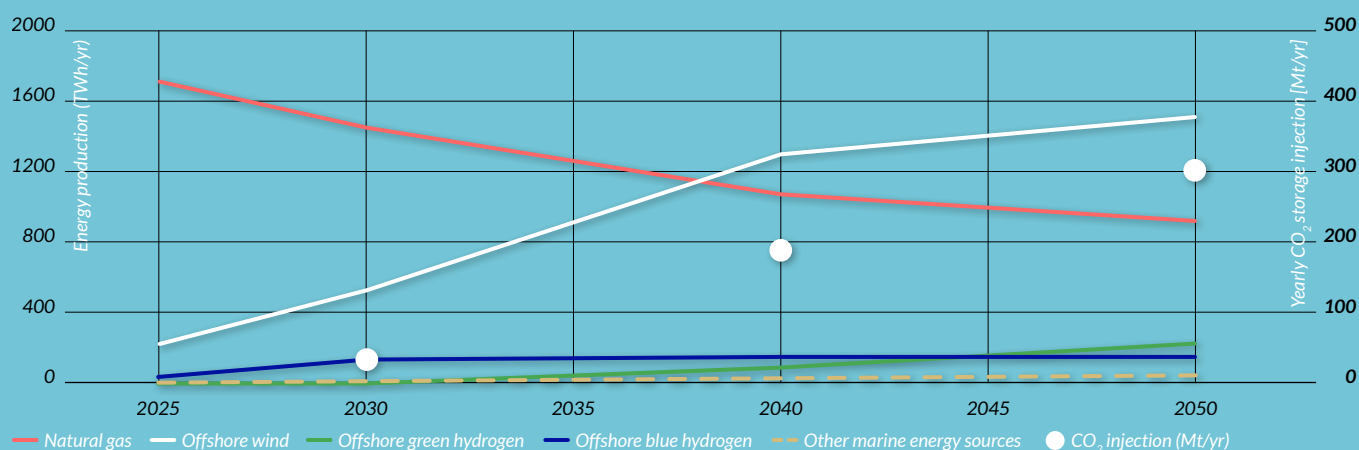
Offshore wind expansion

The yearly production of offshore wind in the North Sea countries will increase almost tenfold by 2050 towards 1500 TWh, accounting for approximately 60% of total European installed capacity³². The installed wind capacity for both on- and offshore is visualized in Figure 9. The Netherlands, the UK and Germany will take the lead in offshore wind expansion, with an increase of around >30TWh/yr³⁰. This large expansion shows the importance of proper planning processes, where countries should to optimize the use of space and supply chain capacity.

Offshore hydrogen production

Hydrogen is expected to play an increasingly important role on the North Sea. While blue hydrogen is likely to be a driving force in the coming decade, projections indicate that green hydrogen is expected to dominate by 2050 with production reaching up to 1200 TWh/yr across the North Sea, as visualized

Figure 8 Indicative pathways for the offshore energy commodities for all North Sea countries, based on various sources and scenarios⁴



4 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 → average of the calculated DE & GA scenarios, other marine energy sources → North Sea Energy, yearly CO₂ injection in the North Sea → Xodus report. Further details are provided in extensive dossiers per energy commodity and can be downloaded [here](#).

