North Sea Energy
offshore system integration

D7.2 WHITE PAPER

North Sea Energy 2023-2025

Empowering & decarbonizing the Netherlands: a national North Sea Energy compass

Towards an affordable, reliable and decarbonized energy system

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Empowering & decarbonizing the Netherlands: a national North Sea Energy compass

Towards an affordable, reliable and decarbonized energy system

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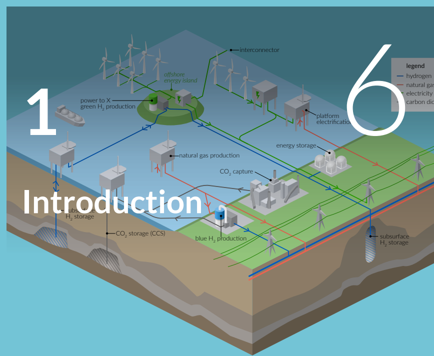
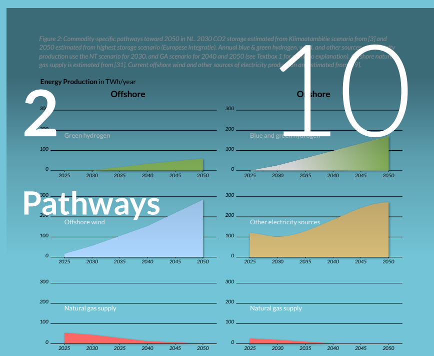
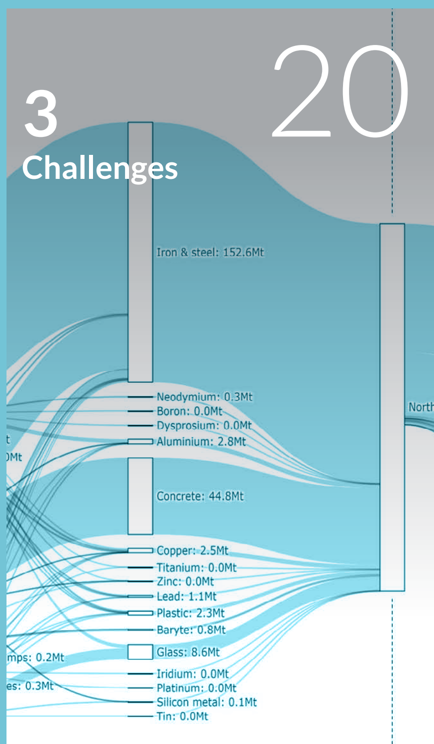
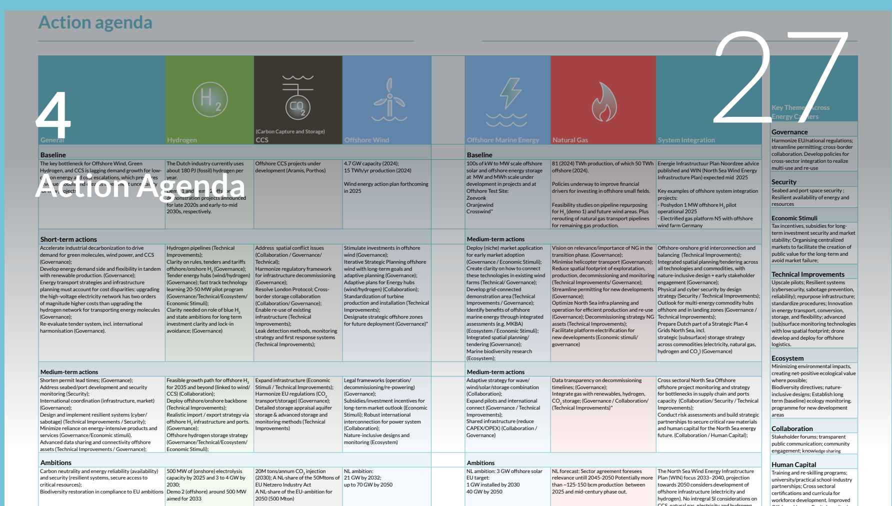








1. Introduction

This whitepaper provides indicative scenarios for the North Sea energy system that could materialize between now and 2050. This includes pathways for offshore energy system integration through the lens of four energy commodities: electricity, hydrogen, natural gas, and CO_2. The paths are based on energy system modelling, which was executed in the North Sea Energy (NSE) program. Here, we focus on the Dutch part of the North Sea. For an international perspective, we refer to D7.1 [1].

The outcomes align with national ambitions to achieve net-zero emissions by 2050. Our scenario shows a possible future of the North Sea as a powerhouse, which can be interpreted as technologically optimistic. The pathways thus provide insights into the potential magnitude of the challenges in the offshore energy transitions. Based on work in NSE and stakeholder interviews, we connect these pathways to an action agenda for offshore system integration.

1.1 Shared vision of the North Sea Energy consortium

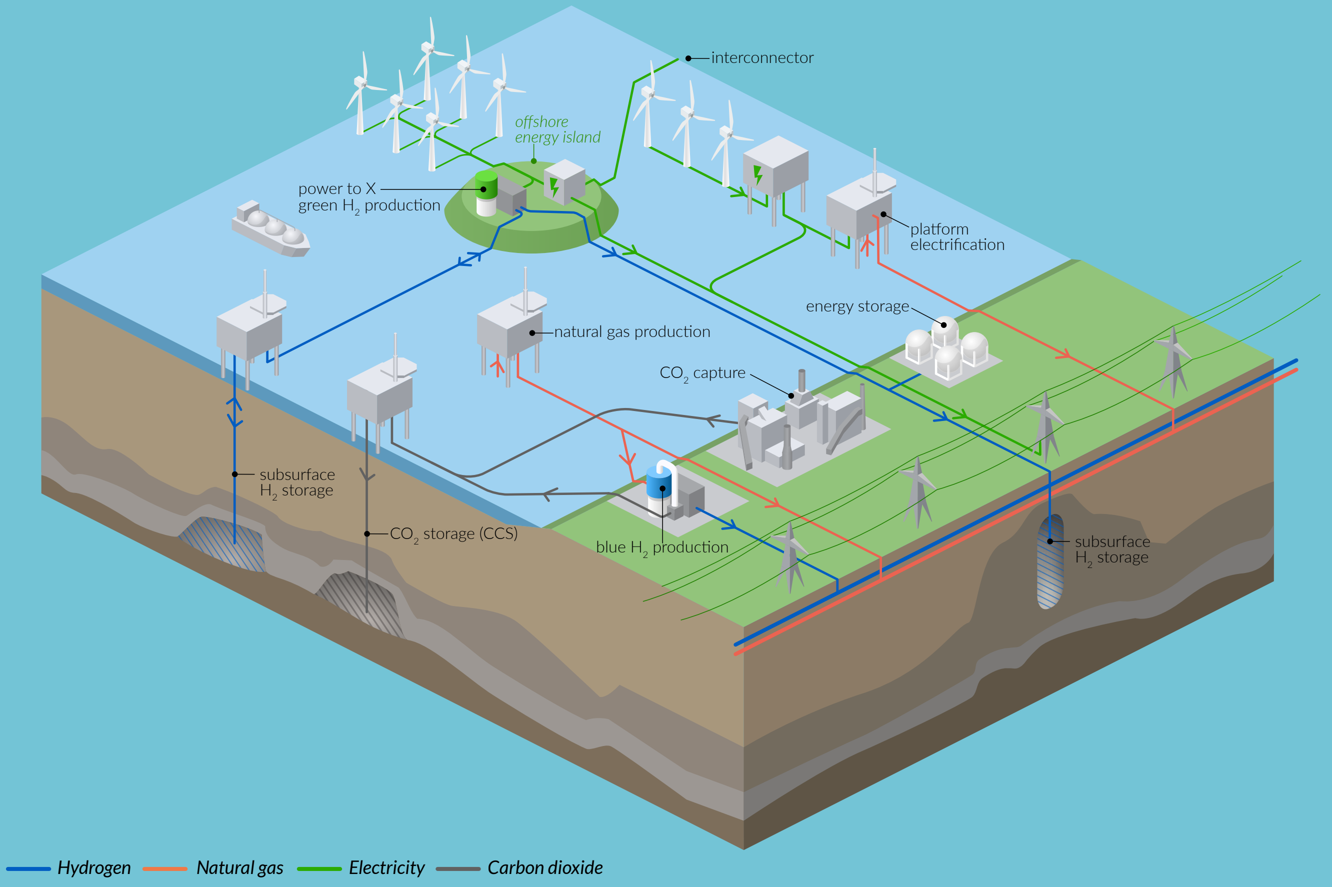
The North Sea has a large potential for renewable and low-carbon energy

The North Sea Energy (NSE) consortium envisions the North Sea as a thriving energy region. By harnessing its renewable and low-carbon energy potential, countries can enhance energy security, reduce carbon dioxide emissions, and drive economic growth in the clean energy sector, making it a critical component of our sustainable energy future.

An energy system perspective is needed to utilize the North Sea's potential effectively

Our future energy system will be more decentralized, with many renewable, intermittent power sources onshore and offshore. The NSE-consortium foresees that such a system requires more sector integration. With stronger links between

Figure 1: Offshore system integration concepts



different energy carriers and consumption sectors, the overall system efficiency can be optimized. 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.

Offshore system integration is one piece of the puzzle towards a sustainable economy
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 the circular economy.

1.2 What is system integration?

In general, system integration is a comprehensive technical and operational approach that involves the seamless coordination, interconnection, and optimization of multiple technological, infrastructural, and operational components. System integration in NSE has been studied at different levels. At the highest level, the (inter-)national energy system and the required infrastructure were studied. The lowest level is concerned with individual technologies or energy conversions. At an intermediate level, system integration was studied in specific offshore regions, so-called hubs.

The energy hub is a central concept to NSE. We define energy hubs as multi-carrier offshore energy systems consisting of production, conversion, and/or storage. Energy hubs are search areas for offshore system integration opportunities. The energy hubs are connected to shore via national (transport) corridors or interconnected internationally. An introduction to the system integration concepts can be found in the North Sea Energy 2020 synthesis paper [2].

As building blocks for these hubs, we consider four energy commodities: electricity (electrons), hydrogen, carbon dioxide (CO_2), and natural gas. Each commodity is associated with specific technologies. Some examples that have been integrally studied in NSE are shown in *Table 1*.

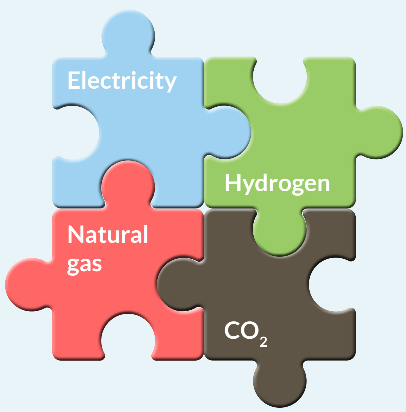
System integration may contribute to the following strategic objectives:

- **Reduce system costs**
- **Enhance operational efficiency**
- **Improve system reliability**
- **Optimize resource utilization**
- **Minimize spatial and environmental impact**

These objectives can be reached through a combination of strategies:

- **Conversion** of one commodity into a different one. For example, the conversion of electricity to hydrogen. This leads to energy losses, but can improve the overall energy system performance.
- **Co-location** of activities. Either within the energy domain (offshore wind and floating solar) or between energy and other North Sea activities (e.g., aquaculture) to make better

Table 1: Four energy commodities for offshore system integration with associated technologies



Commodity	Technologies
Electricity	Offshore wind Offshore marine energy (e.g. offshore solar, wave and tidal) Offshore electricity transport (cables, transformers, interconnectors) Offshore electricity storage Gas-to-wire (offshore electricity production from gas with or without CCS)*
Hydrogen	Offshore Power-to-hydrogen (green hydrogen using electrolysers) Offshore hydrogen transport Offshore hydrogen storage Blue hydrogen production (from natural gas in combination with offshore CCS) Offshore Power-to-X (e.g. ammonia, ethanol)*
CO_2	Carbon capture and offshore storage (CCS) Offshore CO_2- transport
Natural gas	Offshore natural gas production and transport Electrified offshore natural gas production Decommissioning and re-use of infrastructure

* These technologies were studied in former NSE phases. See https://north-sea-energy.eu/en/results/

use of offshore infrastructure and/ or reduce spatial claims via multi-use of offshore space.
- **Collaboration** between sectors and countries to share offshore logistics, improve co-location synergies, or mitigate spatial conflicts, and to find synergies in the strategic deployment of future infrastructure.
- **Repurposing** of existing infrastructure for new uses. When feasible, this avoids costs and environmental impacts associated with the construction of new infrastructure.

1.3 Key message

System integration is complex, but achievable. NSE helps navigate the North Sea energy future.
The North Sea area plays a key role in achieving policy goals for climate and energy security.
However, space is limited, and nature is under pressure. Meeting energy and climate targets, while at the same time ensuring that biodiversity and societal goals are met, requires not only the development of renewable energy production offshore (wind and other marine technologies), but also the conversion to and storage of hydrogen, carbon capture and storage (CCS) and a managed decline of natural gas production. When these four developments proceed in a coordinated manner, this will provide the flexibility and adaptability that is essential in a future renewable energy system. The offshore energy system can be optimized by considering areas for system integration (hubs). This provides an opportunity to develop an energy system that is economically and spatially optimized, thus allowing the strengthening of other functions of the North Sea.

1.4 Reading guide

The rapid development in offshore wind energy reflects the Netherlands' commitment to renewable energy and its goal of transitioning to a more sustainable energy system. However, this creates distinct challenges as wind farms further offshore require ever more costly electrical infrastructure and onshore grid reinforcement. At the same time, the intermittent production profile does not match the demand. To fully utilize the North Sea's potential for the energy transition, a broader perspective is needed.

The ambitions that are set for the offshore energy system in the Netherlands are high. Wind and hydrogen are expected to provide for a large share of the future energy demand. At the same time, remaining natural gas production and storage of CO_2 should be effectively integrated into the energy system. Both in space and time.

This whitepaper identifies the challenges that lie ahead when we try to sketch a path between the current state of play and the ambitions for 2050. The challenges per pathway are discussed in Chapter 2. In Chapter 3, these challenges are generalized and integrated. Finally, in Chapter 4, we give an action agenda with actions per pathway for the medium and short term, combined with general actions.

System integration is complex, but achievable. North Sea Energy helps navigate the future.

Figure 2: Vision of the North Sea in 2050 with blueprints of the three 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 particular scenario).

2. Pathways

2.1 Overview for all commodities

The North Sea Energy programme examines offshore energy system integration through the lens of four energy commodities: electricity, hydrogen, natural gas, and CO_2. For each of these commodities, ambitious developments are expected in the coming decades to realise the envisioned integrated offshore energy system. Nonetheless, considerable gaps remain between the current state-of-play in the various sectors and the vision for 2050. To paint a picture, *Figure 3* compares the current status of each commodity with the possible development scenarios to 2050 for the Netherlands.

The need for system integration is evident when considering how the planned developments are interconnected in achieving commodity-specific goals and ambitions, as detailed in the following sections. The North Sea Energy Roadmap 2050 [8] emphasises the key role of system integration in realising the vision of the North Sea as Europe's Green Power Plant [9]. Furthermore, the Wind Energy Infrastructure Plan for the North Sea (*Windenergie infrastructuurplan Noordzee* or WIN) [10] will outline a comprehensive strategy for bringing the expected offshore wind energy to shore. Preliminary evaluations suggest that the existing power infrastructure is inadequate. This highlights the importance of developing cost-effective, large-scale offshore hydrogen production (sector-coupling). Additionally, there is a need for the rapid expansion of electricity transmission infrastructure in the near term to connect planned wind capacity in time [11].

System integration between wind and hydrogen will be crucial, and therefore, integrated infrastructure planning of cables and pipelines is needed. Under certain technical and commercial conditions, re-use of legacy natural gas infrastructure for CO_2 and hydrogen storage and transport could also play a role. Sector coupling and coordinated developments can help accelerate the transition, use limited human capital more efficiently, and minimise ecological impacts.

