North Sea Energy offshore system integration

Interim Program Findings June 2020

Unlocking potential of the North Sea

North Sea Energy
offshore system integration

Towards an inclusive and integrated design of the North Sea energy system with optimal value for society and nature

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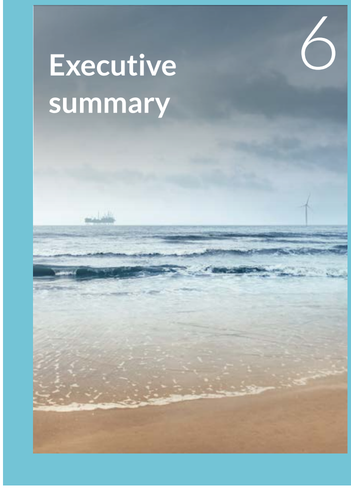
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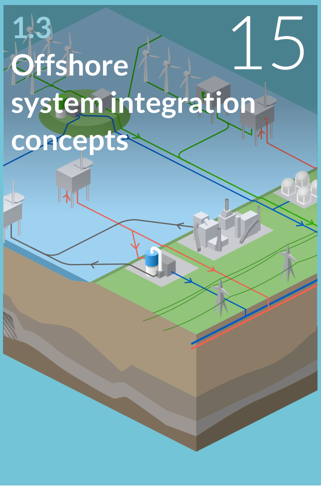
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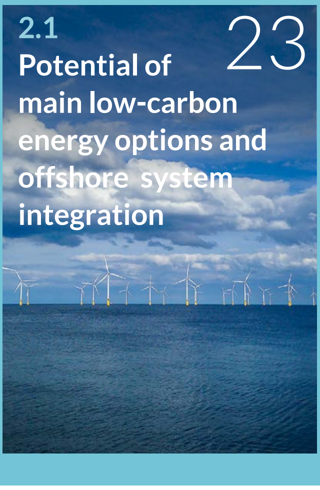
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Executive summary

The international society faces the important challenge to implement the Paris Agreement to substantially reduce greenhouse gas emissions and limit global temperature increase. A transition to a new energy system is needed, i.e. shifting towards renewable and low-carbon energy sources and making more efficient and responsible use of energy. The aim is to keep this energy transition affordable on the way to a clean and reliable energy system.

Exhibit 1 Key insights for offshore low-carbon energy solutions and their strategic integration

Offshore wind

- Important premise is the possible growth towards 60 GW in 2050
- Critical pillar for the Netherlands to reach the climate change mitigation targets
- Stringent limits on offshore wind would incur much higher overall energy system cost towards 2050
- Likely to be dominant source of electricity post 2030
- Transmission of offshore wind energy to shore as electricity will remain dominant
- Offshore green hydrogen production from offshore wind could represent a large share (up to 53%) of total hydrogen production in 2050, though highly sensitive to cost assumptions

Hydrogen

- Key energy carrier in a future energy system with high share of intermittent electricity supply
- No technical showstoppers, but points of attention for use of existing offshore gas infrastructure
- Scenario results indicate a balanced Dutch hydrogen supply mix in 2050 (95-153 TWh/yr) including on- and offshore green hydrogen production and blue hydrogen production.
- Offshore green hydrogen (up to 80 TWh/yr) increasingly prominent post-2030 on platforms and islands; larger scale more likely on energy islands
- Synergy, especially onshore, between green and blue hydrogen production to further lower carbon footprint

Carbon Capture & Storage

- CCS is needed to achieve lowest societal cost for the energy transition; stringent caps on CCS results in increased energy system costs of billions per year in 2050
- Offshore technical storage potential is 1.7 Gt CO_2
- Important role for CCS in blue hydrogen production and provides net atmospheric CO_2 removal options towards 2050
- Existing gas infrastructure can be (partially) used for transport and storage of CO_2
- Electrified platforms beneficial to compress/pump, condition and monitor CO_2

Natural gas

- Platform electrification is short term climate mitigation option with longer term upside potential for system integration
- Platform electrification has short term reduction potential up to 1 Mt CO_2 /yr
- Coordinated and cross-sectoral power grid offshore could save 54-66% in grid costs for electrification
- Natural gas in combination with CCS for blue hydrogen production has important share (18-34%) in future H_2 supply mix

The North Sea Energy research program explores the vast potential of the North Sea for the energy transition

The North Sea area is destined to become a pioneering region for the European energy transition towards a climate neutral economy by 2050 as it holds vast potential to deploy low-carbon energy solutions, including: offshore wind, carbon capture and storage (CCS), offshore hydrogen production transport and storage, energy islands and energy storage. Certain assets from the legacy gas infrastructure can have a strategic function in these future low-carbon energy solutions.

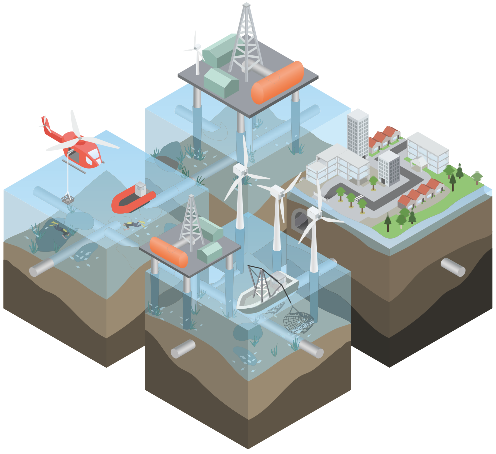
The aim of the North Sea Energy program is to identify and assess opportunities for synergies between energy sectors offshore. The program is a public private partnership of a large number of international partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options. This report summarizes the results from the current phase of the program. In this phase the geographic focus was placed on the Netherlands, although taking into account important international developments.

Unlocking the main climate change mitigation options through offshore system integration will create system value

Strategic sector coupling and integration of low-carbon energy developments provides options to reduce CO_2 emissions, use space more efficiently, enable & accelerate the energy transition and reduce costs (*see also Exhibit 1*). The results show that we need a portfolio of climate mitigation options to achieve an affordable energy transition. Excluding options from the portfolio increases the cost of the energy transition significantly. For example, limiting offshore wind and carbon capture & storage could increase energy system costs up to billions per year in 2050. Unlocking low-carbon energy potential of the North Sea thus requires integrated system thinking rather than merely sectoral optimization.

Coordination and collaboration are essential

To unlock the potential and value on energy system level strong coordination and collaboration is essential. We identified that successful removal or mitigation of some key barriers is needed, including current market failures and regulatory challenges. The Netherlands share the North Sea with neighbouring countries and it is therefore also required to align on national and international level to plan and facilitate the roll-out of new energy infrastructure while fostering strategic legacy infrastructure. The recently concluded Dutch North Sea agreement provides a logical starting point for such coordination and collaboration.[1] On an international level the Political Declaration of North Seas Countries Energy Cooperation provides a basis for further actions.



Towards an inclusive and integrated design of the North Sea energy system

On the North Sea we need to find a delicate balance between different use functions. Nature and food production, and its stakeholders, are important pillars next to the energy transition. The road ahead requires designing and adopting an inclusive stakeholder engagement approach and nature-inclusive design strategies to come to an effective and fair energy transition strategy. Such inclusive and integrated design of the energy system in the North Sea area allows then the balancing of merits for ecology, economy and society as well as their boundary conditions.

The coming decade is critical for laying the foundation for the future energy system on and around the North Sea. For some concepts, positive business cases are possible on the short term (e.g. platform electrification and CCS), but this requires clear and sustainable market signals. For other concepts, such as offshore power-to-hydrogen, power-to-x and hydrogen production on energy islands, a favorable business case most likely appears post-2030. To arrive at commercial projects in time these technologies and concepts need to be tested and demonstrated. The coming decade is thus pivotal for deploying first full-scale or pre-commercial projects and demonstrate concepts with business cases beyond 2030.

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[1] Negotiator agreement for the North Sea, 2020, http://tiny.cc/iliflz

Managementsamenvatting

De internationale samenleving staat voor de belangrijke uitdaging om het VN-Klimaatakkoord van Parijs uit te voeren om de uitstoot van broeikasgassen aanzienlijk te verminderen en de wereldwijde temperatuurstijging te beperken. Een transitie naar een nieuw energiesysteem is nodig, dat wil zeggen overschakelen op hernieuwbare en koolstofarme energiebronnen en een efficiënter en meer verantwoord gebruik van energie. Het doel is deze energietransitie betaalbaar te houden op weg naar een schoon en betrouwbaar energiesysteem.