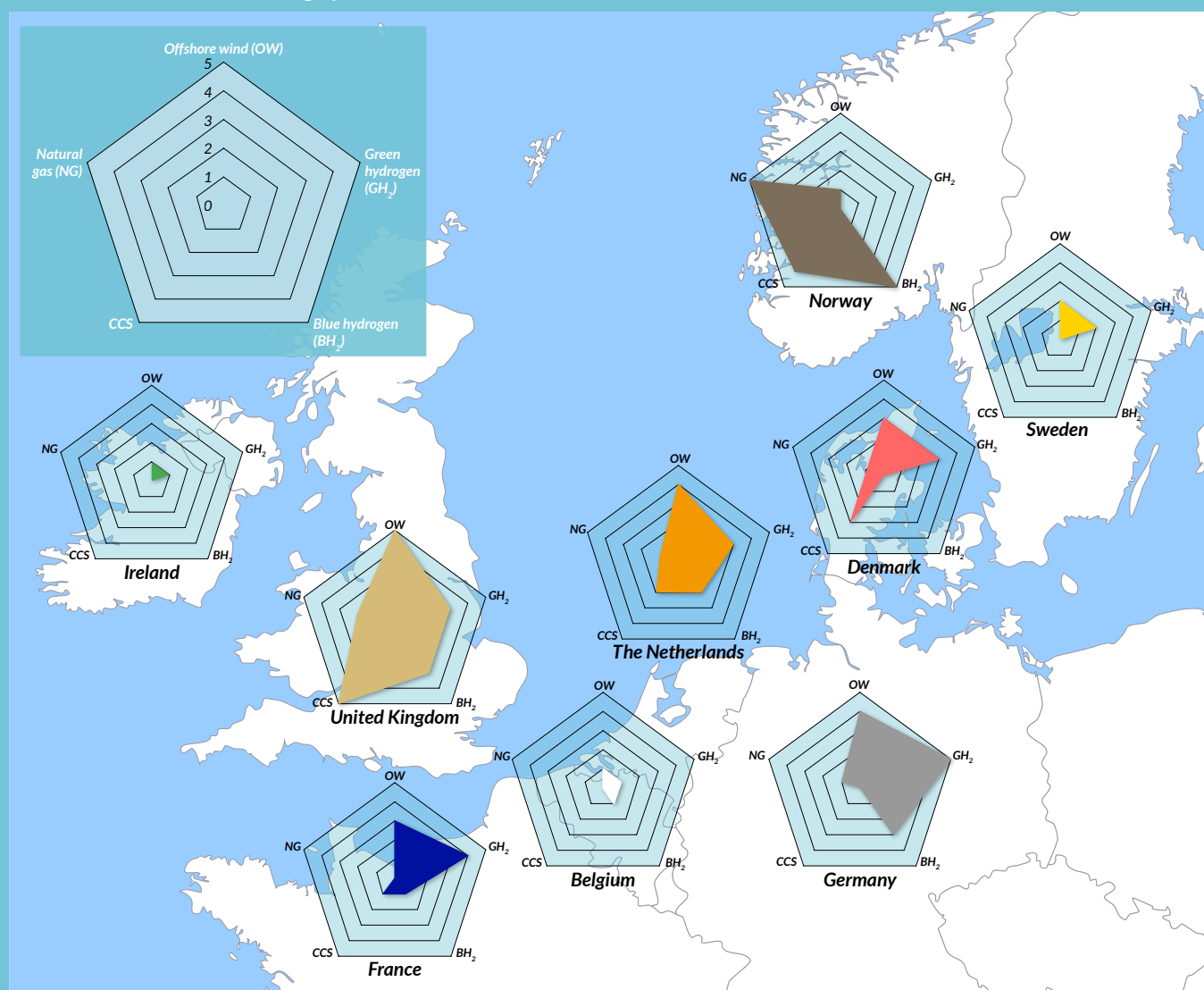
in Figure 10³³. The figures illustrate that the energy transition requires both a rapid expansion of offshore wind, as well as large scale integration with (offshore) hydrogen production. For this, hydrogen should be produced at locations with surplus electricity or limited grid capacity, and an international grid perspective is essential to optimally connect countries and create an integrated energy system.

Natural gas production

Natural gas production will decrease by approximately 50% by 2050 in the North Sea countries³³. It is expected that the

Netherlands and Denmark will phase out their natural gas production towards 2050, while the UK is expected to produce only 5% of its current production in 2050. Norway's natural gas production will decrease only modestly (from 1300 TWh in 2023 to 900 TWh in 2050). This means that a large part of the current infrastructure, both platforms and pipelines, will be dismantled in the coming decades. A cross-country strategy with a clear timeline could be helpful to provide clarity on which pipelines and platforms become available for (joint) decommissioning campaigns or for re-use to properly manage also supply chain capacity constraints.

Figure 9 Indicative share of commodity developments per country towards 2050, compared to the other countries. 0 indicates no foreseen role, and 5 indicates a highly substantial role.



CO₂ transport and storage

The declining natural gas production trends are reflected in the increased planned CO₂ storage projects around the North Sea. Norway takes the lead with several operational and announced projects (such as the Northern Lights project³³). Together with Germany, the Netherlands and Denmark, a yearly CO₂ injection capacity of 300 Mtpa is foreseen towards 2050³³. Adequate research is necessary on which areas are available for CO₂ storage and whether countries can share their available transport and storage capacity.