In summary, to close the gaps between the current state-of-play and the vision for 2050, system integration is expected to play a key role in minimising spatial requirements, bringing down costs, mitigating ecological impact, and accelerating the deployment, decommissioning, and (when appropriate) re-use of relevant energy infrastructure. Careful coordination of developments across sectors through system integration will be paramount to realising the envisaged transition plans for the Dutch North Sea.

Textbox 1: Explanation of scenario data used in figures.

In this white paper, unless otherwise specified, the data source for hydrogen, electricity, and natural gas developments in the Netherlands come from the II3050 [3]. Additional details into the modelling work, as well as a comprehensive list of assumptions, are provided in D3.1 [4]. In that report, other North Sea countries are also considered and TYNDP scenarios are used. ENTSOG and ENTSO-E use three types of scenarios in their TYNDP reports [5]. The National Trends (NT) scenario aligns with national energy and climate targets and is developed for 2030 and 2040. For 2040 and 2050, the TYNDP presents deviation scenarios, which include a Distributed Energy (DE) scenario and a Global Ambition (GA) scenario. The former assumes European energy autonomy and places greater emphasis on decentralized renewable production, while the latter assumes an internationally coordinated transition with centralized renewable energy and higher levels of offshore wind, low-carbon energy imports, and more CCS deployment.

To maintain consistency with D3.1, we occasionally reference these same scenario names, though the data for the Dutch energy system comes from II3050. As such, 2030 figures are denoted NT, while the data behind them comes from the IP2024 scenario, which are the investment plans of grid operators that form the basis of the II3050 scenarios. Accordingly, 2040 and 2050 figures are denoted DE & GA, while the data behind them come from the II3050 Decentrale Initiatieven and Nationaal Leiderschap scenarios, respectively.

In this white paper, we often further simplify the language and refer to the DE scenario as "low" and the GA scenario as "high". It is worth noting that these scenarios present an optimistic outlook on future renewable energy deployment. Nonetheless, they are indicative scenarios that offer disparate (but possible) pathways, yet the realistic timeline for such developments in all likelihood will deviate from what is currently shown in many figures. In this white paper, we aim to sketch a high-level storyline for the future offshore energy developments in the Dutch North Sea. We kindly refer the reader to D3.1 [4] for a more detailed look at the scenario descriptions and data.

Figure 3: Commodity-specific pathways toward 2050 in NL. 2030 CO_2 storage estimated from Klimaatambitie scenario from [3] and 2050 estimated from highest storage scenario (Europese Integratie). Annual blue & green hydrogen, wind, and other sources of electricity production use the NT scenario for 2030, and GA scenario for 2040 and 2050 (see Textbox 1 for scenario explanation). Offshore natural gas supply is estimated from [31]. Current offshore wind and other sources of electricity production are estimated from [49].

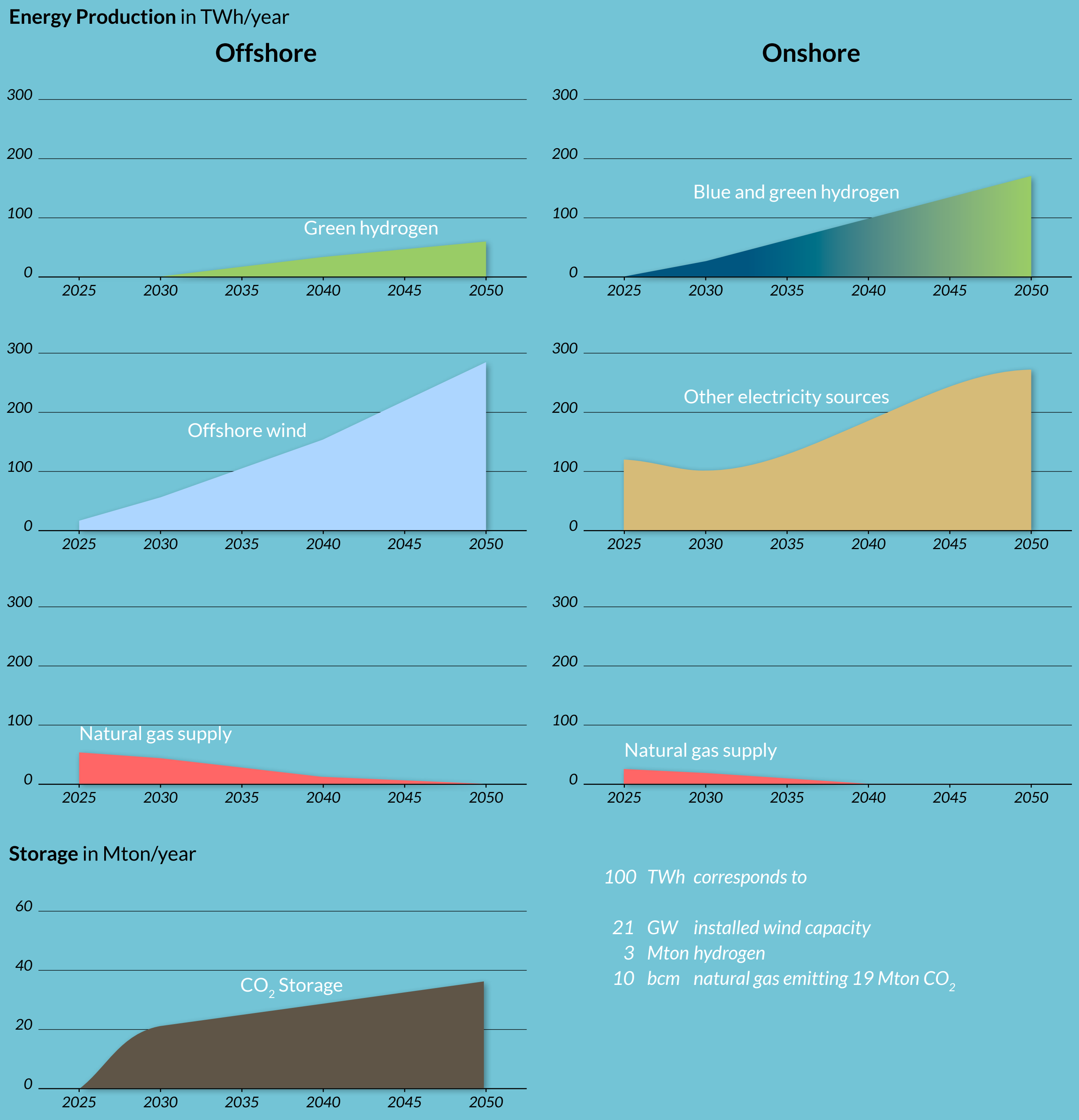


Table 2: The commodity pathways at a glance.

Commodity	Outlook
Electricity	Total annual electricity production could increase almost five-fold by 2050 compared to 2024, with offshore wind capacity accounting for most of the growth and potentially producing 336 TWh per year by 2050.
Hydrogen	Green hydrogen production in the Netherlands could increase from 0.023 (2023) to approximately 213 TWh per year by 2050, though considerable uncertainty remains on the speed of deployment and the demand for hydrogen in the various energy sectors.
CO_2	Although there are no formal targets for CO_2 storage in the Netherlands, the II3050 outlines several scenarios for future CO_2 storage potential in the Dutch North Sea, with the high estimate reaching 35 Mt of CO_2 storage per year by 2050 [3].[1] Other studies have estimates up to 40 Mt of CO_2 storage per year by 2050 (see section 2.4). In the coming decades, depleted oil & gas fields in the Dutch North Sea are anticipated to have a practical total storage capacity of roughly 1,678 Mt of CO_2 (i.e., enabling roughly 50 years of storage at the high estimate of 35 Mt of CO_2 storage per year) [6]. Storage in saline aquifers could provide extensive additional potential and is under research.
Natural gas	Offshore natural gas supply in the Netherlands has peaked at the beginning of this century at just above 240 TWh (LHV[2]) per year and is expected to lie between 50 and 60 TWh per year in 2025. The Sector Agreement foresees a role for natural gas through 2045-2050, with total technical offshore potential ranging from 1.1 to 1.3 PWh (125 to 150 bcm) from 2025 through phase-out around mid-century [7]. There are also ambitious plans for decommissioning of offshore platforms and a vision to reuse legacy pipelines and other infrastructure where possible.

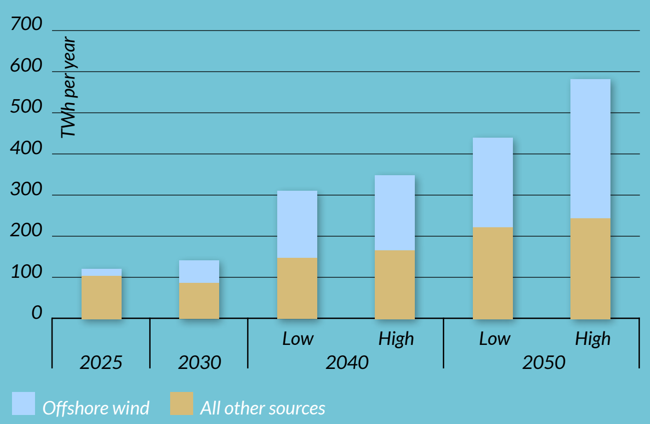
1 This scenario (Europese Integratie) from the II3050 focuses more on blue hydrogen than the other scenarios and also assumes energy generation with negative emissions (BECCS) and import of CO_2 from neighbouring countries for storage in the Netherlands, which helps to explain the large annual storage requirements. The other scenarios, which assume less annual CO_2 storage in 2050 than the Europese Integratie scenario are shown in 3.4 and more information can be found in D3.1 and [3].

2 Lower Heating Value is being used throughout North Sea Energy publications unless otherwise noted.

2.2 Electricity

Electricity demand in the Netherlands is set to surge dramatically in the coming decades, driven by the electrification of end-uses as the country moves toward a sustainable energy future. Accordingly, domestic electricity production is expected to increase, with offshore wind likely to make up approximately 50% of the total electricity production in the Netherlands from 2040 onwards (*Figure 3*).

Figure 4: Future annual electricity production (TWh per year) in the Netherlands. 2025 electricity production is estimated from 2024 figures [49].



Given the sizable role of offshore wind in the future electricity supply mix, the government has set the target to scale the current installed offshore wind capacity in the Netherlands from 4.7 GW [12] to 21 GW by 2032 [13]. Beyond 2032, there is a vision for continued offshore wind capacity deployment up to 50 GW by 2040 and 70 GW by 2050, though these are to be seen as ambitions rather than formal targets. Detailed planning for the near term has been elaborated in a letter to parliament in April 2024. This outlines the planned granting of permits for the various offshore wind projects to be developed in the Dutch North Sea. [3]

Next to offshore wind, there is also a vision to accelerate the development of offshore solar to help achieve the 2030 climate targets, with an initial ambition of 3 GW installed capacity by 2030 [14]. An assessment of the feasibility of this goal suggests that it is too ambitious at this stage. As a result, offshore solar

3 See [13] for a full list of projects and estimated commissioning dates.

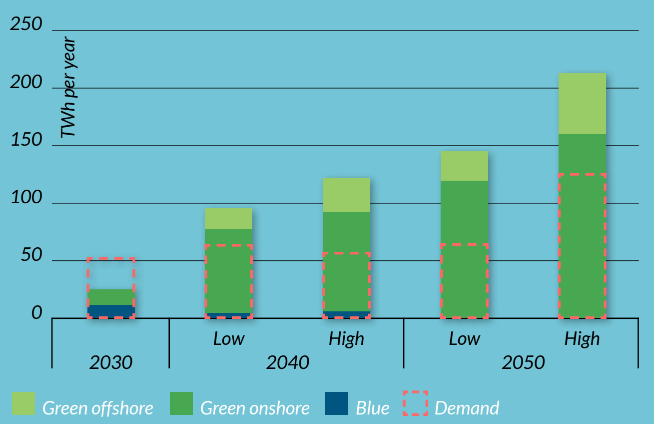
criteria will not be included in the upcoming offshore wind tenders; however, their inclusion will be further explored in future tenders [15]. There are also efforts to scale up other forms of offshore electricity production, such as a tidal energy demonstration project in Zeeland [16], and more potential for wave and tidal energy is being explored in the Wadden Zee region [17]. Furthermore, offshore electricity storage could also play an increasing role: demonstration projects are in progress, such as the subsea lithium-ion battery storage system from Verlume as part of the OranjeWind project [18].

2.3 Hydrogen

The key message is that modelling results suggesting a growing role for hydrogen in the energy system are robust, but the exact mix in hydrogen supply (i.e., the relative importance of imports, green hydrogen, and blue hydrogen production) and the pace of deployment remains uncertain.

The costs of expanding both the offshore and onshore electricity grids to accommodate the planned offshore wind capacity are very high. As a potentially more cost-effective solution from a system perspective, it has been proposed to convert a portion of the offshore wind energy into hydrogen and transport it via pipeline. Transport would take place via a hydrogen transmission grid, which may be new-build, repurposed, or some combination of the two (pending technical, commercial, and regulatory feasibility). In certain cases, this could result in lower transmission costs compared to new cables, reduced curtailment from offshore wind farms, and reduced onshore space (see D3.1 [4]). Pipelines can also enable high-capacity energy transport with low losses (particularly for windfarms located further from shore) and could become increasingly relevant in the future decades as large capacities of offshore wind need to be connected [19]. However, significant uncertainties still exist regarding the role of offshore hydrogen production. More detailed insights on this topic are expected to be provided in the forthcoming WIN report [11].

Figure 5: Projected future annual hydrogen demand versus expected production in TWh per year.



Ultimately, hydrogen production at sea could play a role in the future, but it still needs to be fully demonstrated, and significant cost reductions are necessary before it becomes feasible [19]. Pilot projects and planned demonstrations (e.g., PosHYdon [20] and DEMO-I and II [21]) should provide a proof-of-concept for future offshore electrolysis scale-up. Nonetheless, much of the planned hydrogen production will likely take place onshore, at least in the near future.
A potential development pathway for green and blue hydrogen production is outlined in *Figure 5*.

The portion of green hydrogen production that is expected to take place offshore is estimated here based on the offshore energy hub designs of the NSE programme (see D1.3 [22]), and the system optimal shares of offshore hydrogen are explored further in D3.1 [4].[4] Although there are no concrete targets for offshore hydrogen production, the forthcoming (mid 2025) WIN report should provide further clarity on this matter.

It is important to note that, in other scenarios, both hydrogen imports (not shown here) and blue hydrogen production can vary significantly in their contribution. For instance, some estimates [23] place blue hydrogen production in 2040 in the range of 20 TWh per year or more (33-43 for the II3050 scenarios), which is substantially higher than the DE and GA scenarios depicted in *Figure 5*. Import and export figures for hydrogen are highly uncertain. By 2040, annual imports could range from 15 to 170 TWh, while exports could range from 41 to 102 TWh. The net hydrogen imports range between -31 and +68 TWh per year in 2040 [3]. This indicates a potential role for the Netherlands as a transit hub for hydrogen imports and exports, mainly for Germany and mainland Europe. Comparing potential domestic hydrogen production to domestic demand highlights these opportunities for export (mainly to Belgium and Germany) in 2040 and 2050 (*Figure 5*).

4 D3.1 finds that from a system value perspective, some share of offshore hydrogen production is optimal in the Dutch context.