Exhibit 1 Belangrijkste inzichten offshore energiefuncties in geïntegreerd energiesysteem

Offshore wind

- Belangrijk uitgangspunt is de mogelijke groei richting 60 GW in 2050
- Essentieel voor Nederland voor het behalen van klimaatdoelen
- Strikte beperking voor offshore wind leidt tot hogere kosten van het energiesysteem richting 2050
- Waarschijnlijk belangrijkste elektriciteitsbron na 2030
- Transport van windenergie naar land zal nu en in de toekomst hoofdzakelijk in de vorm van elektriciteit plaatsvinden
- Offshore waterstofproductie met offshore windenergie kan groot aandeel (tot 53%) hebben in de waterstofproductie-mix, maar dit is sterk afhankelijk van kostenaannames

Waterstof

- Belangrijke energiedrager in toekomstig energiesysteem met een groot aandeel variabel aanbod van elektriciteit
- Geen technische showstoppers, maar wel aandachtspunten bij gebruik bestaande offshore gasinfrastructuur
- Scenarioresultaten tonen een gebalanceerde waterstofproductiemix (95-153 TWh/jr) in 2050 inclusief blauwe waterstof en groene waterstof (on- en offshore)
- Offshore groene waterstofproductie (tot 80 TWh/yr) wordt steeds belangrijker na 2030 op platforms en energie-eilanden; grotere schaal waarschijnlijker op energie-eilanden
- Synergie mogelijk, zeker op land, tussen groene en blauwe waterstofproductie om CO2-voetafdruk verder te verlagen

CO_2 afvang, transport en opslag

- CCS is nodig om laagste maatschappelijke kosten van de energietransitie te bereiken; strikte limieten op toepassing ervan leidt to stijging van energiesysteemkosten met miljarden euro's per jaar in 2050
- Technisch opslagpotentieel offshore is 1.7 Gt CO_2
- Belangrijke rol voor CCS bij het produceren van blauwe waterstof en opties voor netto CO_2-onttrekking uit de atmosfeer richting 2050
- Bestaande gasinfrastructuur kan (deels) worden gebruikt voor transport en opslag van CO_2
- Geëlektrificeerde platforms gunstig voor compressie/pompen, conditionering en het monitoren van CO_2

Aardgas

- Platformelektrificatie is korte termijn mitigatie-optie voor klimaatverandering met langere termijn waarde voor systeemintegratie
- Elektrificatie van platforms heeft korte termijn reductiepotentieel tot 1 Mt CO_2 /jr
- Een gecoördineerd en sectoroverschrijdend elektriciteitsnet op zee kan een besparing van 54-66% in netkosten opleveren voor elektrificatie van platforms
- Aardgas heeft in combinatie met CCS voor het produceren van blauwe waterstof een belangrijke aandeel (18-34%) in het toekomstige aanbodportfolio van waterstof

Noordzee sleutelfunctie in de energietransitie

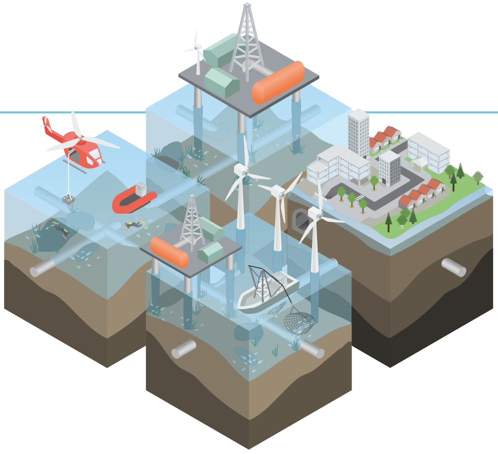
Het Noordzeegebied zal een spil zijn in het realiseren en versnellen van de Nederlandse en Europese energietransitie. Het kan hierbij een voorbeeldregio zijn voor Europa op weg naar een klimaatneutrale economie in 2050. De Noordzee biedt een groot potentieel voor CO_2-arme energieoplossingen, zoals: wind op zee; CO_2 afvang, transport en opslag (CCS); waterstofproductie, -transport en -opslag, energie-eilanden en energieopslag. Bepaalde activa in de bestaande gasinfrastructuur kunnen een strategische functie hebben voor deze toekomstige energieoplossingen.

North Sea Energy (NSE) is een publiek-privaat onderzoeksprogramma met een groot aantal (internationale) partijen die de energiewaardeketen vertegenwoordigen. Vanuit onze activiteiten op en nabij de Noordzee onderzoeken we mogelijkheden waarmee Nederland door integratie van het energiesysteem nieuwe kansen op gebied van de energievoorziening kan verzilveren. Het programma bundelt krachten van het bedrijfsleven en onderzoeksinstellingen en verkent tegelijkertijd de bijdrage en perspectieven van een bredere groep stakeholders. Het NSE-programma biedt nieuwe perspectieven op de realiseerbaarheid van systeemintegratie op het gebied van techniek, markt, milieu & ecologie, veiligheid, wet- en regelgeving en sociale inpassing. Voor u ligt de publieke samenvatting van resultaten van de derde fase het NSE-programma.

Ontsluiten van het potentieel en waarde door systeemintegratie

De diverse offshore ontwikkelingen kunnen en mogen niet los van elkaar gezien worden. De integratie van het bestaande en het nieuwe energiesysteem (wind, aardgas, elektriciteit en waterstof) leidt tot synergievoordelen. Dit levert de samenleving niet alleen besparingen op in de vorm van geld en tijd, maar maakt ook effectief ruimtegebruik mogelijk én zal tegelijkertijd de CO_2-uitstoot aanzienlijk terugbrengen. De resultaten laten zien dat we de energietransitie betaalbaar houden als we het gehele offshore portfolio gebruiken én deze in een systeembenadering optimaliseren. Een voorbeeld is dat energiesysteemkosten miljarden euro's per jaar hoger kunnen uitvallen wanneer sterke restricties worden opgelegd aan de uitrol van offshore wind en CCS. Dit vergt dus optimalisatie op het niveau van het energiesysteem in plaats van alleen op sectorniveau.

Coördinatie en samenwerking onontbeerlijk



Regievoering op nationaal en internationaal niveau is wel nodig om de energiefuncties op de Noordzee te integreren. Zo zijn er belangrijke marktbarrières en belemmeringen op het gebied van wet- en regelgeving die een oplossing behoeven. Internationale samenwerking is ook van groot belang bij het uitrollen van nieuwe energie-infrastructuur en het identificeren en behouden van bestaande infrastructuur met strategische functie in het toekomstig energiesysteem. Het onlangs gesloten Nederlandse Noordzee-akkoord biedt een logisch uitgangspunt voor de noodzakelijke coördinatie en samenwerking op de Noordzee. Op internationaal niveau biedt de politieke verklaring van de samenwerking op energiegebied van Noordzeelanden een basis voor verdere acties.

Naar een inclusief en geïntegreerd ontwerp van het energiesysteem op en rond de Noordzee

De Noordzee kent vele gebruiksfuncties en belanghebbenden (bijvoorbeeld: visserij, natuur- en milieu, scheepvaart, olie- en gasactiviteiten, defensie, recreatie, kustgemeenten en de windenergiesector). In de toekomst moet een delicate balans gevonden worden tussen deze gebruiksfuncties. Natuur en voedselproductie zijn belangrijke pilaren naast de energietransitie op zee. Gezien deze achtergrond is het noodzakelijk om een inclusief proces te ontwerpen en door te voeren voor de betrokkenheid van de belanghebbenden. Natuurinclusief ontwerpen kan hierbij ook bijdragen aan een eerlijke en effectieve energietransitie.

Een belangrijk deel van het fundament voor het toekomstig energiesysteem op en rond de Noordzee wordt het komende decennium gelegd. Voor enkele concepten, bijvoorbeeld voor platformelektrificatie en CCS, is een positieve business case al mogelijk op de korte termijn, maar dit behoeft wel duidelijke en duurzame marktcondities. Voor andere onderzochte concepten, zoals power-to-x, offshore waterstofproductie op platforms en energie-eilanden, lijkt een positieve business case zich na 2030 aan te dienen. Om deze concepten tijdig in commerciële projecten toe te kunnen passen, dienen de innovaties eerst in de praktijk te worden getest en gedemonstreerd. In het komende decennium is het daarom al noodzakelijk om de eerste pre-commerciële en demonstratieprojecten te ontwikkelen en starten.

1

Introduction

Offshore energy transition and the opportunities for offshore system integration

1.1

Climate change mitigation & energy transition

Transition is needed towards a low-carbon energy system

The international society faces the important challenge to implement the Paris Agreement to substantially reduce greenhouse gas emissions and limit global temperature increase. A transition to a new energy system is needed; i.e. shifting towards renewable and low-carbon energy sources, and using energy more efficiently and responsibly.

To pave the way, the Dutch Climate Act contains a reduction target for CO_2 emissions of at least 49% by 2030 and 95% in 2050 (compared to 1990 emission levels as shown in Exhibit 2). A CO_2-neutral electricity system is also strived for towards 2050. This leads to a major challenge for all sectors, but may also offer opportunities for the same sectors on the road towards a CO_2 neutral energy system. Sectoral targets and agreements for the sectors electricity, industry, built environment, traffic and transport, and agriculture are set in the National Climate Agreement *(see Exhibit 3)*.

A significant part of the solution could be unlocked offshore

A considerable share of the required CO_2 reduction is foreseen in the Climate Agreement to be reached by more offshore wind development and implementing carbon capture and storage (CCS). Offshore wind is planned to grow from 4.5 GW in 2023 towards 11.5 GW in 2030. No targets have been set for carbon capture and storage. Indicative is the 7.2 Mt CO_2 stated in the Climate Agreement as the maximum amount subsidised industrial CCS per year in 2030. Hydrogen production from electricity (green hydrogen) and natural gas (blue hydrogen) is also mentioned as one of the levers towards decarbonisation.