4.2 From national pathways to offshore energy clusters

The commodity pathways in Figure 7 show the mutual dependence of the energy commodity pathways on each other, such as offshore wind and green hydrogen production expansion, and blue hydrogen and CCS developments. Furthermore, the national differences are apparent in terms of offshore wind expansion, CO₂ storage capacities and natural gas phase-out. The establishment of international offshore energy clusters could provide a way to align the developments,

Figure 10 Estimated installed capacity of offshore and onshore wind, averaged over the National, Distributed Energy and Global Ambition scenarios

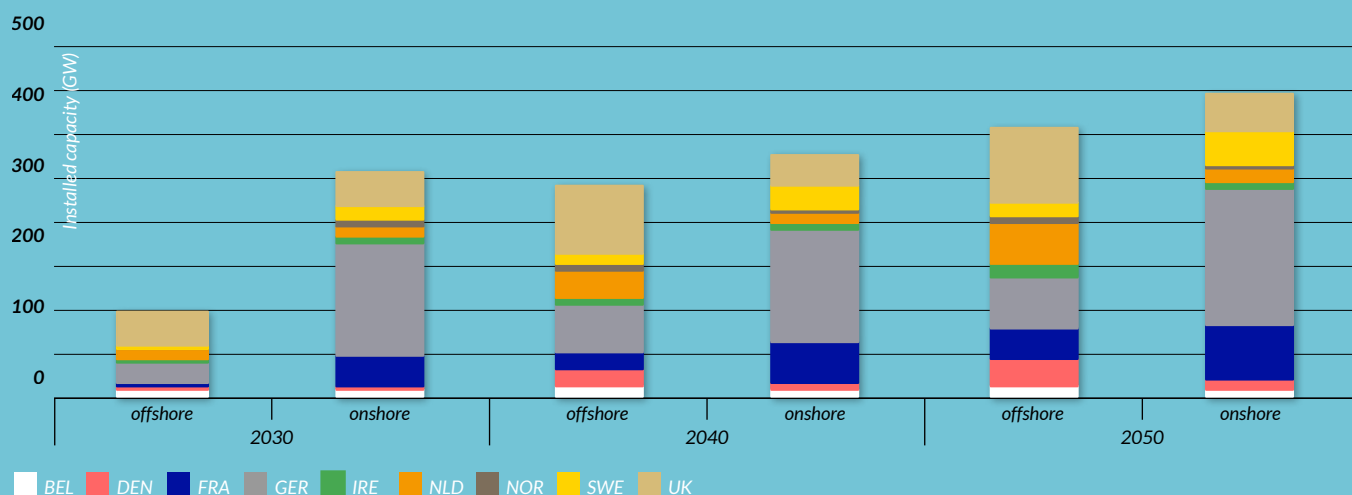
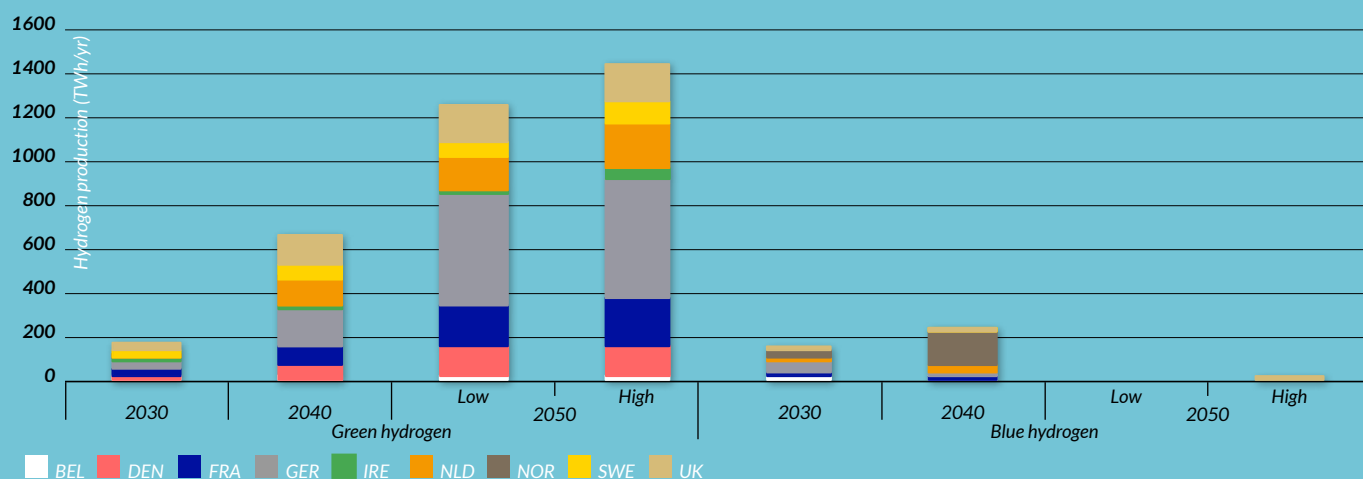