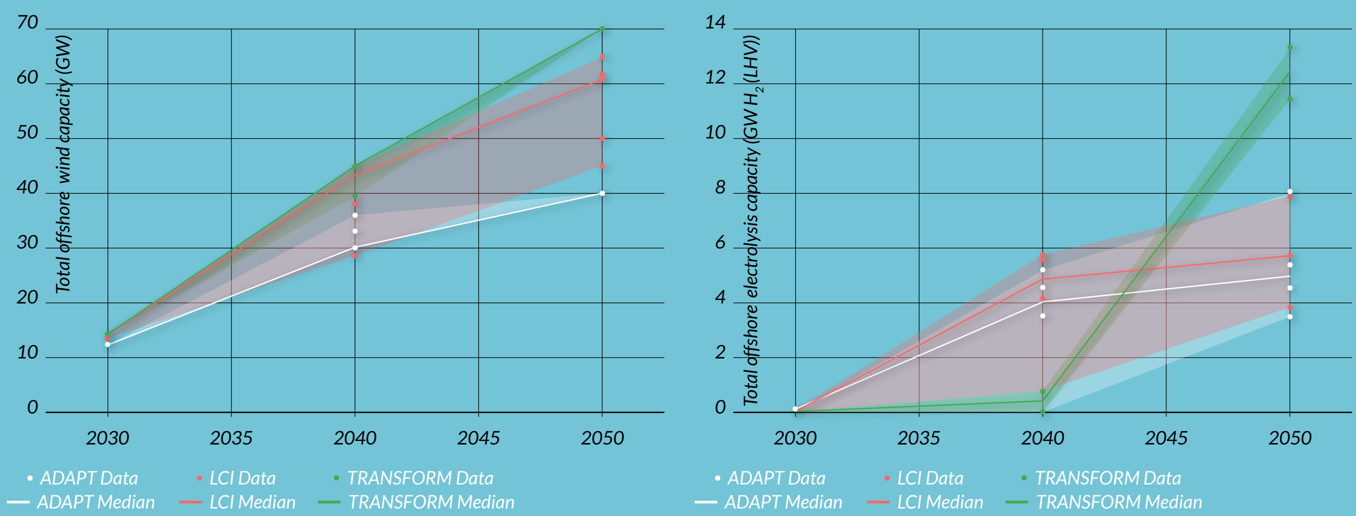
Spotlight: Exploring the role of offshore wind and offshore hydrogen in the Netherlands

North Sea Energy deliverable D3.1 focuses on the integration of electricity and hydrogen in the offshore system and researches its system value. As a result of the societal cost-optimisation analysis, three scenarios are presented. These scenarios build upon the existing ADAPT, TRANSFORM, and LCI frameworks. These trend-reflective scenarios provide a range of possible future developments in industry, renewable deployment, energy demand and more, for an autonomous energy system in the Netherlands.

The development of the energy system is highly uncertain due to developments in technology and cost, domestic and international policy, and geopolitical factors. To gather robust insights under such uncertain circumstances, a large number of sensitivities were tested. The fact that offshore hydrogen production appears in the solution of the cost optimal energy system in all investigated scenarios and sensitivity cases, indicates that offshore hydrogen results in lower cost from a societal perspective. The benefits are, ranging from 30 – 350 million euros annually for the base scenarios.

More information available via the North Sea Energy scenarios database [24], and deliverables D3.1 [4], and D1.3 [22].

Figure 6: The deployment of installed capacity for offshore wind (left) and offshore hydrogen production (right) over the years for the trend-reflective scenarios. Source D3.1 [4],



Spotlight: The Netherlands in international perspective – import & export

The Netherlands plays an important role in the North Sea energy transition and is highly linked to the other countries with pipelines for gases and hydrocarbons, subsea cables for electricity transport and shipping facilities for energy carriers and CO_2. The ports are and will remain to be the gateways to industrial and demand clusters and the European hinterland.

Electricity: In 2024 and the two years before, more electricity was exported (24 TWh) than imported (20 TWh). The highest trade was of electricity (import and export) with Germany and Belgium. With the growth of offshore wind in the North Sea basin, the role of Netherlands as electricity hub also increases. Scenario studies estimate import and export volumes to be well above the hundred(s) of TWh per year, mainly from the North Sea basin serving the high demand areas in Germany. Together, the North Sea countries function as a net-export area for electricity to Europe.

Hydrogen. The present hydrogen demand among the nine countries surrounding the North Sea stands at approximately 145 TWh with Germany and the Netherlands dominating the demand each at around 40-45 TWh per year. A substantial growth of demand is anticipated towards 1.5 PWh in 2050. The trade balance for hydrogen between the North Sea countries remains still highly uncertain, but studies indicate that Norway, Denmark, the Netherlands, and France may become net exporters of hydrogen. The Netherlands may also become a net importer of hydrogen, but is very likely to play a role in transit of hydrogen, mainly for Germany and mainland Europe. Germany and Belgium are very likely to become net importers to meet their high industrial demand. The ports of North Sea countries are well-positioned to facilitate (ship based) hydrogen (derivatives) imports into Europe, leveraging their infrastructure and strategic location.

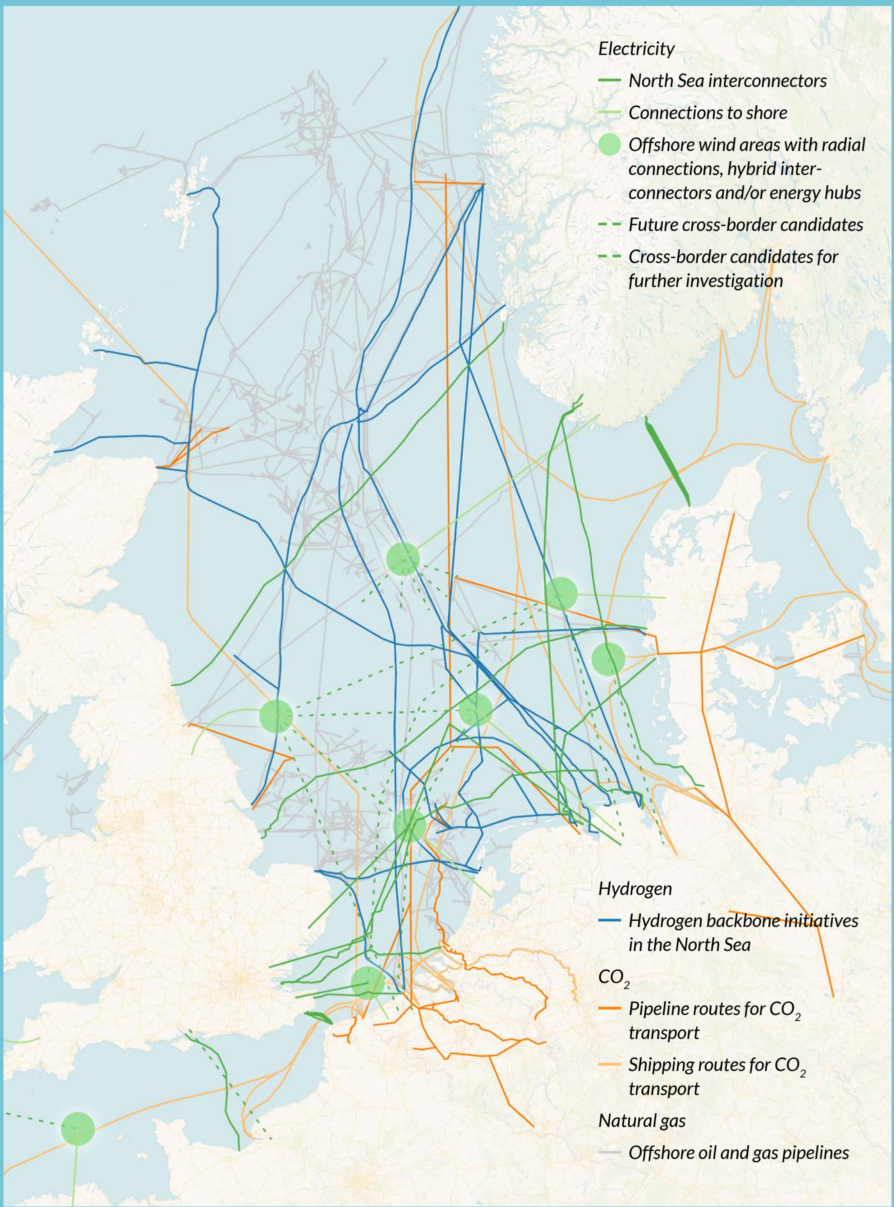
CO_2. The North Sea basin will most likely develop into a net CO_2 sink towards 2040 and beyond as some countries have limited storage potential while others have surplus capacity, allowing CO_2 from other countries to be transported to North Sea nations such as the Netherlands, Denmark, the UK, and Norway. Export of CO_2 from the Netherlands to other North Sea countries is also under development. [5]

5 An example is that Yara will transport carbon dioxide from the Netherlands to Norway with ship transport.

Natural gas. The Netherlands became a net importer of natural gas since 2018 and remains reliant on imports of natural gas for most of its demand of 30 bcm with declining production of 9 bcm. The trade function for natural gas is stipulated by the high import (47.5 bcm) and export (30 bcm) of natural gas via pipelines and LNG. Import via pipelines from Norway dominated in 2024 with 11 bcm (out of 26 bcm gaseous import) but LNG import from the US (14.5 bcm out of 21 bcm) dominated the overall import numbers. Export is mainly towards Germany (24.4 bcm) and Belgium (4.6 bcm) via pipelines. The role as natural gas producer yet also a net importer and natural gas transit hub will most likely remain for the next decades.

More information available via D7.1 [1], D3.1 [4], [25], and [26].

Figure 7: Potential for future energy infrastructure development for the North Sea basin for electricity, hydrogen, CO_2 and natural gas.



2.4 CO_2

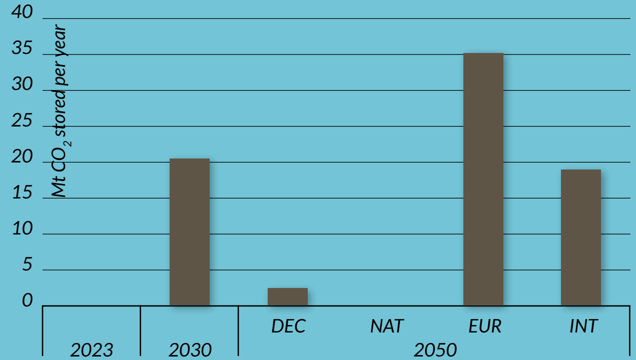
CO_2 storage in the Netherlands is expected to take place only under the seabed, with a principal focus on depleted oil & gas fields with subsea aquifers as a point of future potential. There are no formal targets for CO_2 storage in the Netherlands yet, but for CCS, the NZIA (Net-Zero Industry Act) for Europe is going to be of high importance [27]. The NZIA sets a binding EU target of at least 50 Mt of CO_2 injection capacity per year by 2030. To meet this target, the NZIA places a legal obligation also on Dutch entities holding oil and gas production authorizations to contribute to the development of CO_2 storage capacity. This means that companies already operating in gas production are expected to repurpose or develop infrastructure for CO_2 storage. As the Netherlands contributes quite substantially to natural gas production in the EU (in the past) a significant share (roughly one fifth or one fourth of the 50 Mt) is likely to be allocated to the Netherlands as binding target for 2030.

In the meantime, the infrastructure outlook from Netbeheer Nederland indicates the potential development of annual CO_2 storage capacity under different scenarios [3] (*Figure 8*).

Depleted oil & gas fields in the Dutch North Sea are estimated to be able to accommodate roughly 1,678 Mt of CO_2 in the coming decades [6], thereby facilitating roughly 50 years of storage at the 2050 high scenario estimate of 35 Mt CO_2 per year. [6]

6 See D3.1 [4] for further analysis of the CO_2 storage scenarios based on the II3050 report: https://scenarios.northseaenergy.eu/data/co2_storage. Note that a recent TNO report [50] suggests in their ADAPT and TRANSFORM scenarios a need for 15-40 Mton of CO_2 storage from both fossil and biogenic origin per year, and when deployed requires up to 661 Mton of cumulative storage capacity towards 2050.

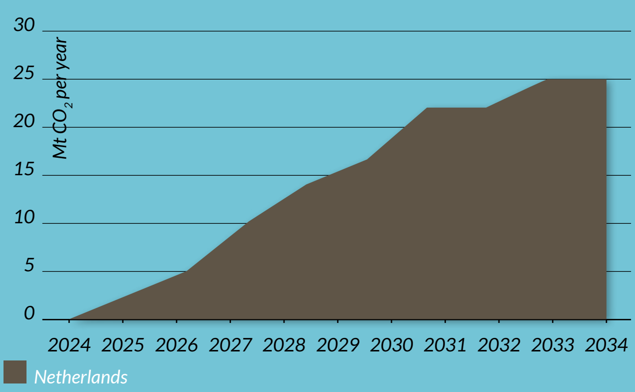
Figure 8: Annual CO_2 storage capacity in Mt per year based on future II3050 scenarios from Netbeheer Nederland. Refer to [3] for further details regarding scenario assumptions



One specific challenge that has recently been highlighted is the high investment risk associated with offshore CO_2 transport infrastructure for commercial project developers [28]. One important factor affecting the business case is that, under the current regulatory framework, CO_2 pipelines must be removed after use, whereas legacy hydrocarbon pipelines are not subject to this removal requirement.

A different manner of estimating the annual CO_2 storage capacity is to look at the currently announced projects, which are expected to have a combined capacity of 25 Mt CO_2 per year by 2034. The first projects are emerging, with two key projects transporting captured CO_2 from the Port of Rotterdam via subsea pipelines to offshore storage locations in depleted fields. The Porthos project [29], currently under construction, will have an annual CO_2 storage capacity of 2.5 million tonnes and a total capacity of 37 million tonnes over its operational lifetime. In comparison, the Aramis project [30] plans to make a Final Investment Decision in 2025 and

Figure 10: Anticipated annual CO_2 storage capacity in the Netherlands compared to other relevant North Sea countries based on announced projects.



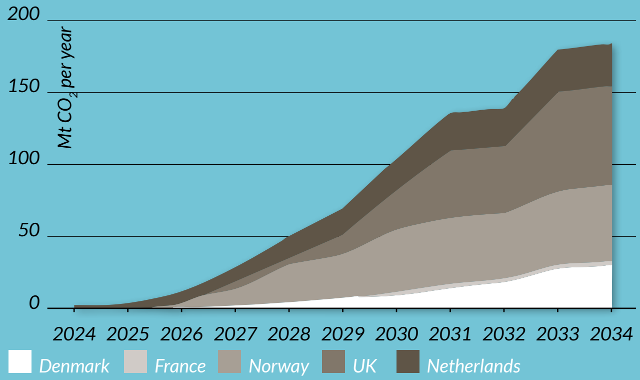
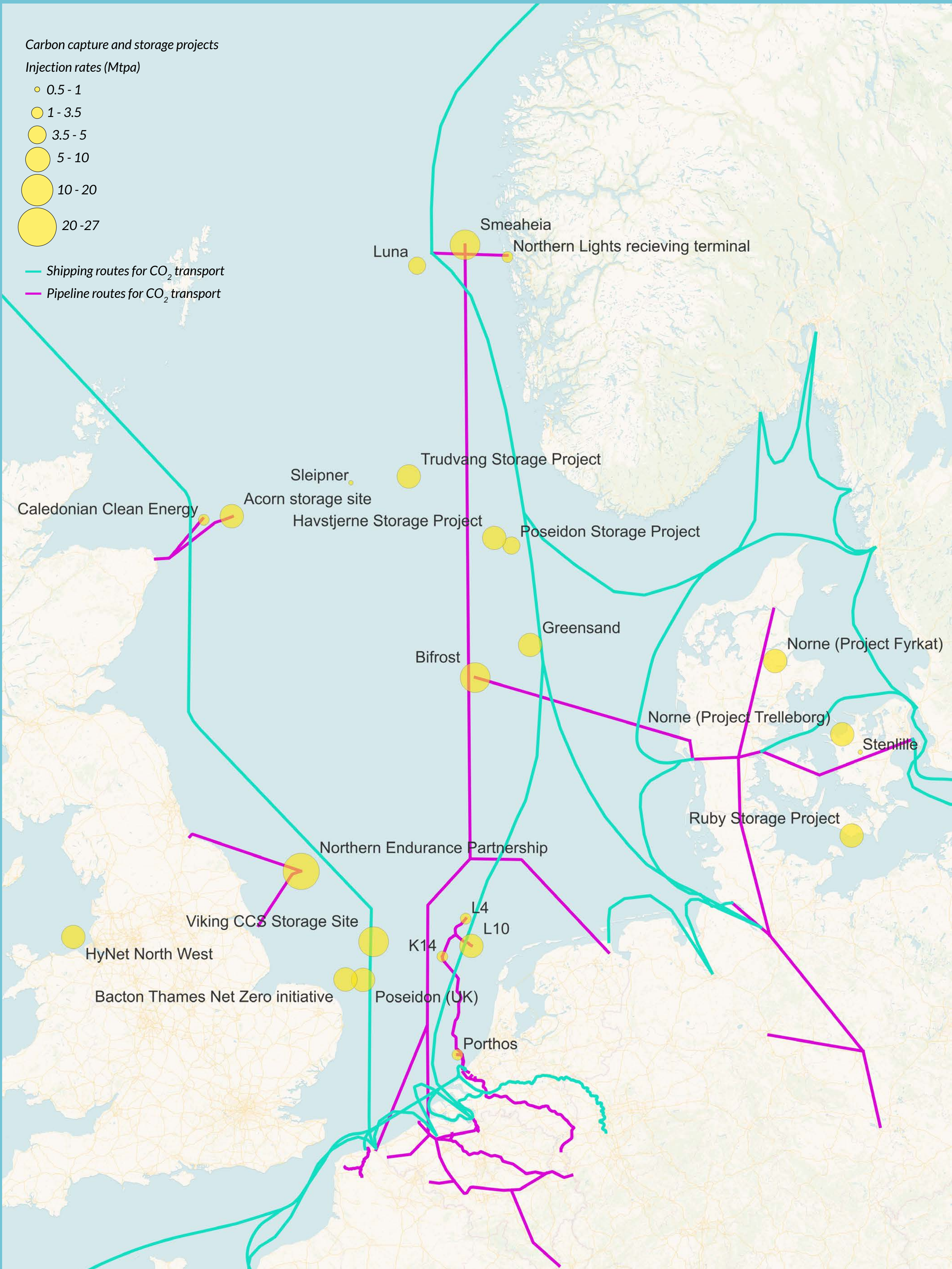