Towards 2050 this means that the Dutch offshore energy sector will likely shift from an oil and gas dominated sector towards an offshore wind dominated sector with in addition marginal hydrocarbon production, electricity production from other renewable energy sources, CO_2 infrastructure (for storage) and hydrogen infrastructure.

Offshore energy challenges & synergies

The offshore energy transition holds some key challenges but also options for synergies between energy sectors offshore. The foreseen strong build-up of offshore wind in the next decades comes with several challenges, including: cost reduction and reducing North Sea spatial claim by multi-use and synergy with other use functions.

Space is an important limiting factor for offshore energy production. In future scenarios PBL (2018) reports 3- 26%

Exhibit 2 National greenhouse gas emissions in 1990 (222 Mton CO_2-eq) and reduction targets for 2030 and 2050.

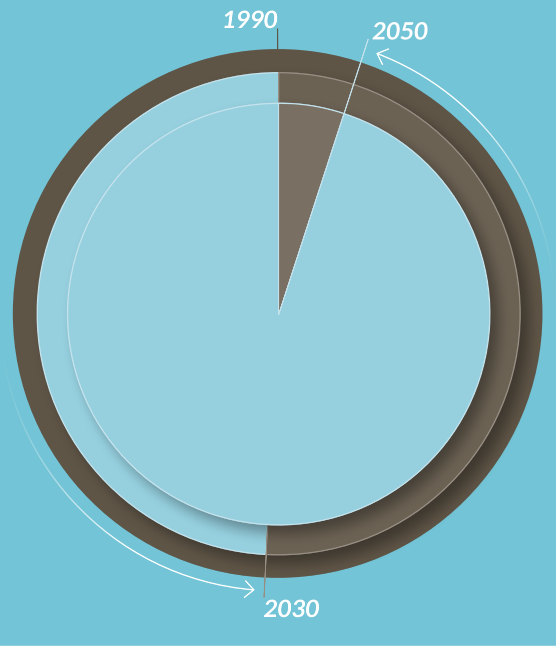
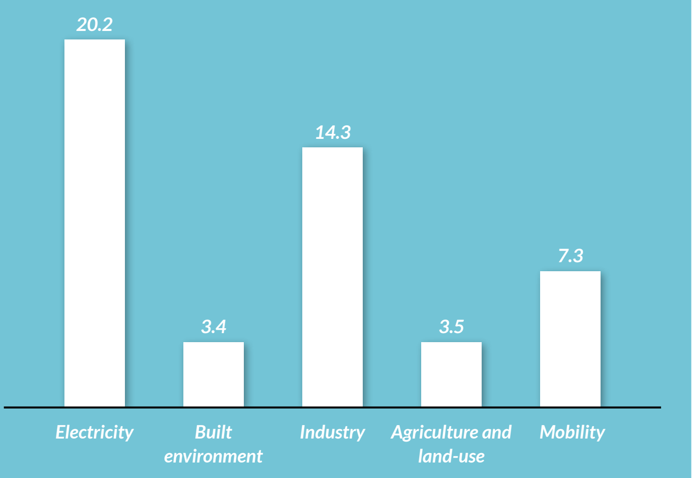


Exhibit 3 Sectoral CO_2 reduction targets for 2030 in the National Climate Agreement – The Netherlands

In $MtCO_2/yr$



of the Netherlands Continental Shelf to be ‘used’ by offshore wind, although this strongly depends on assumptions on the installed capacity (12-60GW in 2050), energy density of wind farms and multi-functional use of space.[1] Strong offshore wind deployment also has the challenge according to the PBL (2018) study that new landing points for offshore energy are difficult to realise and that in periods of high wind electricity production the onshore grid cannot cope with the high volumes, i.e. grid congestion. This already may become a serious issue around or before 2030.

Attaining a stable market outlook is a particular challenge for the offshore wind value chain. The demand for electricity and flexibility of the energy system should grow with the increase of installed wind capacity. This prevents high volatility in electricity prices, insecure industry backlogs and marginal earning potential throughout the offshore wind value chain (e.g. contractors, shippers, equipment suppliers).

Offshore natural gas production on the Netherlands Continental Shelf has yielded about 11 billion m^3 of natural gas in 2018; a 27% share of natural gas consumption in the Netherlands. Thousands of wells, thousands of kilometres of offshore pipelines and ~150 platforms form the backbone of this offshore production. Offshore gas production is however in decline and a large part of hydrocarbon production and transport infrastructure will reach the end of its economic life over the next two decades.[2] The offshore hydrocarbon industry has thus the major challenge of decommissioning of its offshore assets after production has ceased.

Natural gas production offshore currently requires the consumption of part of the produced natural gas which results in offshore emissions of CO$_2$ and NO$_X$. Lowering this footprint compared to alternative sources of natural gas is an important driver for future developments.

Fluctuating and low gas market prices place pressure on operating margins. Minimizing and decomplexing the operational costs offshore is essential for a positive business case for natural gas production. This holds for existing production assets as well as for new developments.

The build-up of offshore wind assets and the need for CO$_2$ transport and storage infrastructure on the one hand and the decline of gas assets on the other hand, offers an opportunity to reduce costs and save space; strategic infrastructure might be suitable for use and supporting the energy transition. An important question is whether and to what extent use of part of this existing infrastructure for low-carbon energy solutions may reduce the cost of achieving medium- and long-term climate goals. Next to merely cost reductions, system integration, or sector coupling, has added value to accelerate the energy transition at the North Sea.

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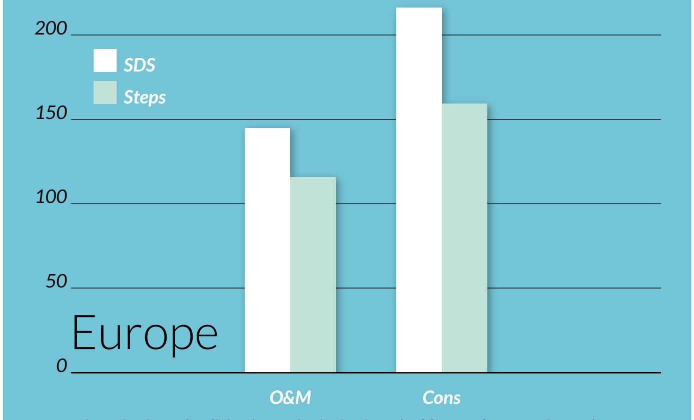
[1] PBL, The Future of the North Sea, 2018, tiny.cc/5hkflz

[2] Nexstep, Re-use & decommissioning report 2019, https://www.nexstep.nl/re-use-decommissioning-report-2019/

Exhibit 4 International Energy Agency: synergy between offshore wind and offshore oil & gas sectors valued at billions

The IEA foresees a bright future for offshore wind growing towards a trillion-dollar business in its recent Offshore Wind Outlook 2019.[1] The IEA sketches potential synergies between offshore wind and oil & gas sectors reaching a value of $275-360 billion in Europe over the next two decades. Chief of International Energy Agency, Fatih Barol, further stipulated during the launch of the World Energy Outlook that Europe needs to focus on offshore wind in combination with hydrogen, carbon capture and storage, and energy storage.[2]

In billion dollars (2018)



Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Con = construction and includes activities considered as potential synergies, e.g. foundations, installation and logistics. O&M includes potential synergies in operation and maintenance of offshore wind installations