Figure 11 Estimated hydrogen production in the North Sea countries, for the low (DE) and high (GA) scenarios.



enable shared infrastructure (and avoid additional costs), and optimize the use of space and supply chains.

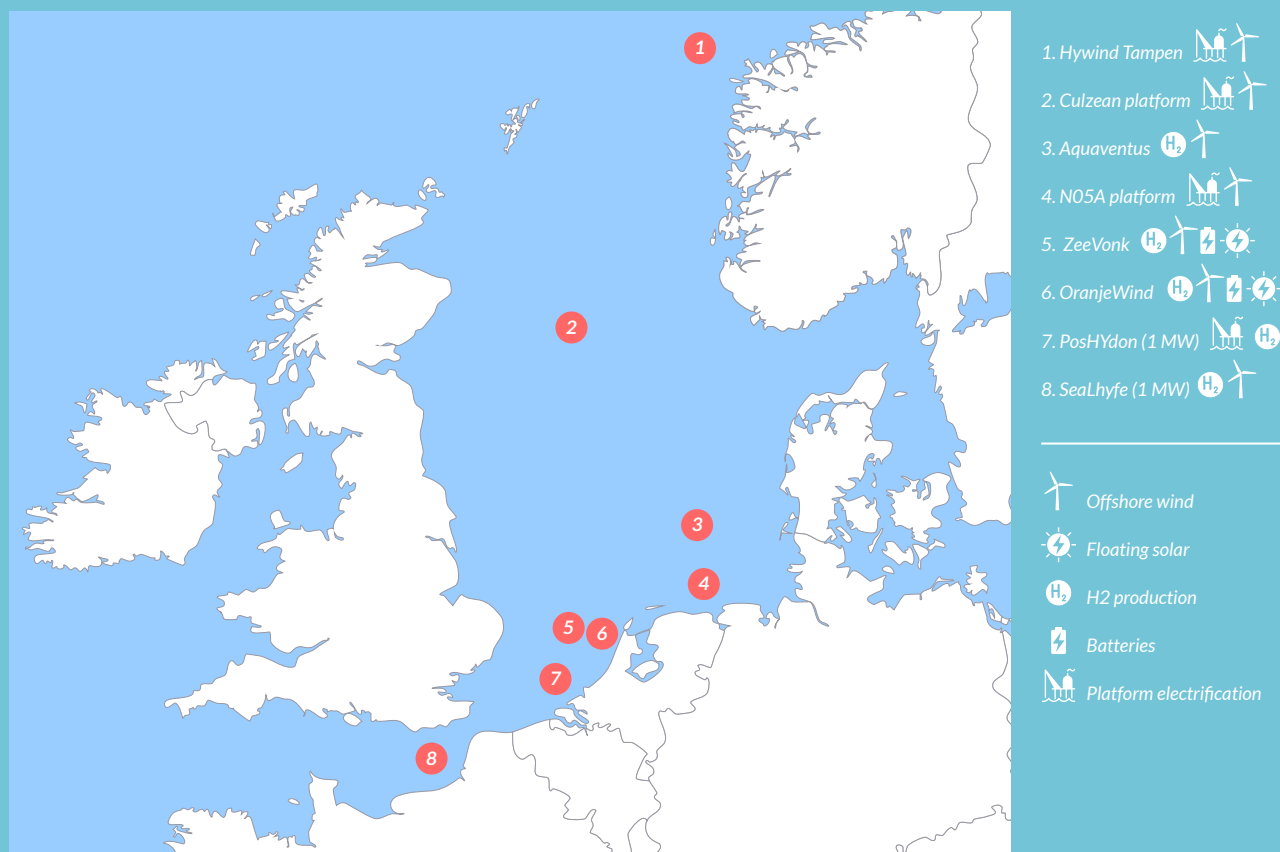
The added value of an international interconnected energy system

An internationally interconnected and integrated energy system can increase the resilience of the European energy system. Due to varying wind profiles across the North Sea, countries can complement each other during supply and demand imbalances³⁴. By establishing a more interconnected energy system, part of the intermittent behavior of offshore wind energy can be mitigated. By making smarter use of countries' strengths, infrastructure can more optimally be used and the spatial impact can be further reduced. Next to this, an interconnected and integrated energy system is less prone to safety and security issues.