Figure 9: CCS grid envisioned for 2030, showing announced projects and including both pipeline and shipping transport networks (see D7.1 [1]).



will start with an initial annual capacity of 5 million tonnes of CO_2. With future infrastructure expansion, Aramis could accommodate up to 22 million tonnes per year, and its total storage capacity is projected to reach 400 million tonnes of CO_2. *Figure 10* illustrates the Netherlands' current development pathway toward achieving the projected annual CO_2 storage capacity of 25 million tonnes. It also compares this progress to other announced projects in relevant North Sea countries.

The development of blue hydrogen is to a certain extent highly linked with that of offshore CO_2 storage as 'blue' hydrogen is produced from reforming natural gas and in this process capturing the CO_2 so that it can be stored in the subsurface reducing the carbon footprint of the energy carrier.[7] A portion of the total required storage capacity can be inferred by looking at the scenarios for blue hydrogen production. For example, the II3050 scenarios – representing some of the higher estimates for future blue hydrogen production – project annual blue hydrogen output of 33 to 43 TWh by 2040. Though highly dependent on the assumed capture rate and applied technology (SMR or ATR[8]), this could translate to a range of 7.5 to 17 Mt of CO_2 storage requirement per year.[9]

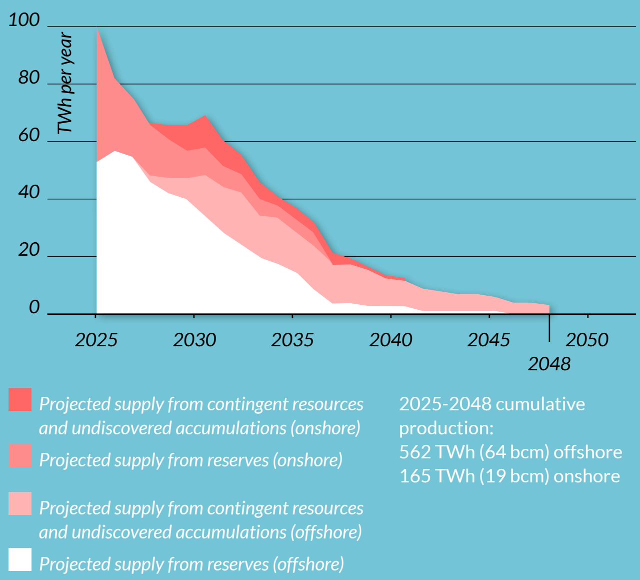
2.5 Natural Gas

Offshore natural gas production began in the 1970s and increased steadily, reaching a peak of 244 TWh in 1999. Between 1995 and 2008, annual production consistently remained above 200 TWh. The decline has set in, both onshore and offshore. The supply of natural gas from onshore gas fields in the Netherlands is expected to cease by 2040, while offshore supply is expected to continue declining, but it is unknown when it will reach zero [31] (*Figure 11*).

The annual review of 2023 on the natural resources in the Netherlands [31] offers three different scenarios for potential future gas supply, with varying degrees of production from contingent resources and undiscovered accumulations. *Figure 11* presents the "Middle scenario," which assumes a modest growth

7 See also [51] for further details.
8 SMR = Steam Methane Reforming; ATR = Auto Thermal Reforming
9 Assumes here 7.5 to 13 kg of CO_2 storage per kg of hydrogen produced, see [51] and [52] for more information.

Figure 11: Expected onshore and offshore natural gas supply in the Netherlands through 2048 in TWh per year. The data represents the "Middle" scenario [31], which assumes a period of continued activity, a small but limited increase in investment level, and highlights contingent resources (development pending) and undiscovered accumulations (not yet proven resources). More details on the scenario and assumptions can be found in [31].



in investment and activity. It includes projects that are likely to be developed soon and assumes some degree of continued exploration (drilling continues at the average rate for the past decade of one well per year on land and three offshore but ceases in 2035).

However, recent developments - such as the Sector Agreement reached between the Dutch government, Energie Beheer Nederland (EBN), and Element NL - set out clear plans for the responsible extraction of the remaining natural gas from the North Sea. The agreement also aims to promote close collaboration between the government and the gas sector, expedite permitting processes, and encourage increased exploration activities [32]. Hydrocarbon production is therefore expected to remain relevant until (at least) the 2045-2050 period, with total potential offshore production between 2025 and 2050 ranging from 1.1 to 1.3 PWh (125 to 150 bcm) (forecast) [7]. These recent developments suggest that the total potential volume of offshore natural gas production through 2050 will be higher than what was projected in [31] and what is shown in *Figure 12*. However, the general negative trend toward phase-out by mid-century is not expected to change. In D1.3 [22], more information is available on the natural gas production potential in the studied offshore areas.

Scenario modelling of natural gas demand in the Netherlands also shows a decline, with current (2024) demand amounting to 264 TWh [33] potentially declining to 12 TWh per year by 2050 in the low scenario (*Figure 12*).[10] The noticeable gap between expected gas production in *Figure 11* and the potential future demand in *Figure 12* will need to be filled by imports and/or the up-scaling of domestic production.

The planned phase-out of natural gas extraction not only contributes to the Dutch emissions target of 95% reduction compared to 1990 levels by 2050 laid out in the Climate Accord (Klimaatakkoord) [34], but also presents opportunities for the re-use of infrastructure for other energy commodities. Reusing existing offshore gas pipelines to transport hydrogen, if technically and commercially feasible, could accelerate the development of offshore hydrogen production by reducing costs and shortening project timelines. However, this potential benefit depends on the time required for permitting and any necessary re-routing of the pipelines. Furthermore, the use of empty natural gas fields for CO_2 storage and also as a potential site for future hydrogen storage could be key to meeting growing CO_2 storage needs and for hydrogen system balancing.

There will be considerable efforts in the coming years to decommission existing offshore oil & gas infrastructure in the Dutch North Sea [35] (*Figure 13*).

10 Conversions assume natural gas LHV of 31.65 MJ/m3

Figure 12: Expected annual natural gas demand in the Netherlands in TWh per year (2030 is the NT scenario, 2040 and 2050 stem from the GA scenario). Current demand is estimated from the 2024 annual demand [33].

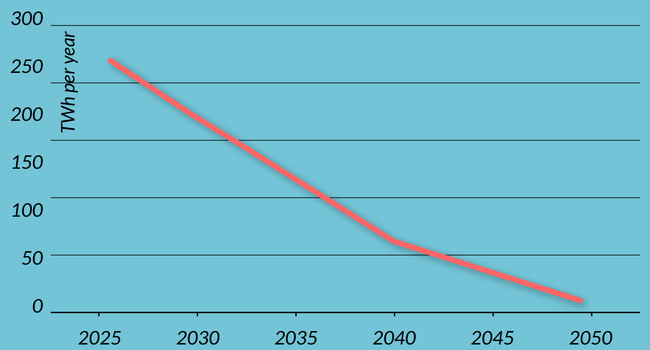
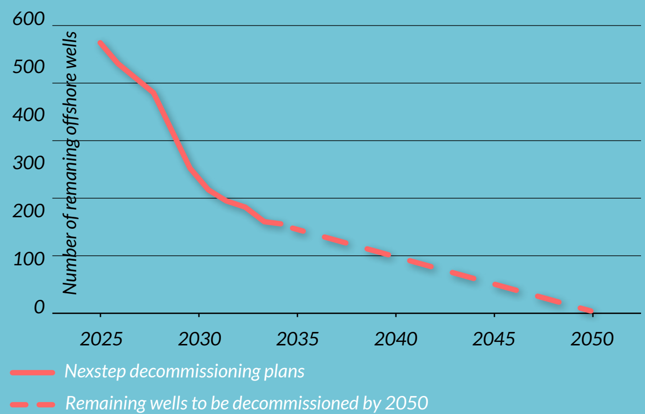


Figure 13: Decommissioning pathway for offshore oil & gas wells in the Dutch North Sea [35].



3. Challenges

The pathways described in the previous chapter involve a fundamental transformation of both our energy system and how we utilize the North Sea. Achieving this is ambitious. North Sea Energy identifies eleven key challenges across three themes that need to be addressed if this is to be feasible.

3.1 Transitioning from fossil fuels to clean energy

The energy transition demands a fundamental transformation of our entire energy system. Climate change puts a deadline on its development, while current challenges to the affordability and security of energy stress the need to meet current demands while building a system that can meet tomorrow's needs. We see 5 key challenges for the offshore energy sector:

1. **Reducing the costs of energy production capacity and infrastructure.**
   We need to deploy large volumes of clean energy generation technologies and the infrastructure to transport this energy to onshore demand. Currently, demand for low-carbon energy remains low, the associated technologies are costly, and developing viable business cases is difficult. Accelerating the pace of the energy transition will require both the growth of demand for low-carbon energy and reductions of capital and operational costs as technologies and processes are further optimized. All offshore energy solutions require substantial upfront capital investment, making project de-risking and access to lower-cost financing critical to their viability. With infrastructure costs rising and project timelines stretching longer, it is more crucial than ever to maximize the efficiency of both existing and planned energy infrastructure. By prioritizing smart and effective use of these assets, we can accelerate the energy transition while minimizing costs and delays. This approach can help lower overall energy prices, reduce grid congestion, and minimize delays in connecting consumers to the grid [36].
2. **Developing energy production, transport, and demand in tandem.**
   In the short term, this means enhancing demand through direct and indirect electrification of the industry. Simultaneously, energy transport strategies and infrastructure planning must account for cost disparities: upgrading the high-voltage electricity network is substantially more expensive, two orders of magnitude higher than upgrading the gas network for transporting energy molecules. In the long term, reducing overall energy demand through innovations in energy efficiency is essential. By minimizing reliance on energy-intensive products and services, we can address many of the challenges associated with the energy transition while optimizing resource use and infrastructure investments.
3. **Innovation in energy transport, conversion, storage, and flexibility.**
   Integrating large amounts of variable renewable energy into our system will require advancements in several areas:
   - Technologies to use this energy when it is available,
   - Methods to transport it to where it is needed (such as through hybrid interconnections),
   - Processes to convert it into other energy carriers like heat, hydrogen, or chemicals, and
   - Solutions for storing it for later use (time shifting) in the form of electricity, heat or chemical storage solutions.
   - For all the above mentioned areas offshore solutions are being researched, piloted and/or demonstrated. An integral plan is required to fast-track these innovations towards market implementation.
4. **Timely scale-up of the supply chains.**
   The deployment of substantial volumes of clean energy generation and associated infrastructure necessitates the rapid expansion of the corresponding supply chains. This presents significant challenges in securing the necessary raw and critical materials, developing a skilled workforce, and ensuring sufficient installation capacity, such as adequate facilities and infrastructure in ports. Strengthening the supply chains and using them efficiently requires (international) coordination of activities to create consistent and predictable demand. Adopting design-for-circularity principles can help address this challenge over the long term by enabling products and infrastructure to be reused, recycled, or repurposed at the end of their life cycle.
5. **Increasing the security and reliability of our energy supply.**
   The events of the past years have underscored the critical urgency of ensuring a reliable and affordable energy supply. The North Sea can be a major European source of energy, reducing our import dependence and enhancing the prospects of the demand-side industry. However, this also introduces new challenges concerning the resilience of the energy system, as well as the physical and digital security of infrastructure that is predominantly located outside our territorial waters.

3.2 Developing within spatial and ecological constraints

The North Sea is the world's most heavily utilized maritime area. Its ecology is also degraded and under severe human pressure. Developing a new offshore energy system requires a well-coordinated plan to efficiently utilize the available physical and ecological space, taking into account both current

Spotlight: scaling up supply chains for the offshore energy transition

Two NSE publications showcase the supply chain challenges we face to meet the desired energy transition pathways. NSE determined the human capital needs associated with the Dutch outlook for offshore wind, hydrogen, decommissioning of existing platforms, and CCS. Quantitative modelling shows the yearly human capital demand to be around 4.000-10.000 FTE. While this number itself is not unreasonably high, the specific skills needed for offshore installation work, the shortage of technical personnel, and the ambitions of various technical sectors make meeting it a challenge. NSE developed an action agenda detailing actions needed to meet the upcoming human capital demand (see D2.3 [37]).

A material flow analysis (see D4.5 [38] shows similarly sized challenges regarding the need for critical raw materials (CRMs) and strategic raw materials (SRMs). The offshore energy system will require large volumes of CRMs used for example in the permanent magnets of wind turbines. Even when aiming for circular use, during the build-up phase these will be mainly primary materials, the supply of which is concentrated in a limited number of countries. For the North Sea energy system to achieve its deployment targets, a continuous balancing act will be required between the cost, efficiency, and availability of energy technologies and infrastructure.

More information available in D4.5 [38].