[1] IEA, Offshore Wind Outlook 2019, tiny.cc/snkflz

[2] IEA, World Energy Outlook 2019, tiny.cc/grkflz

1.2

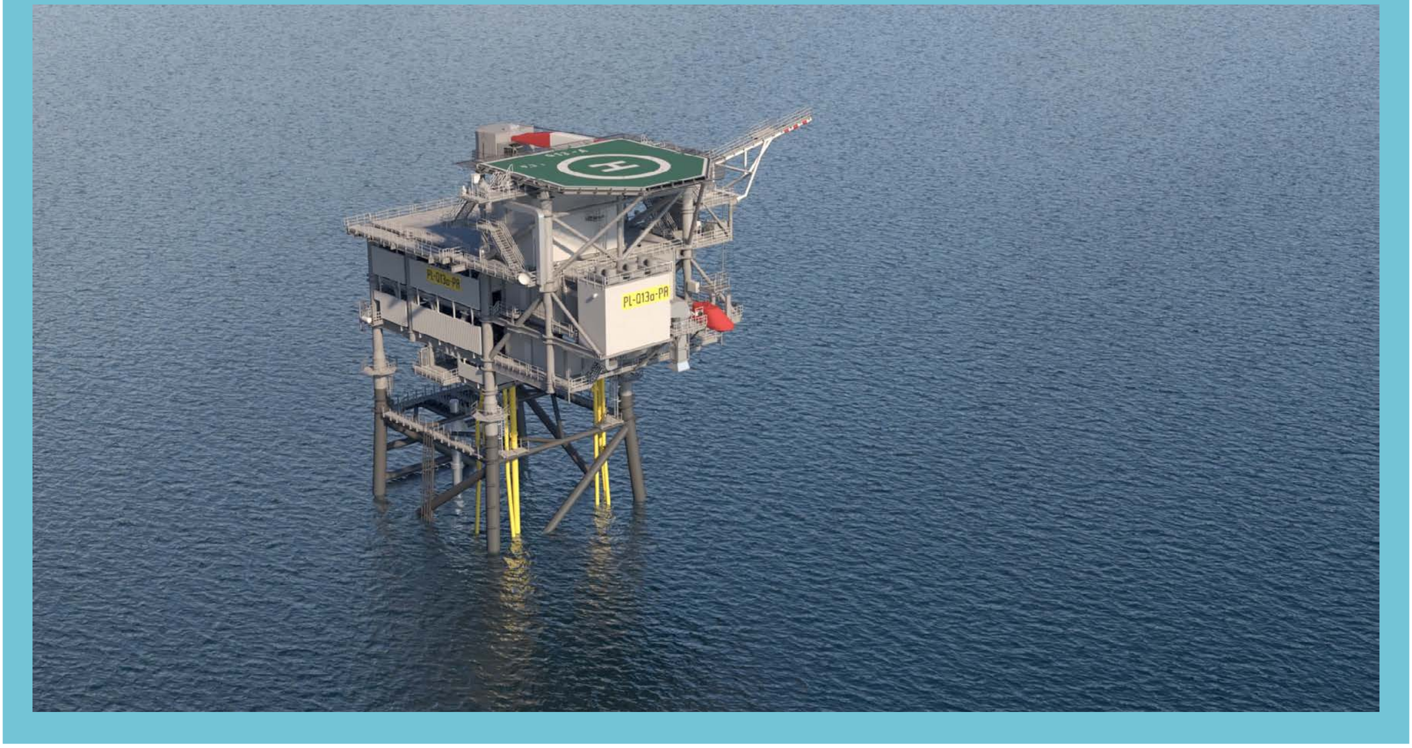
The North Sea Energy program

The North Sea Energy program and its consortium partners aim to identify and assess opportunities for synergies between energy sectors offshore. The program aims to take into account all dominant low-carbon energy developments at the North Sea, including: offshore wind deployment, carbon capture and storage, energy hubs & islands and energy interconnections, hydrogen infrastructure, energy storage and more. Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO_2 emissions, enable & accelerate the energy transition and reduce costs.

The consortium is a public private partnership consisting of a large number of (international) partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options. The next section gives a short description of the various offshore system integration concepts.

Exhibit 5 Offshore hydrogen production pilot

The first North Sea Energy spin-off project PosHYdon will pilot offshore green hydrogen production at 1 MW scale at the operational Q13a-A platform. This is an already electrified platform located near the Dutch coast, 13 kilometres from Scheveningen. Production is expected to start in 2021.

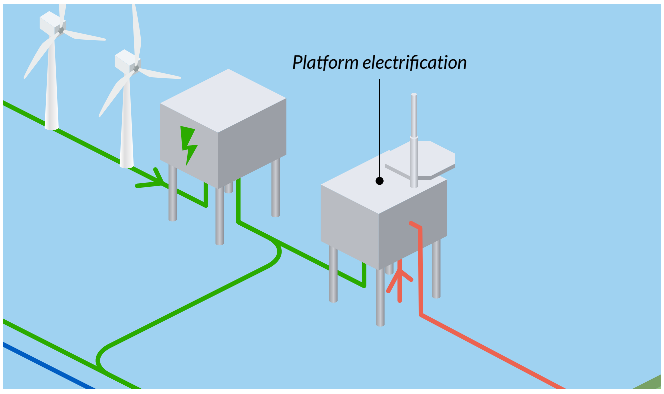


1.3

Offshore system integration concepts

The main studied offshore system integration concepts within the North Sea Energy program are:

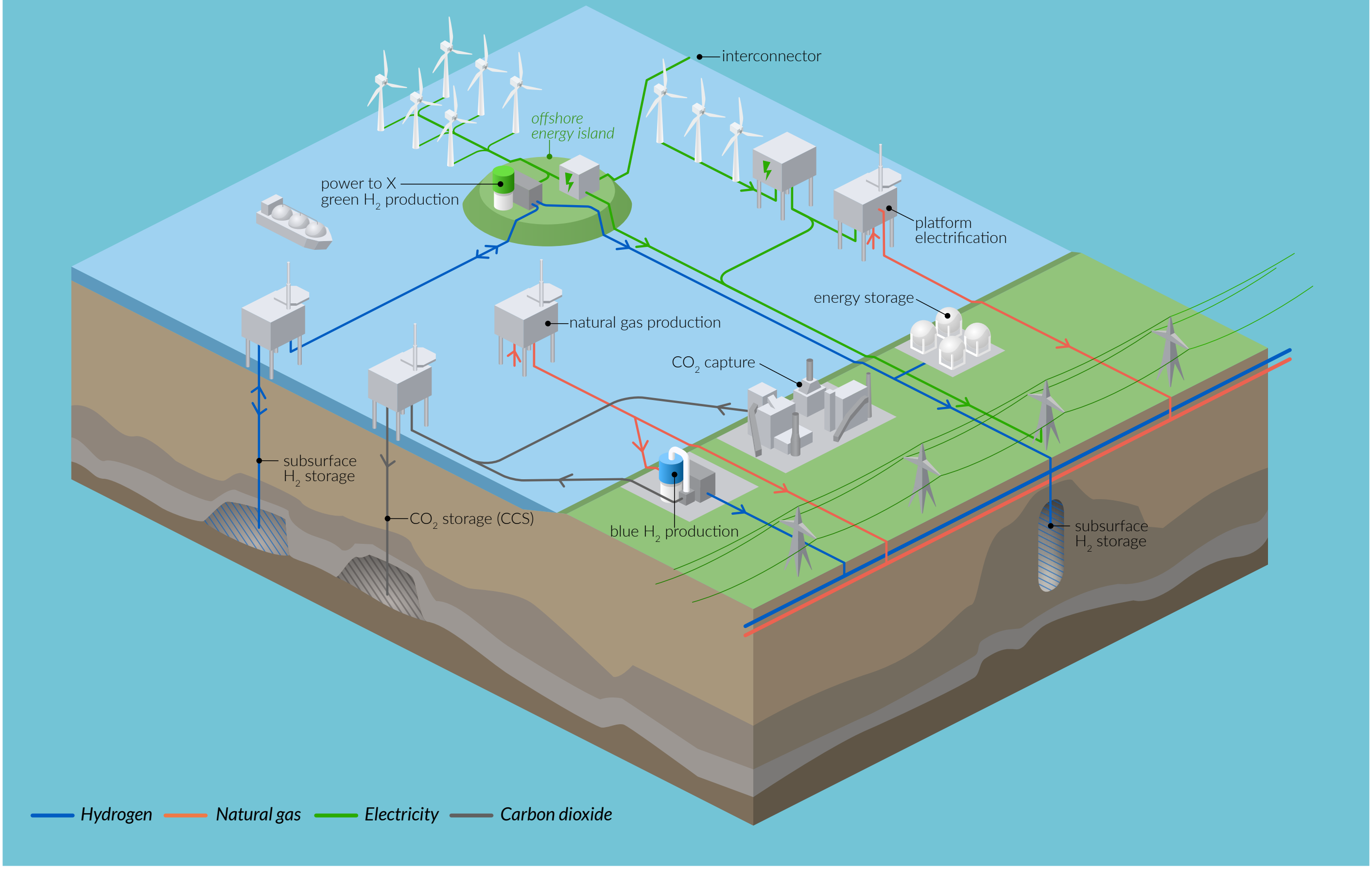
- Electrification of platforms to decrease offshore gas consumption, CO_2 (and other) emissions and feed other future activities with clean energy;
- Offshore power-to-hydrogen on (existing gas) platforms and energy islands;
- Offshore power-to-methanol and -ammonia on (existing gas) platforms and energy islands
- Carbon capture and storage using offshore power infrastructure, (existing gas) pipelines and depleted hydrocarbon fields;
- Energy storage using existing offshore assets.



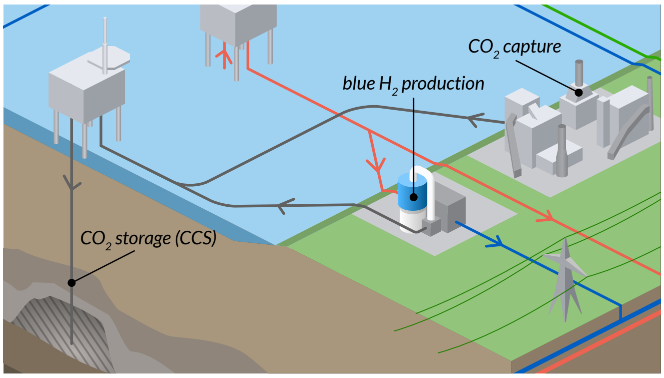
1.3.1 Platform electrification

Electrification of hydrocarbon production platforms concerns electrification of the energy demand for these platforms (mainly processing and compression energy). Currently this energy is primarily being supplied by gas-fired turbines. Electrification replaces relative inefficient fuel gas turbines or engines installed on the platform and thereby reduces overall

Exhibit 6 Offshore system integration concepts



energy consumption, CO_2 and NO_X emissions. Furthermore, electrified production platforms could be important stepping stones for other system integration concepts, such carbon capture and storage. A cabled connection to an offshore power hub provides a reliable, stable power supply, and improves security of supply.