The first examples of co-location are arising, such as the Sealhyfe platform near the French coast, producing its first

kilograms of offshore green hydrogen in 2024 from wind energy³⁵, and the Dutch PosHYdon project, which started the operation of a 1MW green hydrogen electrolyser at the electrified Q13a-A hydrocarbon production platform in 2025³⁶. A map of these pilot projects is shown in *Figure 12*. In these system integration projects, co-location is realized by integrating energy production, conversion, transport and storage with services and logistics, while making multifunctional use of space. From the energy perspective, this suggests to not individually consider the energy carriers, commodities and infrastructure assets, but rather to regard them as part of one holistic and integrated energy system. With the gradual expansion of pilot projects, the learning curve towards operationalized system integration concepts is kickstarted. The next chapter introduces actions that have to be taken to further deploy international interconnected energy clusters on the North Sea.

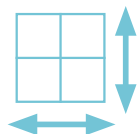
Figure 12 Graphical overview of system integration projects (or energy clusters) that are currently being developed on the North Sea, where various energy commodity functions are combined.



5.

A roadmap towards North Sea Energy clusters

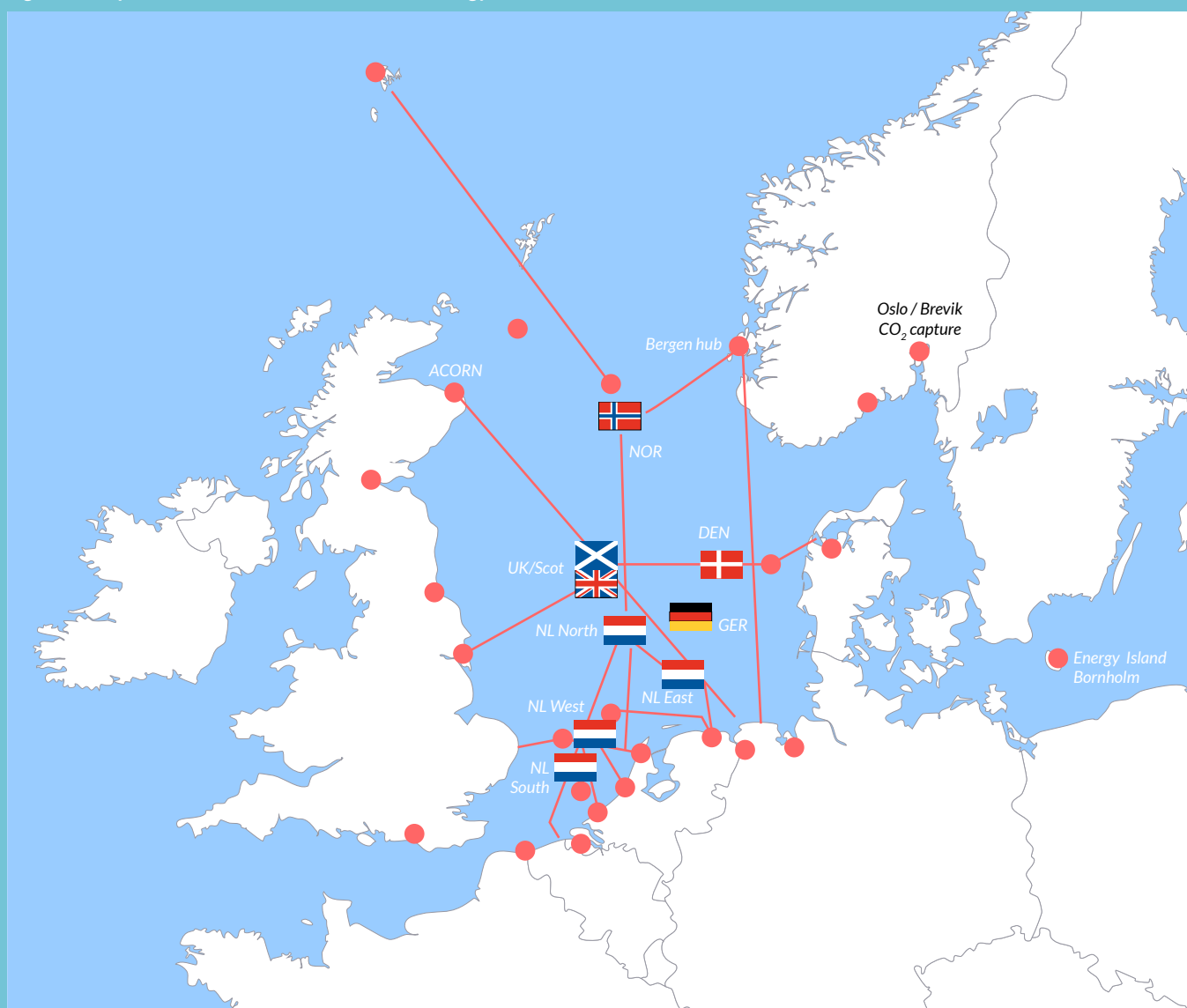
To expand the North Sea's role as a system integration region and pave the way towards international offshore energy clusters, several challenges have to be overcome. Based on the action agenda that was proposed in NSE5³³, Four international actions are highlighted that should be tackled in the coming years. In the next phase of the NSE program (NSE6), the proposed international actions will be facilitated with targeted thematic research on offshore energy clusters, as visualized in Figure 13.