Figure 14: Estimated human capital requirement (in FTE) for selected offshore technologies towards 2050 for the Netherlands

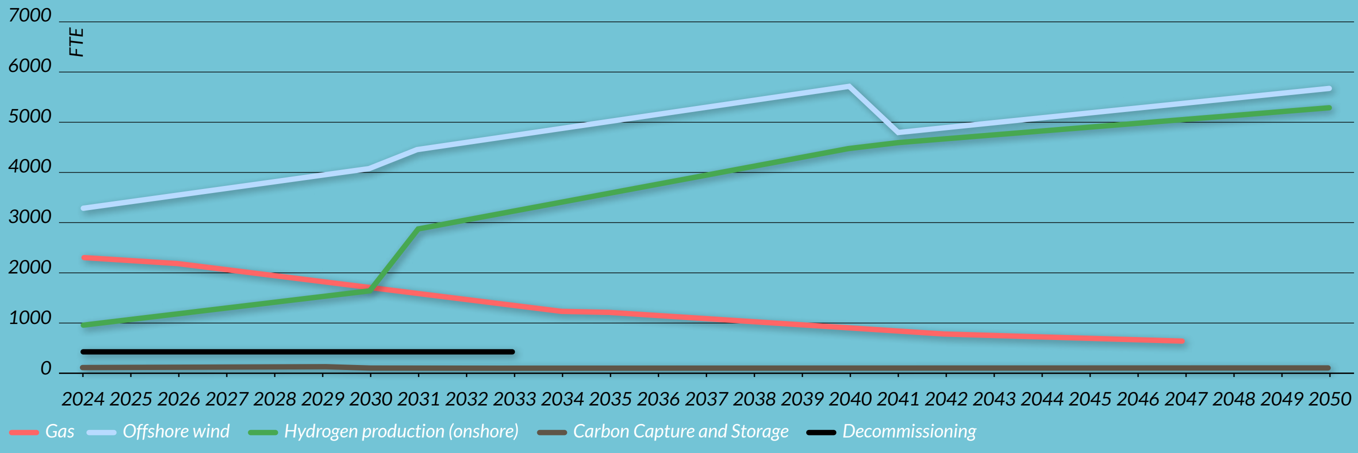
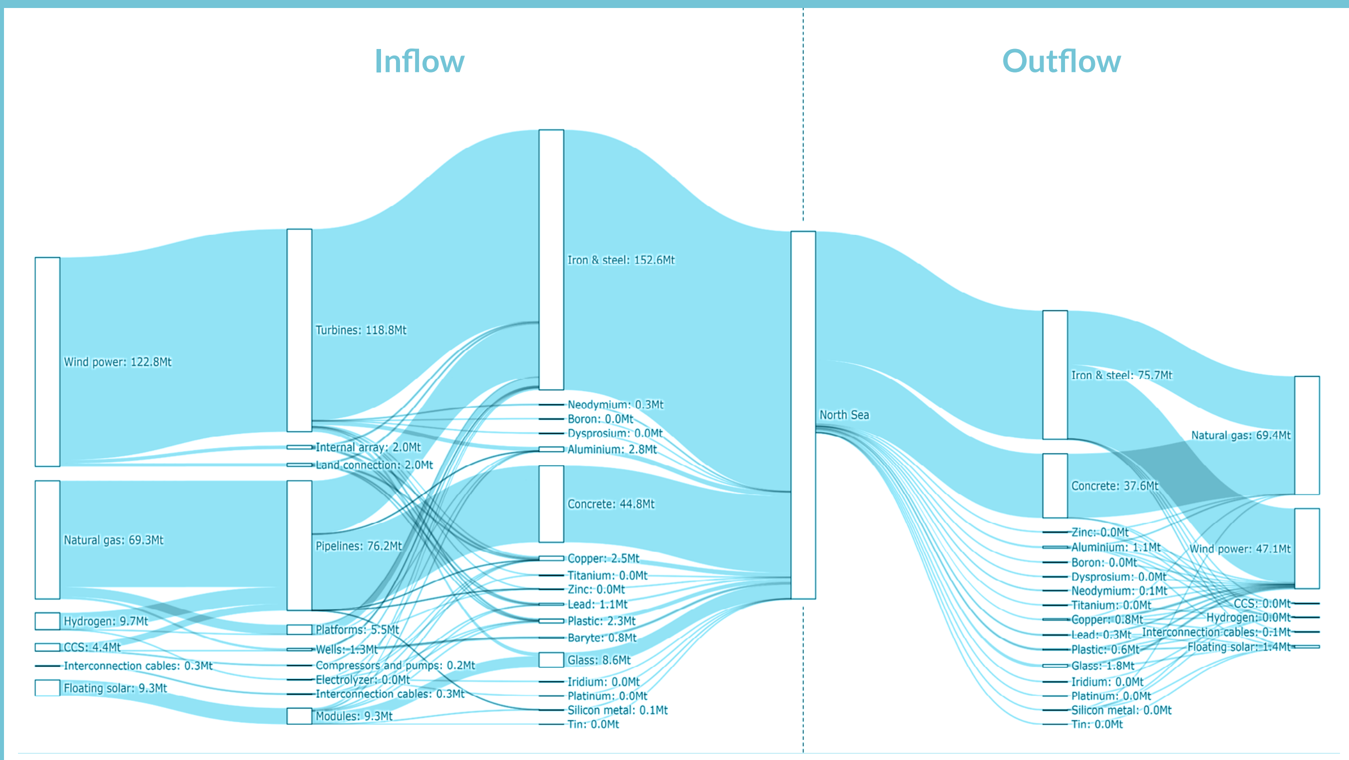


Figure 15: Accumulated inflows and outflows for the offshore transition on the North Sea from 2025 till 2050



activities and future needs. We see three key challenges for the energy sector:

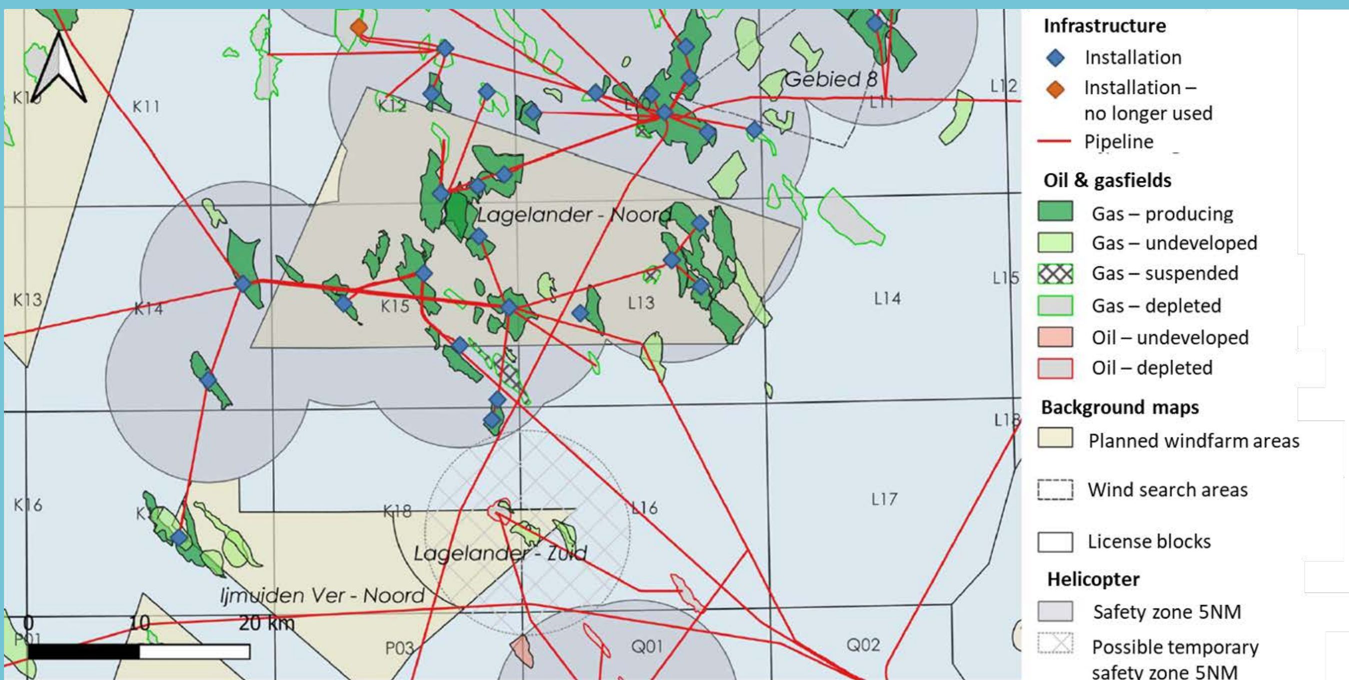
6. **Limiting the spatial needs of the energy system.** Efficient use of space will make it easier to fit the energy system into the North Sea along with other uses. Integrating different energy system functions can help achieve this goal by improving overall system efficiency, which in turn reduces the total amount of energy that needs to be generated. Combining energy functions in space, for example by co-locating offshore wind and floating solar, can also help generate more energy from a smaller area. Specifically for offshore wind, a critical challenge here is to find the fine balance between the spatial footprint for offshore wind farms and their annual yield that is highly influenced by how many turbines (in MW) are installed per surface area (MW/km2) affecting the wake losses within but also between wind farms across the North Sea.
7. **Cross-sector collaboration to realize multi-use and re-use.** Facilitating all the activities planned in the Dutch North Sea, while also leaving space for nature, requires smart ways to combine or layer different uses. This can be sequential, for instance, by maintaining assets that can be repurposed for other uses later, or reusing existing infrastructure and platforms. It can also be simultaneous,

Spotlight: multi-use of offshore space in the North Sea

An NSE whitepaper on multi-use of space in the future North Sea (see D6.4 [39]) demonstrates the need for synergistic uses. Projecting current patterns of multi-use into the future using the ambitions for the energy, nature and protein transitions, the study shows current practices to be untenable. Only through synergistic uses, that reduce cumulative ecological pressures while enhancing cross-sectoral economic synergies, can these transitions be realized simultaneously. The whitepaper identifies current examples of synergistic uses that can help guide future projects and argues the need for holistic planning approaches and the strategic allocation of multi-use areas.

More information available in D1.3 [22], D6.4 [39], [40], [41]

Figure 16: Example of spatial challenges between oil and gas activities in and around de former wind search area Lagelander, including an illustrative safety radius of 5 NM around platforms with a helicopter deck. In the most recent Partial revision of Programme North Sea this search area is omitted due to spatial conflicts with mining and fishing activities. (source: EBN)



for example, by finding ways for shared logistics, to limit the necessary size of helicopter zones around platforms or to enable CCS monitoring in wind farms. Both forms need regulations and planning procedures that support them while still effectively considering user safety. These mentioned challenges and possible solutions are ideally included in a coordinated infrastructure strategy across the four commodities (electricity, natural gas, hydrogen and CO_2)

8. **Minimizing environmental impacts and, where feasible, creating a net-positive effect on the ecosystem.**
To roll out large-scale energy infrastructure within the carrying capacity of the North Sea, we need to limit the associated negative impacts on North Sea flora and fauna by avoiding and minimizing them where possible. Because of the scale of the upcoming changes, limiting negative impacts will likely not be enough to ensure a healthy North Sea. There is an additional need for active nature restoration, both around energy infrastructure and in the wider North Sea, to strengthen the resilience of the regional ecosystem.

Spotlight: nature-inclusive energy hubs

Another NSE whitepaper demonstrates the ecological value that integrated planning of energy infrastructure can have (see D4.1 [42]). NSE developed a nature-inclusive spatial design (NISD) of an energy hub including largescale wind and hydrogen production (see D4.2 [43]). The NISD includes measures like a bird corridor for migratory species, the avoidance of highly stratified areas, and the concentration of added noise and vibrations near shipping lanes. In doing so, the NISD limits negative ecological impacts and promotes restoration while providing the same energy functions as a reference design. A comparative assessment demonstrates the merits of this approach but also shows that large-scale energy infrastructure will still have significant impacts on local ecology. Managing these well will be a key challenge for the future ecological quality of the North Sea.

Spotlight: the capacity challenges of the ports

The ports partnering in North Sea Energy have indicated that the energy transition requires port capacity at scales that are very challenging to meet. There is a significantly greater need for space than the available space at present. They indicate the following challenges:

- Space Shortage: By 2030–2050, there may be a shortfall of approximately 500 hectares of port space needed to support offshore wind projects.
- Expansion Plans: North Sea ports have planned expansions of nearly 200 hectares but are facing difficulties in realizing these projects.
- Current Capacity: The current port capacity is a bottleneck for achieving ambitions.
- Improving Component Storage Capacity: This can be achieved through just-in-time production and delivery, stacking components, higher occupancy of storage areas, and more efficient terminal layout.
- Optimization: Optimize the Operation & Maintenance base and resources for wind farm owners.
- Challenges: The sector faces challenges in terms of personnel and investments.
- Space Pressure: The landing of offshore wind, electricity, and H_2 puts additional pressure on space, both above and underground.
- Solutions: Combine tasks for cables and pipelines into eco-corridors.
- Circular Processing: Ports are actively seeking companies for the circular processing of wind turbine blades.

More information available via D3.1 [4] on the spatial alleviation by deploying offshore hydrogen which is estimated at 140 – 480 hectares in 2050.

Spotlight: the spatial footprint of offshore wind and wake losses

Wind farm power density (WFPD) has a large influence on the overall business case and spatial footprint of offshore wind. The wind farm power density is a way to measure how much electricity a wind farm can produce per square meter it occupies. The unit is often expressed as MW/km² and indicates how dense wind capacity is installed. It is very important for the spatial claims for offshore wind in relation to nature and other users of the sea. In the current planning for new wind areas 10 MW/km² is the guideline for the Netherlands, but deviation is possible if research shows that efficient use of space remains possible, and this results in a better balance between energy production, multi-use of space, and ecological sustainability.

The spacing of wind turbines is crucial for the overall yield of a wind farm. Wind turbines need sufficient space to prevent them from blocking each other's wind, a phenomenon known as wake losses. When turbines are placed too closely together, the airflow behind each turbine is disrupted, reducing the amount of wind available to downstream turbines and thus decreasing their electricity output.

A lower wind farm power density (WFPD)-meaning turbines are spaced farther apart-results in lower internal wake losses within the wind farm. This allows the same number of turbines to produce more electricity, although it requires a larger area. Wake losses can be significant, sometimes causing energy yield losses of more than 20%, although the exact impact depends heavily on the specific design of the wind farm and its surroundings. These wake losses negatively impact the business case for offshore wind developers. The problem is especially pronounced at lower wind speeds, when wake losses tend to be higher. This is particularly challenging because, in the future energy system, electricity prices are likely to be higher during periods of low wind, making lost generation more costly.

Additionally, in years with generally low average wind speeds, the combination of lower energy yield and reduced income can further undermine the financial viability of offshore wind projects.

In the North Sea Energy program, a fast calculation tool – called the DOWA wind profile generator -has been developed and implemented. This tool allows users to:

- Draw a user-specific wind farm within the North Sea Energy Mapeditor environment.
- Generate an energy profile using Dutch Offshore Wind Atlas (DOWA) historical data on wind speeds and directions for multiple years.
- Select wind turbine specifications from a database, including the required power curve data to translate wind speeds into energy yield.
- Calculate wake effects within the wind farm and provide net electricity production estimates on an hourly basis.

More information available via D1.3 [22], D5.1-4 (NSE digital toolbox) , [41], and [44].

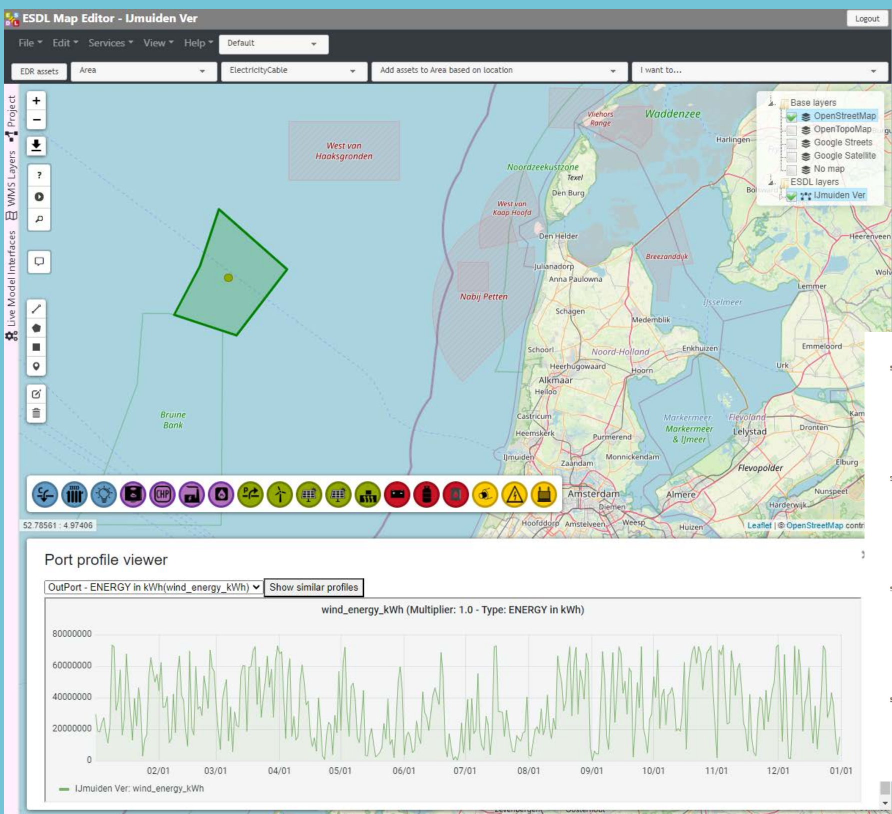
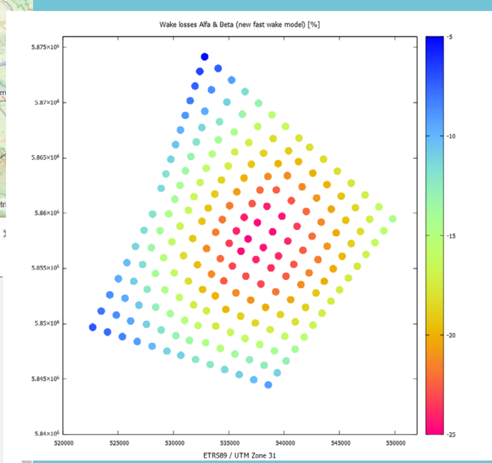


Figure 17: The left graph shows the IJmuiden wind farm area drawn in the North Sea Energy Mapeditor environment with the hourly production profile in the bottom and right graph indicates the energy yield per wind turbine where red highlighted turbines shown to be highly affected by wake losses.