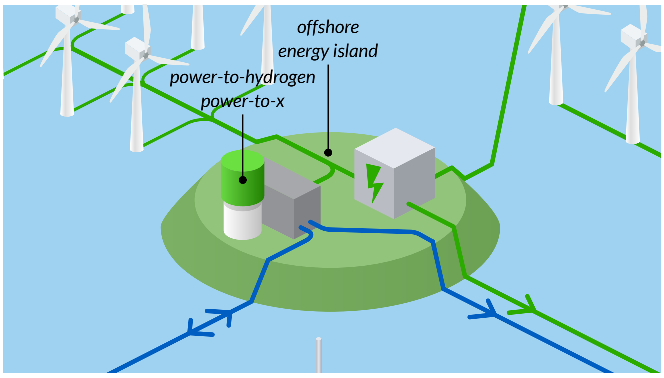
1.3.2 Carbon capture and storage

CCS typically involves CO_2 capture, compression from CO_2 as gas to a liquid or a denser gas, transport and isolation from the atmosphere by storage. [1] Transport of the CO_2 between sources and storage sites will occur most likely by pipeline or by ship. Storage takes place by injecting CO_2 into porous rocks in, for example, (near) empty gas fields or deep aquifers (saline formations). CCS requires a transport and storage infrastructure to be developed in the North Sea. An important aspect is to possibly use parts of the existing oil- and gas infrastructure (wells, platforms, pipelines) for CCS, which become available once hydrocarbon production ceases.

CCS is an important example of system integration because the existing gas infrastructure can be (partially) used for transport and storage of CO_2. Furthermore, electricity is highly beneficial on platforms to compress, condition and monitor CO_2, even though offshore CO_2 transport and storage power requirements are low compared to power required for natural gas production. Synergy thus can be achieved by electrifying oil & gas platforms and using them for CCS.

CCS is essential in the production of blue hydrogen, which is produced by reforming natural gas to hydrogen and CO_2. Blue hydrogen differs from grey hydrogen as the CO_2 released in this process is captured and stored. It is an important hydrogen production route as it allows for fast and stable decarbonization, while the considerable volumes already possible on the shorter term justify (partial) conversion of the gas infrastructure for hydrogen.[2]

CCS could also contribute to net removal of CO_2 from the atmosphere, for example by applying CCS in combination with bioenergy (BECCS) or direct capture (DAC) of CO_2 from the air.



1.3.3 Power-to-hydrogen

Power-to-hydrogen concerns the conversion of electricity to hydrogen gas. Purified (sea)water is split into hydrogen and oxygen with the input of electricity. The main source of electricity is foreseen to be offshore wind, but could in the future also include offshore solar or other power sources. Main offshore locations for conversion are considered to be existing and new platforms and/or energy islands. However, a very important limiting factor is the space available on platforms to reach economies of scale.

Power-to-hydrogen is interesting to allow sectors that cannot be (fully) electrified to decarbonise and as one of the attractive methods to offer flexibility to the energy system. It offers added value because energy production and use can be decoupled. Furthermore, future large-scale storage of hydrogen is possible at competitive costs compared to other means of energy storage with a special feature that hydrogen storage is foreseen at very large scale in subsurface caverns or depleted gas fields (ca 0.1–10 TWh). This could offer security of demand and supply in an energy system with a high supply of intermittent sustainable electricity.

The identified advantages of implementing power-to-hydrogen offshore are:

- Offshore conversion of power-to-hydrogen can benefit from already available gas infrastructure and lowers the cost of transport. Energy transport capacity of gas infrastructure benefits from economies of scale and has better flexibility.

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[1] Global Energy Assessment, 2012, tiny.cc/32kflz

[2] Contouren van een Routekaart Waterstof, 2018, tiny.cc/84kflz

- Avoiding or delaying onshore power infrastructure extension. Onshore power grid extension with substations and power lines is known to have long lead and development timelines.
- Use of existing offshore platforms which prolongs the business case for existing infrastructure and delays decommissioning expenditures of offshore infrastructure. Space available on existing platforms is an important limiting factor.
- Space: putting the conversion and storage offshore may carry more acceptance than onshore variants; especially when scaling-up electrolysis capacity to hundreds of MW or GW scale.

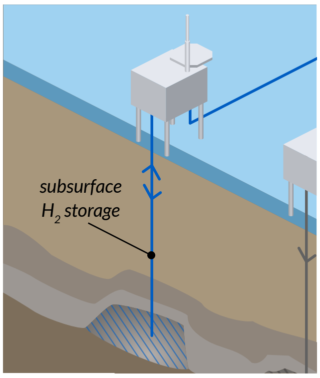
These advantages obviously need to be viewed in context with the disadvantages and trade-offs of producing hydrogen offshore (see section 2.1.2 for detailed discussions).

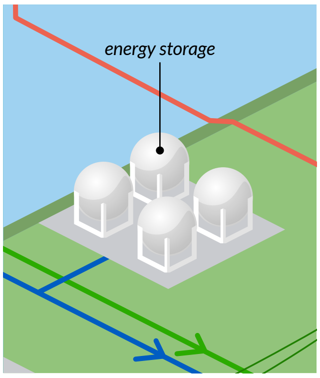
1.3.4 Power-to-x

Besides power-to-hydrogen, renewable electricity can also be converted into other gasses or liquids with existing markets and market value. In this phase of the program we investigated hydrogen to be used in the production process of ammonia and methanol (see section 2.1.2). Methanol requires CO_2 in the production process, which could be sourced from a CO_2-infrastructure. Ammonia synthesis requires nitrogen production from ambient air. The production of power-to-x on an offshore location requires a substructure, either platform or island, that will be able to offer a multitude of functionalities. Transport is then possible via pipelines, but also using ships.

1.3.5 Offshore energy islands

Offshore energy islands are currently considered as an option to enable cost-effective onshoring of large amounts of offshore wind energy. A main energy system service function considered for the islands is the conversion of alternating current (AC) to direct current (DC), which allows for transport of vast amounts of electricity to shore over longer distances. Interconnection and hydrogen production are also identified as interesting use functions of such offshore islands that could improve the business case. Typically, multiple foundation and construction types can be discerned, including: sand-, caisson- and platform-based structures. Within this phase of the North Sea Energy program, the sand-based structure was studied in more detail.

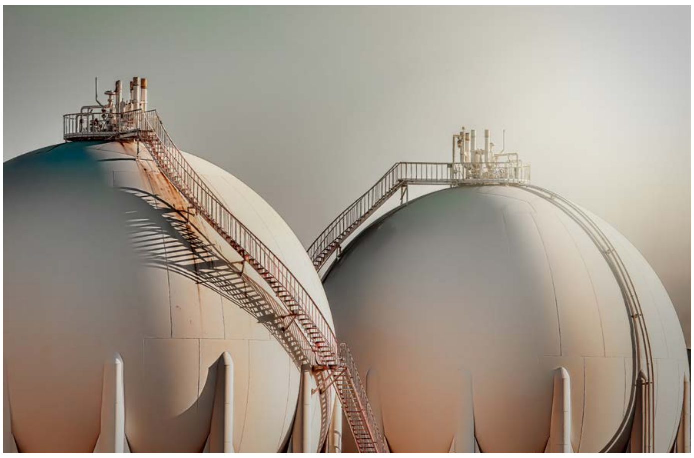




1.3.6 Energy storage

One of the possible applications to offer flexibility to the energy system is through storage. This may be done on a small scale in batteries on existing platforms, but also in the form of gas storage (hydrogen) in small tanks, caverns or gas fields. This could be placed on, or unlocked via, platforms or islands. Both batteries and integrated power-to-hydrogen solutions offer flexibility into the electrical system with their specific advantages and disadvantages. The biggest advantages of power-to-hydrogen are its potential integration into the gas system and access to the large flexibility of that system, whereas, battery storage technologies have generally higher roundtrip efficiencies.

Integrated concepts will unlock the offshore potential



1.4

Reading guide & starting points

This report summarizes the results from the most recent phase[1] of the North Sea Energy program. This includes techno-economic analyses to assess technical feasibility and the business case of system integration options (including power-to-hydrogen, power-to-x, CCS and platform electrification). From the technical perspective we assessed the feasibility of using existing hydrocarbon infrastructure for offshore hydrogen transport. For offshore production of hydrogen, we identified the hazards (HAZID) to create insights into the additional functional safety requirements of hydrogen production offshore.

In comparison to earlier phases of North Sea Energy we added power-to-x (i.e. ammonia and methanol) and offshore islands to the portfolio of technologies studied. On the topic platform electrification, we explored the merits and challenges of a coordinated offshore power grid.