Reduce the spatial pressure through coordinated planning

The expansion towards an interconnected North Sea energy system requires coordinated international spatial planning, with embedded ecological design principles. An expansion of offshore energy clusters provides opportunities for the co-location and multi-use of space, however, coordinated action is needed between countries to coordinate the infrastructure

Figure 13 Impression of interconnected offshore energy clusters and onshore harbor clusters on the North Sea.



re-use and roll-out. Next to this, nature- and societal-inclusive design principles should be incorporated in the design process. The Dutch case can act as an example for other countries, although adequate research and monitoring programs are needed to study the environmental and ecological impacts of new offshore energy systems. Participatory processes and co-creation are key to ensure broad societal support and align with ecological goals. Together, these enhanced international coordination measures can ensure a smooth and effective further roll-out of the North Sea energy system.



Bridge the economic gap for offshore system integration

To unlock investments in offshore energy clusters and achieve climate and energy targets, the economic mismatch between system-level benefits and project-level business cases has to be resolved. Long-term uncertainty, slow infrastructure developments and a lack of committed off-takers currently hinder further expansion. A key challenge is that the added value of energy clusters, particularly their ability to enhance energy security and lower infrastructure cost offshore and onshore, are often not reflected in individual businesses cases. Further research is needed on market reforms, including appropriate compensation for (offshore) flexibility, energy storage and stronger incentives for interconnectors, which can reduce system costs and improve system resilience. In addition, creating downward cost trends for offshore wind and offshore electrolysis are crucial for viable business cases. It should be researched further which support mechanisms, market designs or regulatory adjustments could help to drive down investment costs. Together, these mechanisms should enable the mobilization of public and private resources for offshore system integration, with the goal to unlock sufficient investments for offshore energy clusters to arrive at a future energy system with lowest cost for society.