3.3 Achieving a fair distribution of benefits and negative impacts

The offshore energy transition entails social change in addition to technological change. The changing energy system results in new activities becoming necessary while old ones become obsolete. Managing the necessary build-up, conversion and phase-out will require new ways to collaborate and interact as well as mechanisms to make sure private interests are aligned with public values, including the interests of later generations and people elsewhere in the world. We identify three key challenges for the energy sector:

9. **Organising markets to facilitate the creation of public value in the long term and avoid market failure.** To enhance the value of the energy system that we will create, we need continued and timely development of market mechanisms and incentives that strengthen this link and result in fair prices for the various energy commodities. A clear illustration is the recognized public value of offshore wind in the future Dutch and North Sea energy system, as highlighted by numerous studies and international strategic collaborations. However, the current business case for offshore wind developers faces increasing challenges due to high material and financing costs, limited demand, supply chain constraints, market cannibalization, and interference between wind farms resulting in wake losses.[11] Another strong example is the disconnect between the significant public value offered by offshore hydrogen production - which could substantially reduce the need for costly electrical infrastructure both offshore and onshore - and the current business models for offshore hydrogen projects, which have yet to reflect these potential cost savings and overall system benefits.

10. **Strengthening international collaboration and coordination.** As our use of the North Sea intensifies, so do cross-border interactions. Planning solely at the national level runs the risk of inefficiency when each country tries to (solely) meet its climate ambitions without regard to comparative advantages. It can also lead to the displacement of problems and inadequate accounting for cumulative effects, for example on ecology. This ties back to the coordination of marine spatial planning, but also to supply chain management for the energy commodities under study. It further relates to the cost-benefit sharing of cross-border infrastructure investments. This requires a fair distribution of benefits and costs over the stakeholders affected by enhanced interconnection between North Sea countries.

11. **Stakeholder engagement and public support.** Sharing an increasingly busy North Sea requires effective mechanisms to address the concerns of co-users and create mutual gains. This is also true for attention from the wider public onshore. As the North Sea turns from a backwater into a core part of our energy system, public attention is bound to increase, and there is a need for increased public knowledge as well as determined acceptance.

11 Related to this challenge an action plan is being drafted following the motion "Cabinet Approach to Climate Policy" of March 2025, submitted by Members of Parliament Wytske Postma and Suzanne Kröger, where the minister of Climate and Green Growth is requested to "present a concrete action plan before the summer [of 2025] for industry, grid operators, and potential wind energy producers to ensure that the 2025 tender will be a success, and to also investigate the possibility of a PPA guarantee fund." More information in: eerstekamer.nl/behandeling/20250311/motie_van_de_leden_postma_en/document3/f=/vmllhbrkfkap.pdf

Spotlight: system and business value of offshore hydrogen production

The public value of activities does not automatically translate to a viable business case. An example of this is provided by the NSE whitepaper on the system value and market opportunities for offshore hydrogen production (see D3.4 [45]). Energy system modelling shows offshore green hydrogen production to be cost-effective in reducing onshore grid congestion and curtailment. Business case analyses show that offshore production struggles with high CAPEX and uncertain hydrogen wholesale prices. A key challenge lies in translating systemic cost savings into incentives for private investments. The whitepaper offers several recommendations to resolve this mismatch, such as:

- Tailored support instruments, strategic infrastructure planning, and predictable offshore hydrogen tender volumes are needed to guide the technology through its "valley of death" and into scalable deployment.
- Additionally, the sizing ratio between offshore wind capacity and electrolysis capacity emerged as a critical design parameter for aligning societal value and project developer incentives: smaller electrolyser-to-wind ratios can improve utilization, lower hydrogen cost requirements, and help bridge the gap between societal value and viable project economics especially in early demonstration phases.

Spotlight: international collaboration

International collaboration has become a buzzword in political discourse on the North Sea. In a whitepaper on this topic, NSE has clarified the concept and assessed its current state-of-play and what actions could strengthen collaboration in the coming years (see D7.2 [46]). NSE identifies six key challenges, ranging from harmonising regulatory frameworks to resolving supply chain bottlenecks. Already, a wide range of efforts is underway to address these challenges, including initiatives like North Seas Energy Cooperation and Greater North Sea Basin Initiative. The whitepaper categorizes these initiatives and shows what challenges are covered by this emerging patchwork of collaborations, while also identifying the need for a more integrated approach.

Spotlight: best practices for offshore stakeholder engagement

As the North Sea is increasingly busy, there is an increasing need to engage stakeholders in the development of plans and projects. There is plenty of experience with stakeholder engagement on land. Offshore however, experiences are more limited and not as available. NSE has analysed the stakeholder engagement of seven international innovative offshore energy projects, for example on CCS and hydrogen production. D2.2 [47] presents lessons from these cases, showing for example the importance of embedding offshore projects in a vision that appeals to multiple perspectives on the future of the North Sea.

International offshore energy cases

1. Baltic Power
2. Brent Spar
3. Australia CarbonNet
4. Dogger Bank Wind
5. Northen Lights
6. Princess Elisabeth Island
7. West of Orkney

4. Action agenda

The baseline and ambitions outlined in the previous chapters are consolidated in an action agenda, providing a structured framework for advancing the energy transition in the North Sea region, with a focus on the Netherlands. North Sea Energy also has created an international roadmap and action agenda created for the whole North Sea region, see D7.1.

Among the four key energy commodities, electricity is further divided into offshore wind and offshore marine energy, while system integration is addressed in a dedicated section. The agenda presents short-term and medium-term actions as recommendations to bridge the gap between the current baseline and long-term ambitions.

Purpose of the Action Agenda

This action agenda offers an overview of the current state, actionable steps, and future ambitions across energy carriers and system integration efforts. It highlights challenges, opportunities, and practical measures to drive the energy transition while prioritizing sustainability, energy security, and economic viability.

Key Themes Across Energy Carriers

The agenda includes cross-cutting themes-such as governance, security, economic stimuli, technical improvements, collaboration, and human capital - to ensure effective implementation across all energy carriers and technologies. By addressing these overarching issues, the agenda supports system integration and coordinated progress throughout the entire offshore energy system. These themes promote an integrated, collaborative, and future-proof approach to the energy transition.

Structure of the Action Agenda

- **Baseline.** Describes the current state of energy carriers and system integration, identifying bottlenecks and opportunities in the North Sea region.
- **Short-Term Actions.** Focuses on immediate, actionable steps to address pressing challenges and accelerate progress.
- **Medium-Term Actions.** Outlines strategies to build resilience, scalability, and effectiveness in energy systems over time.
- **Ambitions.** Indicates long-term goals and targets for energy carriers (or its absence), paving the way for a sustainable energy future in the North Sea region

Action agenda

General	Hydrogen	(Carbon Capture and Storage) CCS	Offshore Wind
Baseline			
The key bottleneck for Offshore Wind, Green Hydrogen, and CCS is lagging demand growth for low-carbon energy and cost escalations, which pressures revenue models and creates investment uncertainty for new projects.	The Dutch industry currently uses about 180 PJ (fossil) hydrogen per year. Demo 1 and Demo 2 offshore demonstration projects announced for late 2020s and early-to-mid 2030s, respectively.	Offshore CCS projects under development (Porthos, Aramis and not yet disclosed projects)	4.7 GW capacity (2024); 15 TWh/yr production (2024) Wind energy action plan forthcoming in 2025
Short-term actions			
Reduce electricity grid congestion (Governance, Technical). Accelerate industrial decarbonization to drive demand for green molecules, wind power, and CCS (Governance); Develop energy demand side and flexibility in tandem with renewable production. (Governance); Energy transport strategies and infrastructure planning must account for cost disparities: upgrading the high-voltage electricity network has two orders of magnitude higher costs than upgrading the hydrogen network for transporting energy molecules (Governance); Re-evaluate tender system, incl. international harmonisation (Governance).	Hydrogen pipelines (Technical Improvements); Clarity on rules, tenders and tariffs offshore/onshore H_2 (Governance); Tender energy hubs (wind/hydrogen) (Governance); fast track technology learning 20-50 MW pilot program (Governance/Technical/Ecosystem/ Economic Stimuli); Clarity needed on role of blue H_2 and state ambitions for long term investment clarity and lock-in avoidance; (Governance)	Address spatial conflict issues (Collaboration / Governance/ Technical); Harmonize regulatory framework for infrastructure decommissioning (Governance); Resolve London Protocol; Cross-border storage collaboration (Collaboration/ Governance); Enable re-use of existing infrastructure (Technical Improvements); Leak detection methods, monitoring strategy and first response systems (Technical Improvements);	Stimulate investments in offshore wind (Governance); Iterative Strategic Planning offshore wind with long-term goals and adaptive planning (Governance); Adaptive plans for Energy hubs (wind/hydrogen) (Collaboration); Standardization of turbine production and installation (Technical Improvements); Designate strategic offshore zones for future deployment (Governance)"
Medium-term actions			
Shorten permit lead times; (Governance); Address seabed/port development and security monitoring (Security); International coordination (infrastructure, market) (Governance); Design and implement resilient systems (cyber/ sabotage) (Technical Improvements / Security); Minimize reliance on energy-intensive products and services (Governance/Economic stimuli). Advanced data sharing and connectivity offshore assets (Technical Improvements / Governance);	Feasible growth path for offshore H_2 for 2035 and beyond (linked to wind/ CCS) (Collaboration); Deploy offshore/onshore backbone (Technical Improvements); Realistic import / export strategy via offshore H_2 infrastructure and ports. (Governance); Offshore hydrogen storage strategy (Governance/Technical/Ecosystem/ Economic Stimuli);	Expand infrastructure (Economic Stimuli / Technical Improvements); Harmonize EU regulations (CO_2 transport/storage) (Governance); Detailed storage appraisal aquifer storage & advanced storage and monitoring methods (Technical Improvements)	Legal frameworks (operation/ decommissioning/re-powering) (Governance); Subsidies/investment incentives for long-term market outlook (Economic Stimuli); Robust international interconnection for power system (Collaboration); Nature-inclusive designs and monitoring (Ecosystem)
Ambitions			
Carbon neutrality and energy reliability (availability) and security (resilient systems, secure access to critical resources); Biodiversity restoration in compliance to EU ambitions	500 MW of (onshore) electrolysis capacity by 2025 and 3 to 4 GW by 2030; Demo 2 (offshore) around 500 MW aimed for mid 2030s	20M tons/annum CO_2 injection (2030); A NL-share of the 50Mtons of EU Netzero Industry Act A NL-share of the EU-ambition for 2050 (500 Mton)	NL ambition: 21 GW by 2032; up to 70 GW by 2050

	Offshore Marine Energy	Natural Gas	System Integration
Baseline	100s of kW to MW scale offshore solar and offshore energy storage at MW and MWh scale under development in projects and at Offshore Test Site: Zeevonk Oranjewind Crosswind"	81 (2024) TWh production, of which 50 TWh offshore (2024). Policies underway to improve financial drivers for investing in offshore small fields. Feasibility studies on pipeline repurposing for H_2 (demo 1) and future wind areas. Plus rerouting of natural gas transport pipelines for remaining gas production.	Energie Infrastructuur Plan Noordzee advice published and WIN (North Sea Wind Energy Infrastructure Plan) expected mid 2025 Key examples of offshore system integration projects: - Poshydon 1 MW offshore H_2 pilot operational 2025 - Electrified gas platform N5 with offshore wind farm Germany
Medium-term actions	Deploy (niche) market application for early market adoption (Governance / Economic Stimuli); Create clarity on how to connect these technologies in existing wind farms (Technical/ Governance); Develop grid-connected demonstration area (Technical Improvements / Governance); Identify benefits of offshore marine energy through integrated assessments (e.g. MKBA) (Ecosystem / Economic Stimuli); Integrated spatial planning/ tendering (Governance); Marine biodiversity research (Ecosystem);	Vision on relevance/importance of NG in the transition phase. (Governance); Customise agreements for Helicopter transport and minimise where possible (Governance); Reduce spatial footprint of exploratation, production, decommissioning and monitoring (Technical Improvements/ Governance); Streamline permitting for new developments (Governance); Optimize North Sea infra planning and operation for efficient production and re-use (Governance); Decommissioning strategy NG assets (Technical Improvements); Facilitate platform electrification for new developments (Economic stimuli/ governance)	Offshore-onshore grid interconnection and balancing (Technical Improvements); Integrated spatial planning/tendering across all technologies and commodities, with nature-inclusive design + early stakeholder engagement (Governance); Physical and cyber security by design strategy (Security / Technical Improvements); Outlook for multi-energy commodity hubs offshore and in landing zones (Governance / Technical Improvements); Prepare Dutch part of a Strategic Plan 4 Grids North Sea, incl. strategic (subsurface) storage strategy across commodities (electricity, natural gas, hydrogen and CO_2) (Governance)
Medium-term actions	Adaptive strategy for wave/ wind/solar/storage combination (Collaboration); Expand pilots and international connect (Governance / Technical Improvements); Shared infrastructure (reduce CAPEX/OPEX) (Collaboration / Governance)	Data transparency on decommissioning timelines; (Governance); Integrate gas with renewables, hydrogen, CO_2 storage; (Governance / Collaboration/ (Technical Improvements)"	Cross sectoral North Sea Offshore offshore project monitoring and strategy for bottlenecks in supply chain and ports capacity (Collaboration/ Security / Technical Improvements); Conduct risk assessments and build strategic partnerships to secure critical raw materials and human capital for the North Sea energy future. (Collaboration / Human Capital);
Ambitions	NL ambition: 3 GW offshore solar EU target: 1 GW installed by 2030 40 GW by 2050	NL forecast: Sector agreement foresees relevance untill 2045-2050 Potentially more than ~125-150 bcm production between 2025 and mid-century phase out.	The North Sea Wind Energy Infrastructure Plan (WIN) focus 2033–2040, projection towards 2050 considers development of offshore infrastructure (electricity and hydrogen). No intregral SI considerations on CCS, natural gas, electricity and hydrogen.

Key Themes Across Energy Carriers

Governance

Harmonize EU/national regulations; streamline permitting; cross-border collaboration. Develop policies for cross-sector integration to realize multi-use and re-use

Security

Seabed and port space security ; Resilient availability of energy and resources

Economic Stimuli

Tax incentives, subsidies for long-term investment security and market stability; Organising centralized markets to facilitate the creation of public value for the long-term and avoid market failure;

Technical Improvements

Upscale pilots; Resilient systems (cybersecurity, sabotage prevention, reliability); repurpose infrastructure; standardize procedures; Innovation in energy transport, conversion, storage, and flexibility; advanced (sub)surface monitoring technologies with low spatial footprint; drone develop and deploy for offshore logistics.