A new focus in this phase is placed on offshore energy islands to better understand the business case of such solutions versus offshore platforms. Finally, for both CCS and power-to-hydrogen we have identified possible development pathways to also feed a new perspective to the North Sea Energy program: future energy system modelling of offshore system integration options (*see Exhibit 7*).

Next to techno-economics we zoom in on the regulatory aspects of offshore system integration with a focus on power-to-hydrogen and energy islands. Furthermore, mapping has been initiated of the relevant existing standards as well as the standards in preparation regarding CCS; offshore power grids; and technical, structural integrity and safety performance of offshore hydrogen.

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[1] See for other phases also https://www.north-sea-energy.eu

Exhibit 7 Energy system modelling in North Sea Energy

The techno-economic assumptions and insights gathered in studies on individual system integration technologies are also used in a national energy system model, OPERA[1], to understand energy system effects of offshore and onshore hydrogen production. The model has been applied using a modified version of an existing scenario: the National Management scenario. "In this scenario, the national government is the big coordinator and goes all out for national energy self-sufficiency via a mix of mainly centralized energy sources like offshore wind. There is a substantial need for hydrogen-based storage, given the temporal mismatch between supply and demand. Electricity-to-hydrogen conversion takes place on the coast or even offshore." CE Delft[2] . It is important to note that the selected scenario is neither the final vision nor sole development pathway considered within the program. It is an exploratory scenario using several sensitivity cases that provides insights about why, how much and under which circumstances on- and offshore hydrogen production might have a role within the Dutch energy system.

[1] Netbeheer Nederland https://etrm.nl/

[2] CE Delft, Energy scenarios for the Netherlands to 2030, https://www.cedelft.eu/en/publications/download/1675. Note that this scenario and related scenarios for the infrastructure outlook are being updated, but they were not available during the analysis period within the program.

Exhibit 8 Grey, blue and green hydrogen production options

H_2	H_2	H_2
Grey hydrogen	***Blue hydrogen***	***Green hydrogen***
Reform natural gas into CO_2 and hydrogen.	*Reform natural gas into CO_2 and hydrogen.*	*Split water into hydrogen and oxygen using electrolysis powered by renewable energy sources such as wind or solar*
CO_2 emitted in the atmosphere.	*CO_2 stored or used*	*No CO_2 emitted*

Current production of hydrogen is dominantly produced from natural gas reforming. This is so called grey hydrogen and has CO_2 emissions. Blue hydrogen is produced by reforming natural gas while capturing the CO_2 emissions from the process. This CO_2 is then available for use or storage. This results in low direct CO_2 emissions. Green hydrogen is made by splitting water in hydrogen and oxygen with the use of renewable electricity. This process has no direct CO_2 emissions.

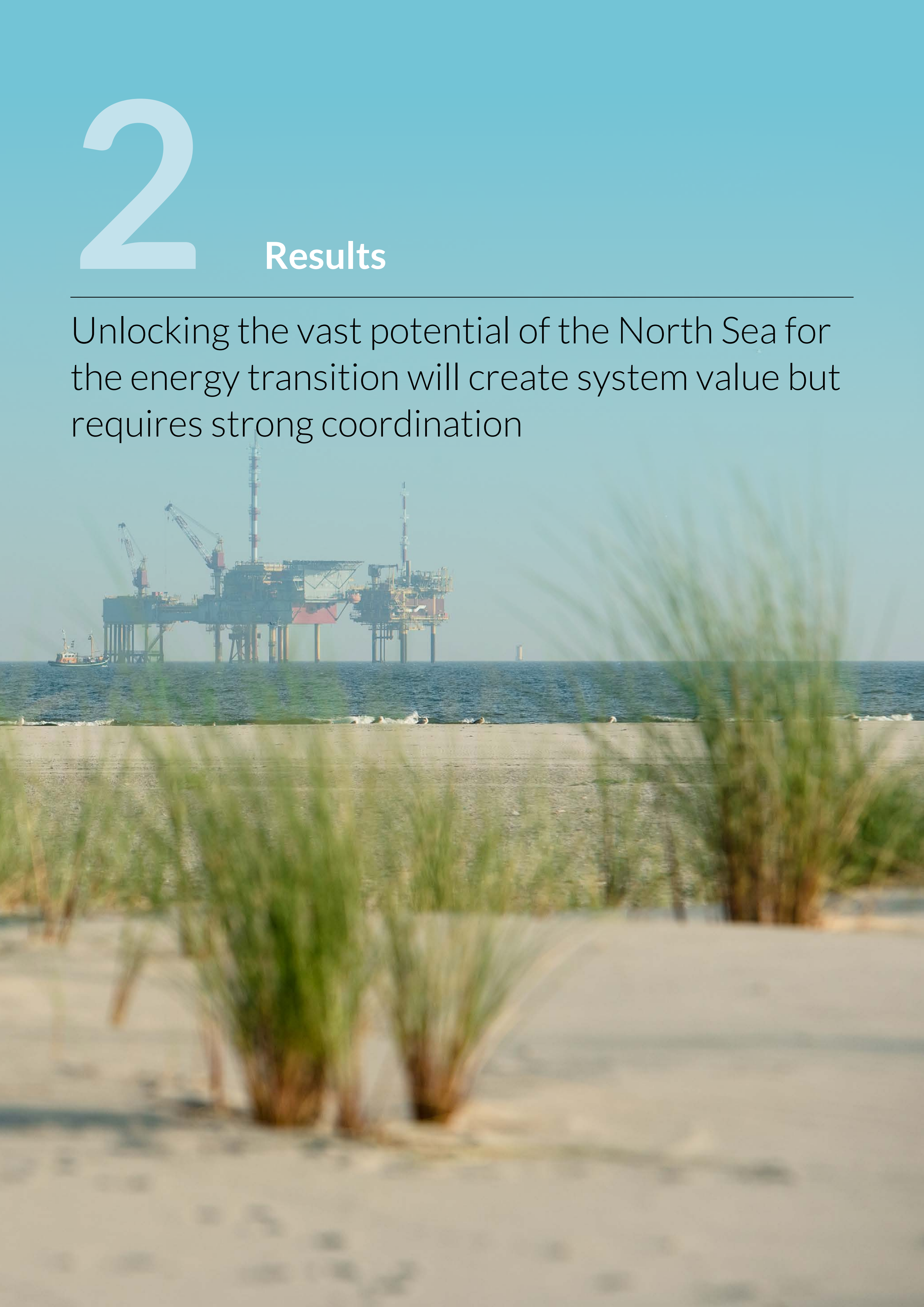
The environmental perspective on offshore system integration is enriched by performing a screening on the environmental merits and impacts of offshore energy islands; and by assessing the carbon footprint of grey, blue and green hydrogen production options. Regarding the societal perspective on offshore system integration we have performed a first screening on stakeholder perspectives related to platform electrification.

Regarding the geographical scope it is important to mention that in this phase the focus was applied on the Netherlands, although taking into account important international developments. A key action for the next phase of the program is to further expand the geographical scope of research towards the other North Sea countries.

2

Results

Unlocking the vast potential of the North Sea for the energy transition will create system value but requires strong coordination



The North Sea holds vast potential for low-carbon energy solutions

The North Sea has played an important role in the European energy system; and will play a very important role in the future. Over the last 50 years significant quantities of oil and gas has been produced on the North Sea. The energy transition offshore has taken off and over the last decades the North Sea is being used more and more for renewable energy generation. In time the production of renewable energy will dominate the offshore energy sector in Europe. Next to energy production the North Sea holds large potential for subsurface storage of CO_2 and energy. Hydrogen is also foreseen to play an important role in the North Sea region, both on- and offshore.

All in all, the North Sea is destined to become a pioneering region for the European energy transition towards a climate neutral economy by 2050. However, we found that strong coordination is needed to unlock the vast potential of the North Sea for the energy transition. Successful removal or mitigation of identified barriers will make this possible and will create optimal system value for economy, society and nature. In the following sections we summarize the research findings to highlight the vast potential, system value and the need for coordination.

2.1 Potential of main low-carbon energy options and offshore system integration

2.1.1 Offshore wind potential

Offshore wind has vast potential and is pivotal to reach Paris
The growth of offshore wind in Europe has been significant over the last years and high capacity growth is anticipated for future decades. Current installed capacity in the North Sea is 17 GW and projections for future offshore wind capacities vary between 34 - 100 GW for 2030 and up to 250 GW by 2050.[1][2] Offshore wind is a critical pillar for the Netherlands to reach the climate change mitigation targets set in the Climate Agreement. Plans are tangible for 11.5 GW in 2030; towards 2050 this could grow towards 60 GW of installed capacity. In the exploratory North Sea Energy scenario (*see Exhibit 7 for details*) offshore wind is by far the largest source of electricity from 2030 onwards *(see Exhibit 9)*.