Extend cross-border integrated planning and strengthen international cooperation

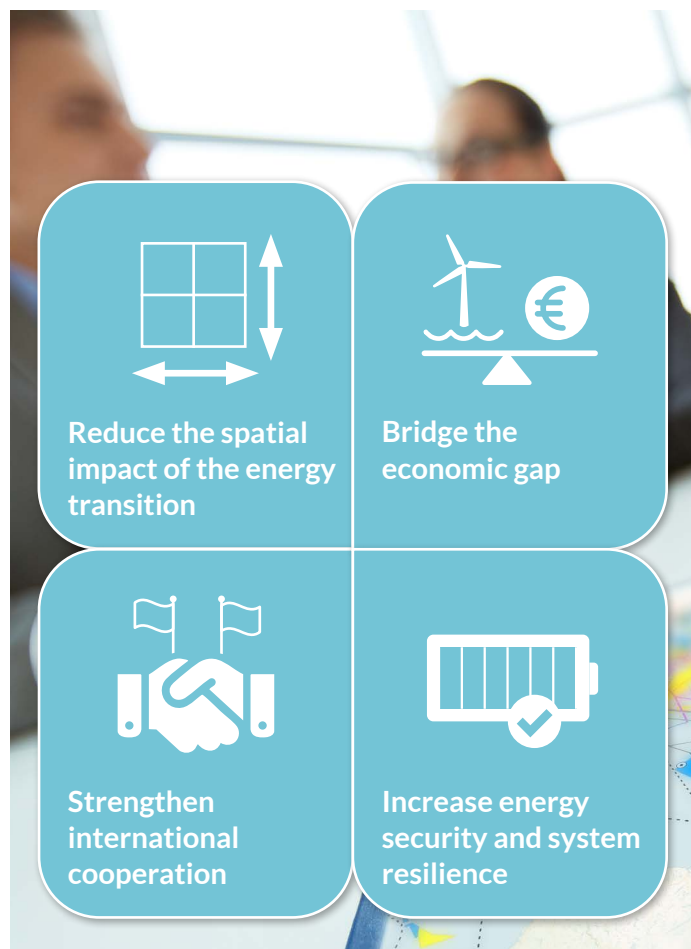
The development of an offshore renewable energy system demands extensive international collaboration and planning. A shift from isolated national approaches to a coordinated, cross-border strategy is essential. As advised by the Offshore TSO Collaboration (OTC), cross-border projects should be expanded to test the benefits for the region, instead of continuing on a project-by-project basis³⁷. To achieve this, it is recommended that an extensive European infrastructure roadmap is developed that addresses how the four commodity grids will be integrated in the future. Clear prioritization and timelines

are critical to guide investments. The roadmap should identify which infrastructure can be re-used within what timeframe and where the major energy clusters will emerge. In this way, the energy transition would not be tackled on a purely national basis, and smart synergies can be created focusing on the strengths of each country.



Increase offshore energy security and system resilience

Amid rising geopolitical tensions and infrastructure threats, ensuring a secure and resilient offshore energy system is increasingly important. Even though an international interconnected energy system can enhance the overall resilience by building in redundancy, it also introduces new physical and cyber vulnerabilities. More research is needed to assess and address these risks, so that offshore energy clusters can reliably support Europe's energy transition. This should also be supported by improved monitoring of existing infrastructure, for example through real-time sensor networks.