Ecosystem

Minimizing environmental impacts, creating net-positive ecological value where possible;
Biodiversity directives; nature-inclusive designs; Establish long term (baseline) ecology monitoring. programme for new development areas

Collaboration

Stakeholder forums; transparent public communication; community engagement; knowledge sharing

Human Capital

Training and re-skilling programs; university/practical school-industry partnerships; Cross sectoral certifications and curricula for workforce development. Improved Offshore Human Capital monitoring

4.1 Detailed actions per technology

Offshore wind

The offshore wind sector is already under significant pressure, with one of the major bottlenecks being the lack of alignment in offshore wind strategies among the countries bordering the North Sea. In the short term, these strategies must be harmonized to enable coordinated development and deployment. With the increasingly crowded North Sea, governance and regulatory actions are needed to designate strategic offshore zones. Additionally, the growing size of wind turbines, intensified competition, and the fragmented value chain highlight the need for standardization within the turbine production chain. Such standardization is essential to establish a positive business case for the sector and create a resilient, future-proof foundation for offshore wind development. Furthermore, it is strongly recommended to implement economic stimuli and establish legal frameworks not only for the operation, but also for the repowering and decommissioning of offshore wind infrastructure. Making better use of offshore electricity infrastructure is economically and spatially very important and ensuring the robustness of international interconnections will be essential for effectively managing and distributing the generated electricity, and therefore for reaching the offshore wind ambitions.

Making better use of offshore electricity infrastructure is economically and spatially very important.

Offshore Marine Energy

In the short term, it is crucial to establish a grid-connected demonstration area to showcase and validate innovations, which will require governmental support. Furthermore, integrated assessments, such as cost-benefit analyses (e.g., MKBA), should be encouraged to highlight the advantages of offshore marine energy. This includes researching marine biodiversity to ensure sustainable development. To drive early (nice) market adoption, this commodity must also be economically stimulated by identifying practical market applications. In the long term, it is essential to establish integration between wave energy, wind energy, solar power, and offshore energy storage systems. Clarity on how to connect (physically and regulatory) new marine energy technologies to existing energy projects and infrastructure so that space and infrastructure can be shared is very important for increasing the adoption rate of these technologies.

Offshore hydrogen as part of the hydrogen supply mix

The short-term actions for the hydrogen commodity include, governmental measures such as stimulating offshore hydrogen production in combination with offshore wind within the tenders for energy hubs. Additionally, harmonizing rules, tariffs, and tender processes is essential to remain aligned with offshore hydrogen ambitions. While onshore pipelines for hydrogen are currently under construction, pace must be kept high towards repurposing pipelines or developing new offshore hydrogen pipelines to ensure that infrastructure does not become a bottleneck. For the long term, a more well-founded and strategic pathway for offshore hydrogen must be established by 2035, with a focus on the connection of the onshore and offshore backbone. This also includes a strategy regarding the need of offshore storage of hydrogen and how offshore hydrogen fits into the mix of onshore produced green and blue hydrogen and import of hydrogen (derivatives). Regarding blue hydrogen clarity is needed and ambitions for blue hydrogen to create long-term investment clarity on one hand, but meanwhile state a clear phase out timeline to avoid lock-in.

Carbon capture and storage

The short-term actions for CCS focus on harmonizing the regulatory framework for decommissioning infrastructure currently used for gas, which is a prerequisite for enabling CCS to utilize this infrastructure. In addition to regulatory measures, technical advancements are required to facilitate the re-use of existing infrastructure. Priority areas for investigation include leak detection methods and first response systems, both of which are critical to scaling up and achieving the ambitions for this commodity. The London Protocol, a key policy mechanism outlining CO_2 storage guidelines, also requires updating, as it was originally established in 1996. Its latest amendment from 2009, which permits the transboundary export of CO_2 streams, has been ratified by ten countries but needs ratification by 36 countries to become legally binding for all signatory nations.

For the medium term, both governmental and technical actions are essential. Continued research and development is needed into advanced storage methods and detailed storage appraisal to establish a portfolio of storage options, including aquifer storage appraisal. This is necessary to drive technical improvements, but also non-technical developments in parallel, such as harmonizing EU (and European) regulations which will be pivotal in establishing a robust and cohesive system for CCS on the North Sea.

Natural Gas

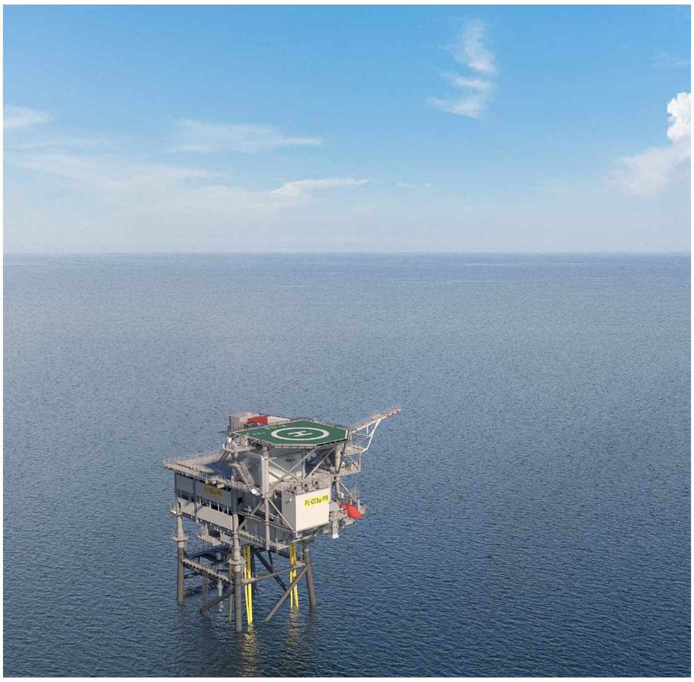
Natural gas is often given limited consideration in energy transition strategies. However, a clear vision of its relevance and importance during this transitional phase is needed to serve as a springboard for progress and provide clarity for investments. Governance challenges, such as streamlining permitting processes, must be addressed through regulations. Additionally, aligning North Sea infrastructure planning will accelerate the development of the natural gas commodity.

To achieve an optimal energy system outlook, natural gas and its phase out should be integrated in the future plans with renewables, hydrogen, and CO_2 storage. Transparency on possible decommissioning timelines for assets that facility re-use of legacy infrastructure but also allow for cross sectoral supply chain management is in this sense important for the wider offshore energy sector. In the meantime the natural gas system must be kept in good condition to ensure that the domestic gas production is sustained to maintain import dependency to acceptable levels and to have an infrastructure in place to provide the flexibility and security of supply in a an energy system that undergoes massive transformation. This can be facilitated by promoting the development of hybrid systems that combine these energy commodities and technologies (e.g. platform electrification for new developments and perhaps even revisit the research into offshore gas-to-wire[12] options).

System Integration

In the pas years the recognition of the need for offshore system integration has resulted in very important (forthcoming) steps in strategic policy documents, especially related to offshore wind and offshore hydrogen development. However, a very important missing link in the energy strategy for the Netherlands is the absence of a strategic and spatial explicit

12 In earlier NSE phases gas-to-wire of mature and stranded offshore gas assets was researched where offshore gas power plants convert produced natural gas and transport the produced electricity with the offshore electricity. This option can be combined with offshore CCS infrastructure. In principle this could allow for cost effect production and transport of low-carbon electricity from the offshore to shore.



We need a strategic and spatial explicit plan that covers the key four energy commodities for the next decades.

plan that covers the key four energy commodities for the next decades including potential development pathways for electricity, hydrogen, CCS and natural gas. Boundary conditions on the nature-inclusive design of such plans and the limits of the societal carrying capacity (stakeholder perspectives and human capital) warrant a process with early stakeholder engagement.

As the integration of commodities progresses, attention must then also be given to the interconnection and balancing of the onshore and offshore grid. This will be equally important as advancing and distributing the energy arriving onshore. Additionally, the link between offshore system and onshore landing points requires more attention, as this has not been addressed before. These landing points are suggested to be equipped to receive and process multi-energy flows, necessitating the development of multicommodity energy hubs at these locations.

In the medium term, it will be essential to focus on the North Sea offshore energy supply chain and ports with again the perspective on these four energy commodities to avoid cross-sectoral supply chain bottlenecks. Lessons should be learned from the offshore wind sector to establish a resilient framework from the outset. Furthermore, risk assessments and strategic partnerships must be conducted to secure access to critical raw materials, ensuring the creation of a future-proof and resilient North Sea energy system.

> **The lagging growth in demand puts pressure on revenue models and generates investment uncertainty for new projects.**

4.2 Conclusion

The primary bottleneck for Offshore Wind, Hydrogen, and Carbon Capture and Storage (CCS) is the lagging growth in demand, which puts pressure on revenue models and generates investment uncertainty for new projects. To address this, it is essential to:

- **Accelerate industrial decarbonization:** Drive demand for green molecules, wind power, and CCS by supporting the transition to cleaner industrial processes.
- **Develop the energy demand side alongside renewable production:** Ensure balanced growth between energy supply and demand to strengthen business cases for renewable projects.
- **Integrated and coordinated energy infrastructure planning:** Ensure a strategy to arrive at the lowest overall system cost and creation of public value in the long term without sectoral or even national borders. This strives to minimize environmental impact and spatial conflicts between energy commodity development and other users of the North Sea.

Key Focus Areas

- **International Coordination.** Align infrastructure and market strategies across borders to optimize energy transport and trade.
- **Resilient Systems.** Build robust systems to safeguard against cyber threats and sabotage, ensuring reliable energy infrastructure.
- **Cross-Border Collaboration.** Develop policies that support cross-sector integration, enabling multi-use and re-use of infrastructure to maximize efficiency and resource sharing in the supply chain.
- **Environmental Considerations**. Minimize environmental impacts and strive to create net-positive ecological value wherever possible, integrating sustainability into all energy transition efforts.

This holistic approach ensures that renewable energy development is both economically viable and environmentally sustainable while fostering collaboration across sectors and regions.

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North Sea Energy
offshore system integration