2.1.2 Hydrogen potential

Offshore green hydrogen production and transport is technically feasible
Strongly related to offshore wind is the development of hydrogen as a key energy carrier in the energy system. From our literature review and earlier work in the North Sea Energy program we conclude that offshore production of green hydrogen and its transport to shore is technically feasible. Several components of such a system were scrutinized in this phase of the program. For pipelines the material properties have been investigated on their compatibility with different natural gas/hydrogen mixtures. The focus was placed on the influence of hydrogen on the fatigue properties of relevant steel grades and the resulting crack propagation. No showstoppers have been identified; while noting that the

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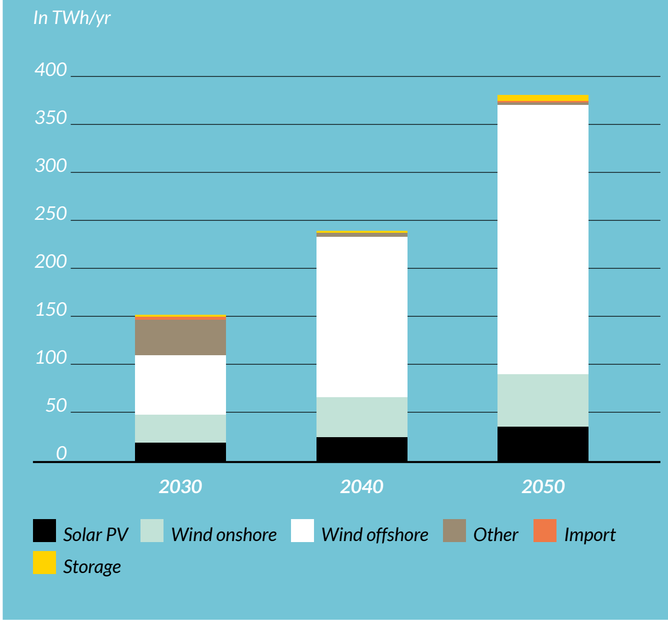
[1] WindEurope, Offshore Wind in Europe Key trends and statistics 2019, tiny.cc/kxiflz

[2] NSE1 D1.2 Review of scenarios for offshore system integration on the North Sea towards 2050 https://north-sea-energy.eu/

Exhibit 9 Electricity supply development towards 2050 in the exploratory North Sea Energy scenario



Hydrogen is one of the key components in the climate change mitigation portfolio.

state of existing infrastructure will govern the possibility to use certain assets for hydrogen transport. For case-specific conclusions this warrants detailed scrutiny of the state of the infrastructure via inspections. For compressors hydrogen admixing up to 10%voldubbele spatie?has been claimed to be acceptable in existing mechanical compressors. Engines and turbines are found to be sensitive to hydrogen additions. Finally, flow meters are found to be impacted by the presence of hydrogen in different ways depending on the measuring principle of the meter.

No showstoppers in offshore safety when transitioning towards hydrogen production on an offshore platform

A HAZID[3] and literature study were executed to provide an overview of the additional functional safety of hydrogen production offshore in comparison to hydrocarbon production. No major show stoppers for hydrogen production offshore were found regarding safety. Furthermore, a literature study identified suitable sensors for the detection of hydrogen gas and hydrogen flames.

Offshore green hydrogen production increasingly prominent towards 2050

Economic assessments in this study included various concepts for both on- and offshore production of green hydrogen: on legacy and new platforms; and on energy islands at different scales. The analyses further included different variants relating to distance, share of offshore wind energy converted, timing and market price parameters.

From a project perspective it was found that offshore hydrogen production is not of economic interest until 2030. This changes significantly post-2030 and even more towards 2050. In that period also offshore hydrogen production on energy islands is advantageous over onshore production under the condition that certain economies of scale can be reached, offshore hydrogen production costs do not escalate and that distance to shore is such that offshore transport of hydrogen significantly outperforms offshore transport of electrons *(see Exhibit 10)*.

In our exploratory energy system scenario green hydrogen production offshore is the most dominant (37%) hydrogen producing option in 2050, although transmission of offshore wind energy as electricity will remain dominant. For the cases where offshore hydrogen production appears, production values range from 16 – 80 TWh/yr. Also, in various sensitivity analyses the offshore green hydrogen production remains viable. However, the results across the analyses in North Sea Energy show to be highly sensitive to assumptions on the

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[3] HAZID = Hazard Identification Study

Exhibit 10 Green hydrogen production: offshore platforms, offshore islands or onshore?

At the current prices for green hydrogen and without the investors in conversion capacity being reimbursed for possible savings on electricity grid investment - there is not much evidence that use of existing platforms for conversion purposes will be an economically interesting option until 2030. It is likely that the installation and maintenance of electrolysers systems offshore will lead to higher costs than if those would have been installed onshore. These results have been found both for the case in which pure hydrogen would be transported to shore, as well as for the cases in which the hydrogen would be admixed and subsequently separated again from natural gas.

For the period 2030-2050, use of existing platforms for conversion purposes show opportunities for a positive business case (excluding admixing options). Especially platforms located further offshore (e.g. >120km) could be interesting locations for offshore hydrogen production. This distance is typically lower when cost for hydrogen production reduces and the cost ratio of offshore vs. onshore hydrogen production is below 1.5.

For the energy island concepts, we investigated three main variants with 2, 5 and 20 GW of offshore wind capacity connected. For these variants we analysed what the Net Present Value (NPV) would be when bringing wind energy to shore as electrons and hydrogen. We assumed that either 30% or 70% of the electricity collected at the island is converted to hydrogen. A reference scenario with 100% electricity transport to shore is used to benchmark the outcomes.

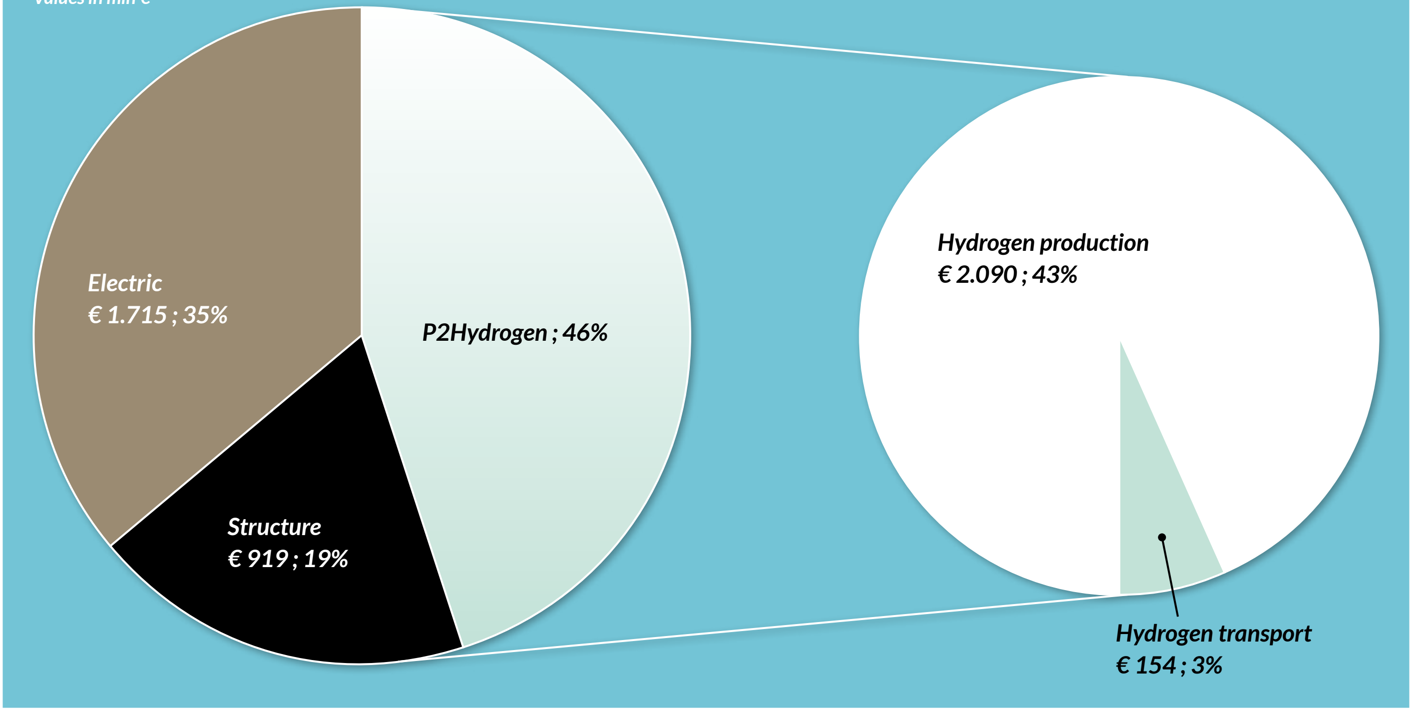
The reference scenarios with 100% electron transport show the best NPV for all island variants. However, under the assumption that green hydrogen has a significant role to play in our future energy system the NPV results indicate a small preference for offshore production of hydrogen on energy islands over onshore production. In general, we observed that the major cost trends are favourable for the mid-sized island scenarios (2, 5 GW of connected wind capacity), which is in accordance with studies of the North Sea Wind Power Hub.[1]

As seen in the graph below the hydrogen production facility is the important driver for the total cost of the energy island. The CAPEX of island construction is relatively minor compared to the costs of electrolysers.