References

- 1 [2030 climate targets - European Commission](#)
- 2 [The North Seas Energy Cooperation](#)
- 3 north-sea-energy.eu/about
- 4 [Will more wind and solar PV capacity lead to more generation curtailment? – Renewable Energy Market Update - June 2023 – Analysis - IEA](#)
- 5 E.F. Dute, J.E. Fokkema, M.J. Land, J.C. Wortmann, M. Douwes, Determining onshore or offshore hydrogen storage for large offshore wind parks: The North Sea Wind Power Hub case, *Journal of Cleaner Production*, Volume 472, 2024, 143395, ISSN 0959-6526, <https://doi.org/10.1016/j.jclepro.2024.143395>.
- 6 Espen Flo Bødal, Sigmund Eggen Holm, Avinash Subramanian, Goran Durakovic, Dimitri Pinel, Lars Hellemo, Miguel Muñoz Ortiz, Brage Rugstad Knudsen, Julian Straus, Hydrogen for harvesting the potential of offshore wind: A North Sea case study, *Applied Energy*, Volume 357, 2024, 122484, ISSN 0306-2619, <https://doi.org/10.1016/j.apenergy.2023.122484>.
- 7 Taieb, Aya & Shaaban, Mostafa. (2019). Cost Analysis of Electricity Transmission from Offshore Wind Farm by HVDC and Hydrogen Pipeline Systems. 632-636. 10.1109/GTDAAsia.2019.8715900.
- 8 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
- 9 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
- 10 Rafael Martínez-Gordón, Manuel Sánchez-Diéguez, Amirhossein Fattahi, Germán Morales-España, Jos Sijm, André Faaij, Modelling a highly decarbonised North Sea energy system in 2050: A multinational approach, *Advances in Applied Energy*, Volume 5, 2022, 100080, ISSN 2666-7924, <https://doi.org/10.1016/j.adapen.2021.100080>.
- 11 [2023.23.11 NSWPH Cost Benefit Analyses for Offshore Hybrid Infrastructure projects Cost & benefit Discussion paper #2.pdf](#)
- 12 Jeroen R. Vreeburg, Julio C. Garcia-Navarro, The potential of repurposing offshore natural gas infrastructure on the Dutch Continental Shelf for hydrogen production and transport, *International Journal of Hydrogen Energy*, Volume 115, 2025, Pages 37-48, ISSN 0360-3199, <https://doi.org/10.1016/j.ijhydene.2025.03.030>.
- 13 Germán Morales-España, Ricardo Hernández-Serna, Diego A. Tejada-Arango, Marcel Weeda, Impact of large-scale hydrogen electrification and retrofitting of natural gas infrastructure on the European power system, *International Journal of Electrical Power & Energy Systems*, Volume 155, Part B, 2024, 109686, ISSN 0142-0615, <https://doi.org/10.1016/j.ijepes.2023.109686>.
- 14 Rafael Martinez-Gordon, Laura Florentina Gusatu, Srinivasan Santhakumar, Jos Sijm, André Faaij, Decarbonisation pathways towards a net-zero North Sea energy system by 2050, *Renewable Energy*, Volume 250, 2025, 123286, ISSN 0960-1481, <https://doi.org/10.1016/j.renene.2025.123286>.
- 15 [Greater North Sea Basin Initiative - Antwerp Ministerial Declaration | Report | Government.nl](#)
- 16 [Expert Paper II Offshore TSO Cooperation](#)
- 17 Ahmad Abdallah Mohammad Aljabery, Hasan Mehrjerdi, Sajad Mahdavi, Reza Hemmati, Multi carrier energy systems and energy hubs: Comprehensive review, survey and recommendations, *International Journal of Hydrogen Energy*, Volume 46, Issue 46, 2021, Pages 23795-23814, ISSN 0360-3199, <https://doi.org/10.1016/j.ijhydene.2021.04.178>.
- 18 S. Blom, J. van Stralen, L. Eblé, I. Magan, S. Hers, "Public Value Assessment of Offshore System Integration", *North Sea Energy*, 2025
- 19 [Het Akkoord voor de Noordzee | Rapport | Rijksoverheid.nl](#)
- 20 [Rapport II3050 Scenario's | Netbeheer Nederland](#)
- 21 [Kamerbrief "Windenergie op zee 2030-2050"](#)
- 22 [Kamerbrief "Update aanvullende routekaart wind op zee"](#)
- 23 [Het Windenergie Infrastructuurplan Noordzee](#)
- 24 [Offshore Energy Infrastructure | RVO.nl & Het Windenergie Infrastructuurplan Noordzee](#)
- 25 [Kamerbrief "Het Windenergie Infrastructuurplan Noordzee"](#)
- 26 [Petrogas en Gasunie onderzoeken hergebruik bestaande Noordzeeleidingen voor waterstoftransport › Gasunie](#)
- 27 Taieb, Aya & Shaaban, Mostafa. (2019). Cost Analysis of Electricity Transmission from Offshore Wind Farm by HVDC and Hydrogen Pipeline Systems. 632-636. 10.1109/GTDAAsia.2019.8715900.
- 28 Peter Enevoldsen, Mark Z. Jacobson, Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide, *Energy for Sustainable Development*, Volume 60, 2021, Pages 40-51, ISSN 0973-0826, <https://doi.org/10.1016/j.esd.2020.11.004>.
- 29 [Offshore wind energy in Europe](#)
- 30 A. Satish, H. Yousefi, J. Koornneef, J. Mohanan Nair, M. Laarhoven, "Empowering and Decarbonizing Europe: an Integral Grid Compass for North Sea Energy System Integration", *North Sea Energy*, 2025
- 31 [TYNDP 2024 Scenarios Storyline Report, July 2023](#)
- 32 [Offshore wind energy in Europe](#)
- 33 [What we do - Northern Lights](#)
- 34 Blokhuis, N. (2024) Spatial Modelling of International Offshore Energy Scenarios and Investigating Offshore Interconnections (Master's thesis). Utrecht University & TNO
- 35 [Sealhyfe produces its first kilos of green hydrogen in the Atlantic](#)
- 36 [Poshydon | Green Hydrogen Energy](#)
- 37 [Expert Paper III Offshore TSO](#)



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