Design; www.knoeff.nl

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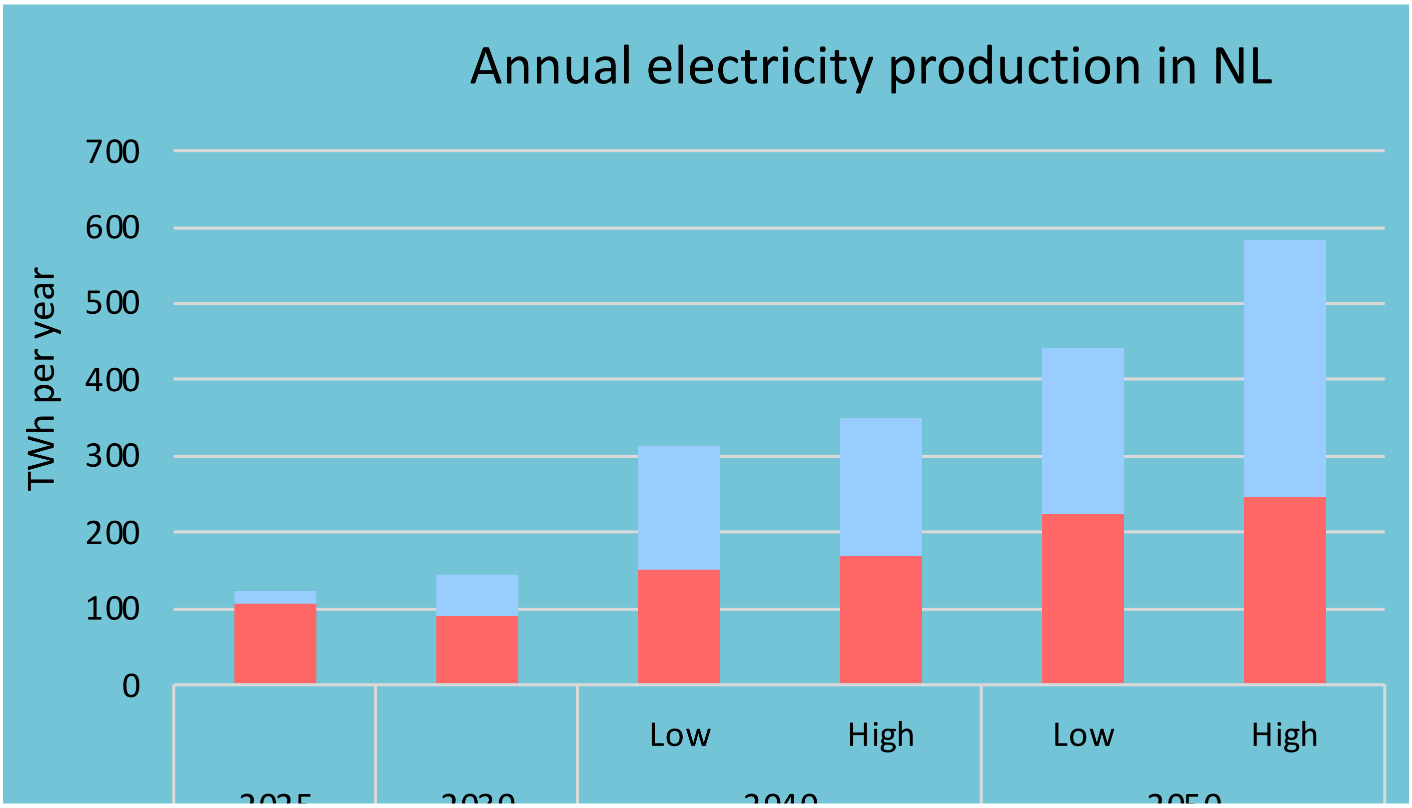
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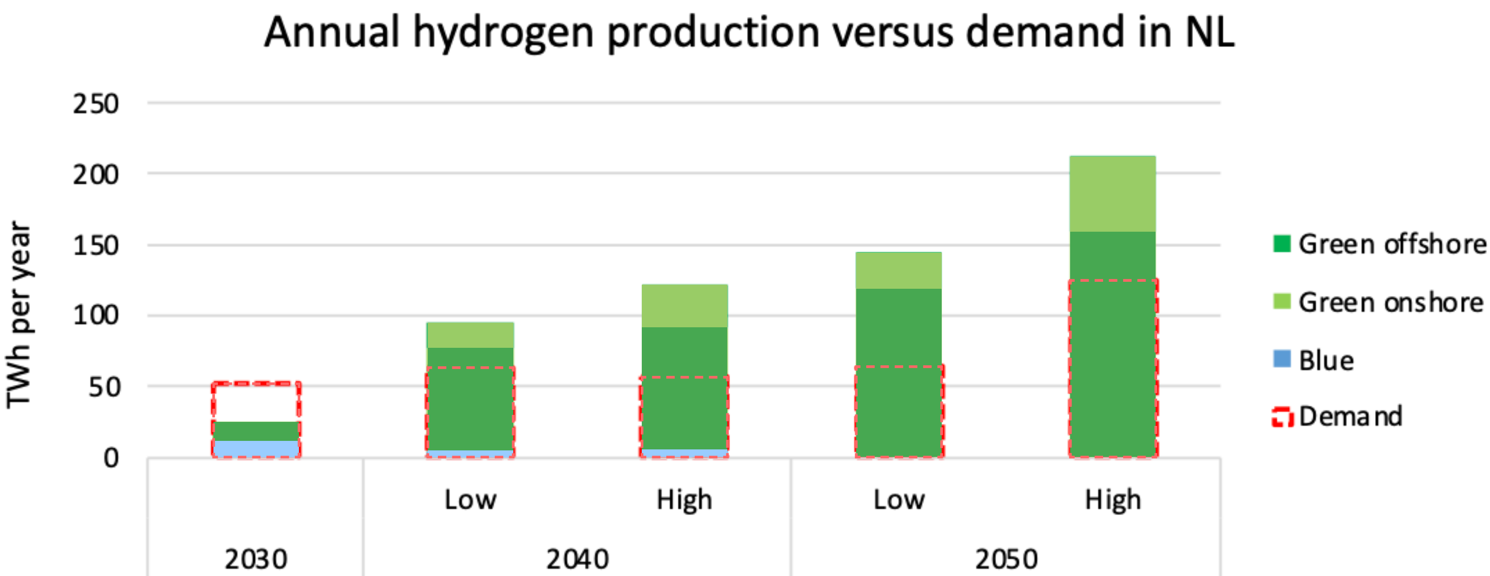
700
600
500
400
300
200
100
0
Low
High
Low
High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High
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High
2030
2040
2050
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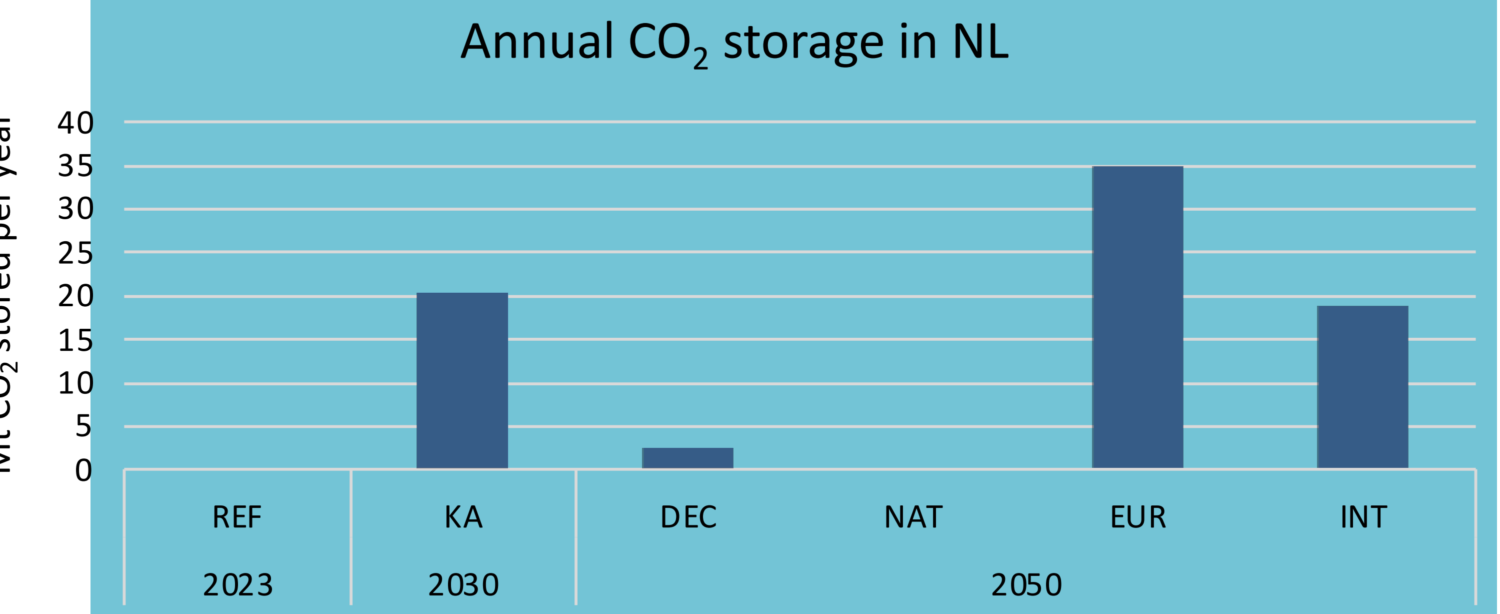
Green onshore
Blue
Demand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10
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REF
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2023
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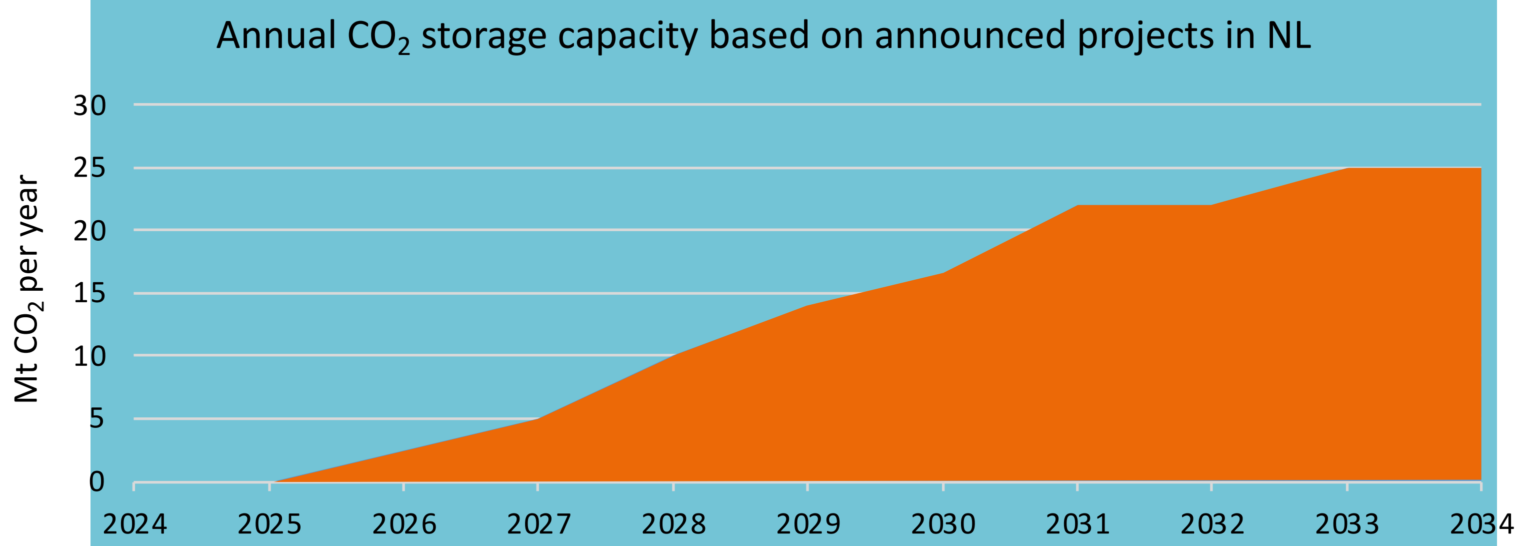
2050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Mt CO_2 per year
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25
20
15
10
5
0
2024
2025
2026
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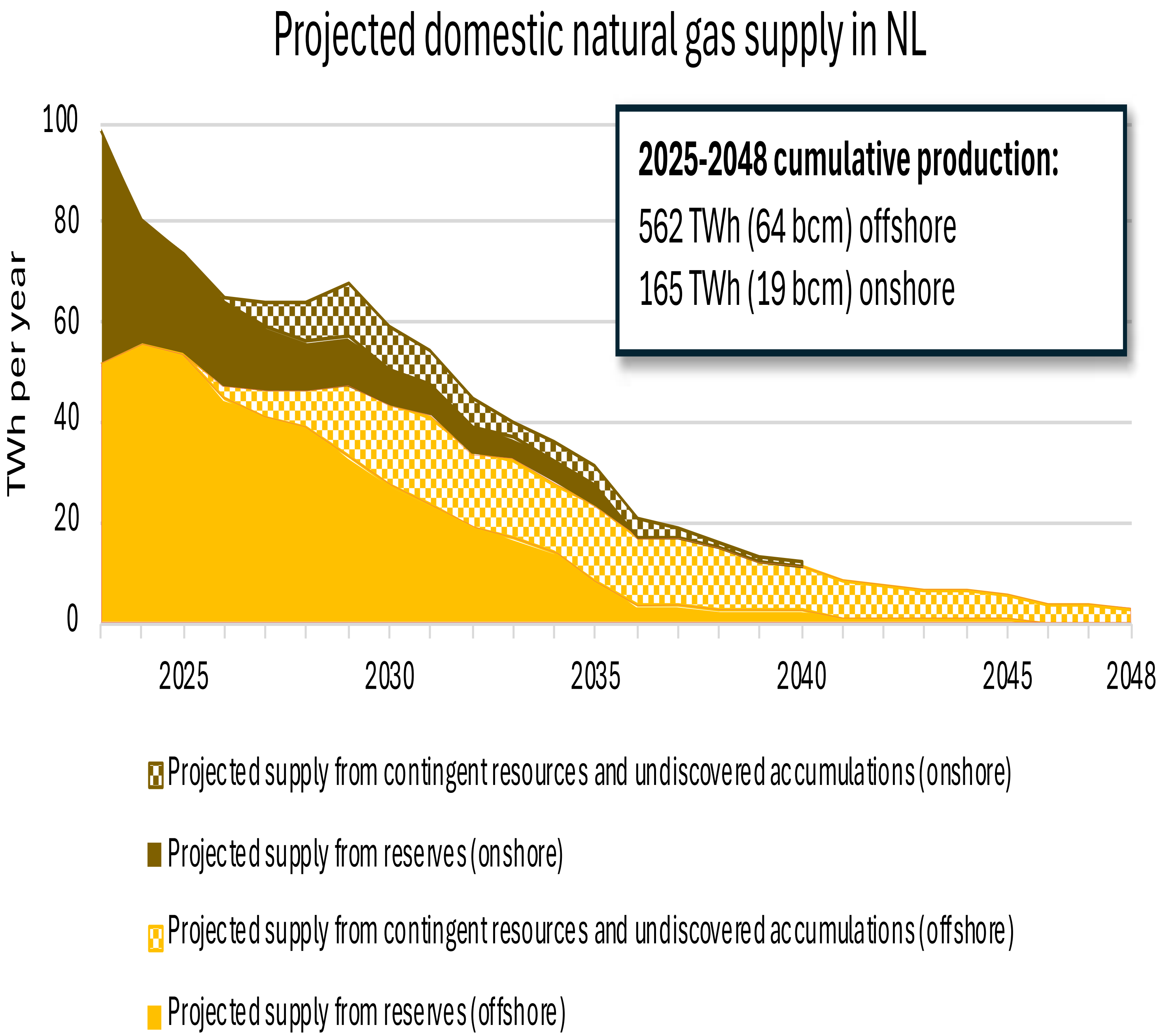
2031
2032
2033
2034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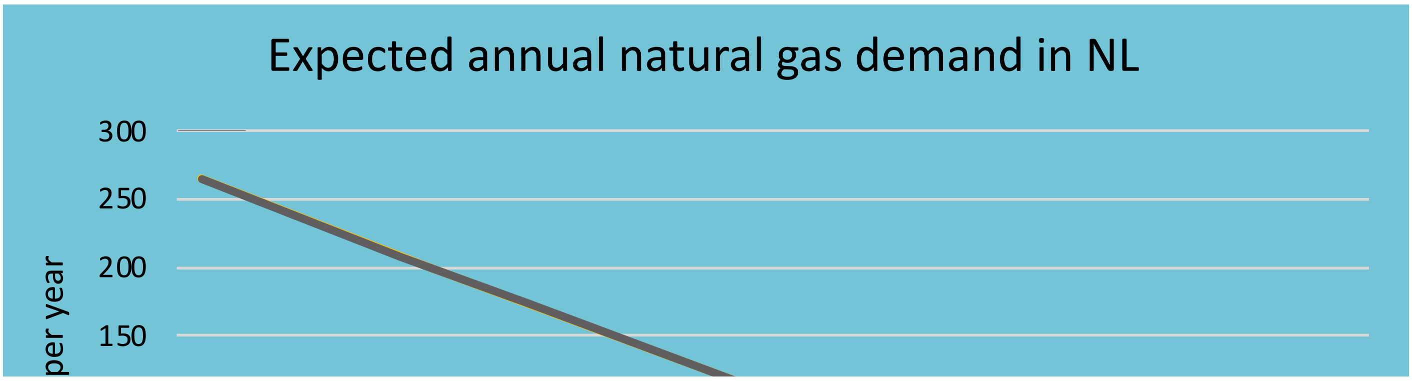
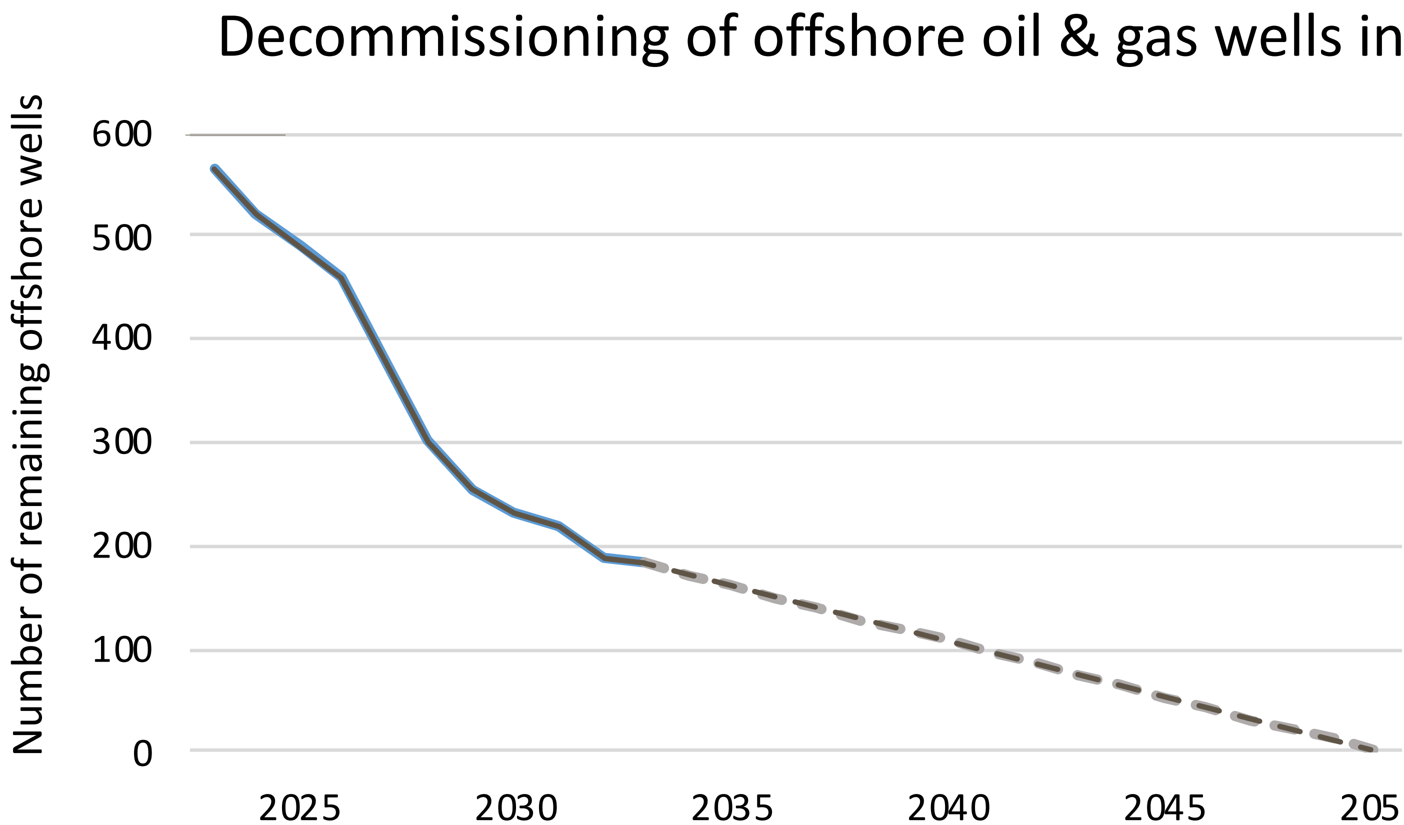
TWh per year
100
80
60
40
20
0
2025
2030
2035
2040
2045
2048
2025-2048 cumulative production:
562 TWh (64 bcm) offshore
165 TWh (19 bcm) onshore
Projected supply from contingent resources and undiscovered accumulations (onshore)
Projected supply from reserves (onshore)
Projected supply from contingent resources and undiscovered accumulations (offshore)
Projected supply from reserves (offshore)


Expected annual natural gas demand in NL
per year
300
250
200
150


Decommissioning of offshore oil & gas wells in
Number of remaining offshore wells
600
500
400
300
200
100
0
2025
2030
2035
2040
2045