[1] https://northseawindpowerhub.eu/

CAPEX distribution of the island variant with 5 GW wind connected and 30% hydrogen conversion

Values in mln €



difference between offshore and onshore costs of installing and operating hydrogen production facilities.

With a share of 29%, onshore green hydrogen production is somewhat smaller in comparison to offshore hydrogen production; values ranging from 21 – 83 TWh/yr in 2050. Blue hydrogen is with 23 – 44 TWh/yr also a stable hydrogen supply option for feedstocks. Its role is mainly limited by the caps on natural gas import and CCS that have been applied in the scenario study.

The most important applications of hydrogen are expected to be in the transport, built environment and industry sectors. Feedstock applications, in particular the fertilizer industry and the production of synthetic fuels, present a significant share of the demand. The admixing of hydrogen in the natural gas grid is not expected to have a substantial role in 2050, this is likely related to the extreme greenhouse gas emission reductions targeted in the exploratory scenario. If an international hydrogen market is developed, the Netherlands will import and export hydrogen as well, but this will depend very much on the market price.

Offshore methanol and ammonia production as added value for green hydrogen production

Produced hydrogen could be further converted into other gasses or liquids. A broad qualitative screening is conducted to select the power-to-x technologies that show a high potential for offshore and onshore application, based on the following criteria: Storage potential, Efficiency, Technology readiness & scalability, Health, safety and environmental aspects, Offshore applicability and Market potential. This brought forward power-to-ammonia and power-to-methanol as interesting options. For the latter the sourcing of CO_2 is very important. This could be delivered through a CO_2-infrastructure.

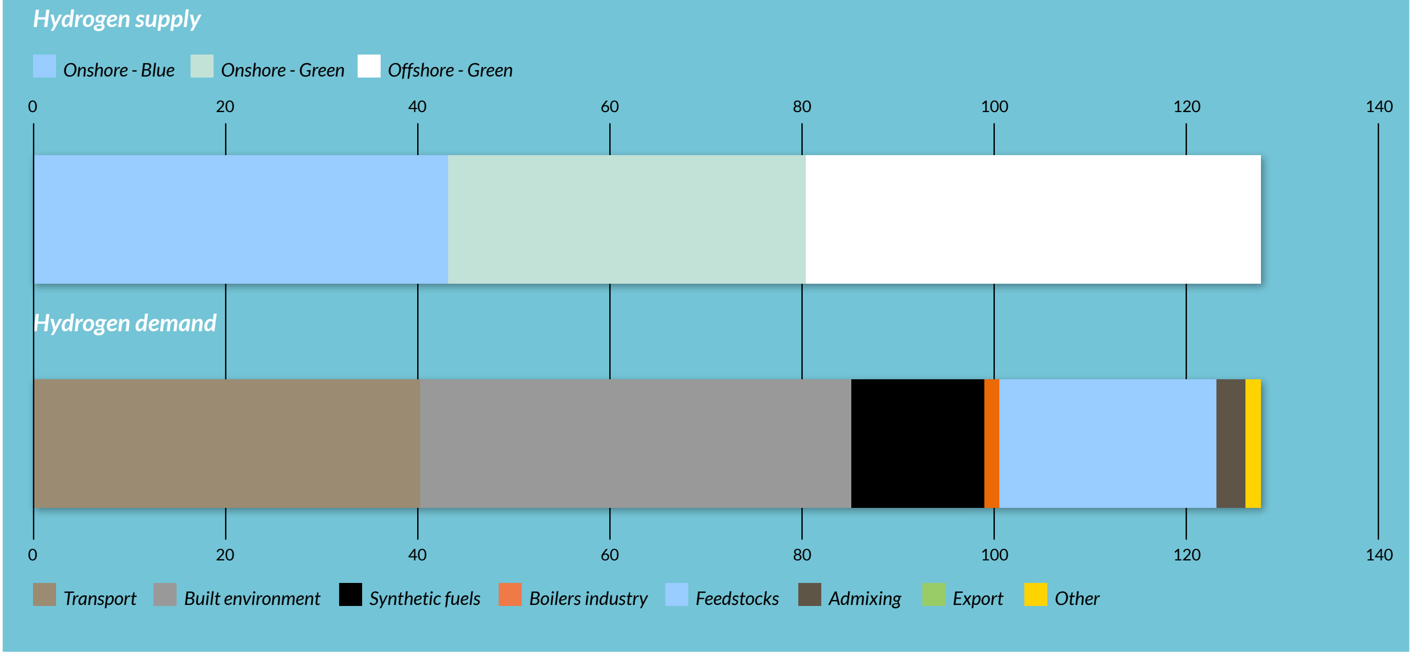
Based on the current cost figures and prices for the energy carriers we see little promise for a positive business case for both the onshore and offshore methanol and ammonia production. A value needs to be added for green versions of these products to support a sustainable business case, for example though a higher market value in some offshore niche markets (e.g. offshore bunkering and shipping) or with policies and measures.

Synergy possible between blue and green hydrogen to further improve carbon footprint

We compared the carbon footprint of grey, blue and green hydrogen production options – for both onshore as offshore locations. A carbon footprint is determined for hydrogen production by on- and offshore electrolysis, by natural gas reforming via steam methane reforming (SMR) and

Exhibit 11 Hydrogen supply and demand in 2050 in the exploratory North Sea Energy scenario.

In TWh/yr



autothermal reforming (ATR) onshore. For SMR and ATR options with and without carbon capture and storage were included. In the analysis, renewable electricity from offshore wind was assumed for electrolysis whereas electricity from the Dutch grid for SMR and ATR.

In line with literature we find higher footprints for SMR and ATR, either with or without CCS, than for electrolysis using electricity from offshore wind. Electrolysis carbon footprints are about 0.01 kg CO_2eq/MJ hydrogen. SMR without CCS shows a carbon footprint of 0.09 kg CO_2eq/MJ. The footprint for ATR with CCS, if being also fed with green electricity[4], could be brought on par with that of onshore electrolysis. The primary energy source is especially very influential for carbon footprints. This has two consequences: on the one hand, almost all carbon footprints (not related to natural gas) can be expected to decrease in time if electricity mixes become less carbon intensive. This also indicates that electrolysis is not per definition the 'greener' technology. If instead of renewable electricity, the average national mix is used as electricity source, electrolysis can have a higher carbon footprint than natural gas based production routes.

Based on the carbon footprint, onshore production of hydrogen seems preferable. In general, differences are small, but the proximity to consumers of the by-products from electrolysis, heat and oxygen, seems beneficial. Synergy between blue and green hydrogen also became apparent as electricity use for oxygen provision was an important contributor to the carbon footprint of ATR, which could be lowered if oxygen is available from electrolysis.

Large hydrogen storage capacity exists; offshore options need to be explored further

Exhibit 12 shows the map of offshore subsurface storage potential of hydrogen related to offshore hydrocarbon reservoirs in the Netherlands. A recent study by EBN and TNO has indicated that the offshore hydrocarbon reservoirs could offer 60 billion m^3 of working volume equalling 179 TWh of hydrogen.[5] The challenge for the near future is to further screen and assess the individual suitability and opportunity for storing hydrogen offshore. And assessing the storage option (i.e. above ground in tanks, subsurface in reservoirs or caverns) that provide a balanced fit with the needs of the energy system, society and nature.

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[4] It is important to note that the blue hydrogen production with ATR+CCS requires significant electricity demand to produce oxygen as part of the process.

[5] Juez-Larré et al., Assesment of underground energy storage potential to support the the energy transition in the Netherlands, 2019, tiny.cc/kxiflz

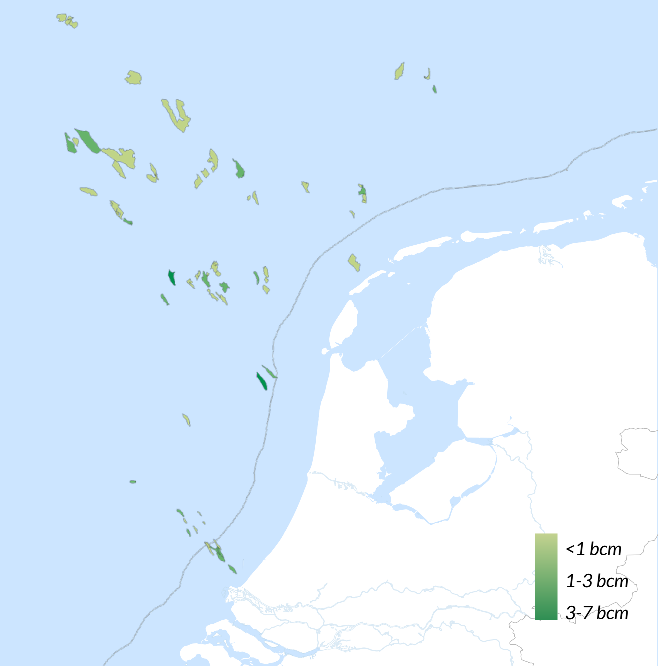


Exhibit 12 Offshore subsurface storage potential for hydrogen in hydrocarbon reservoirs

2.1.3 Carbon capture and storage potential

Carbon capture and storage is needed to achieve lowest societal cost for the energy transition

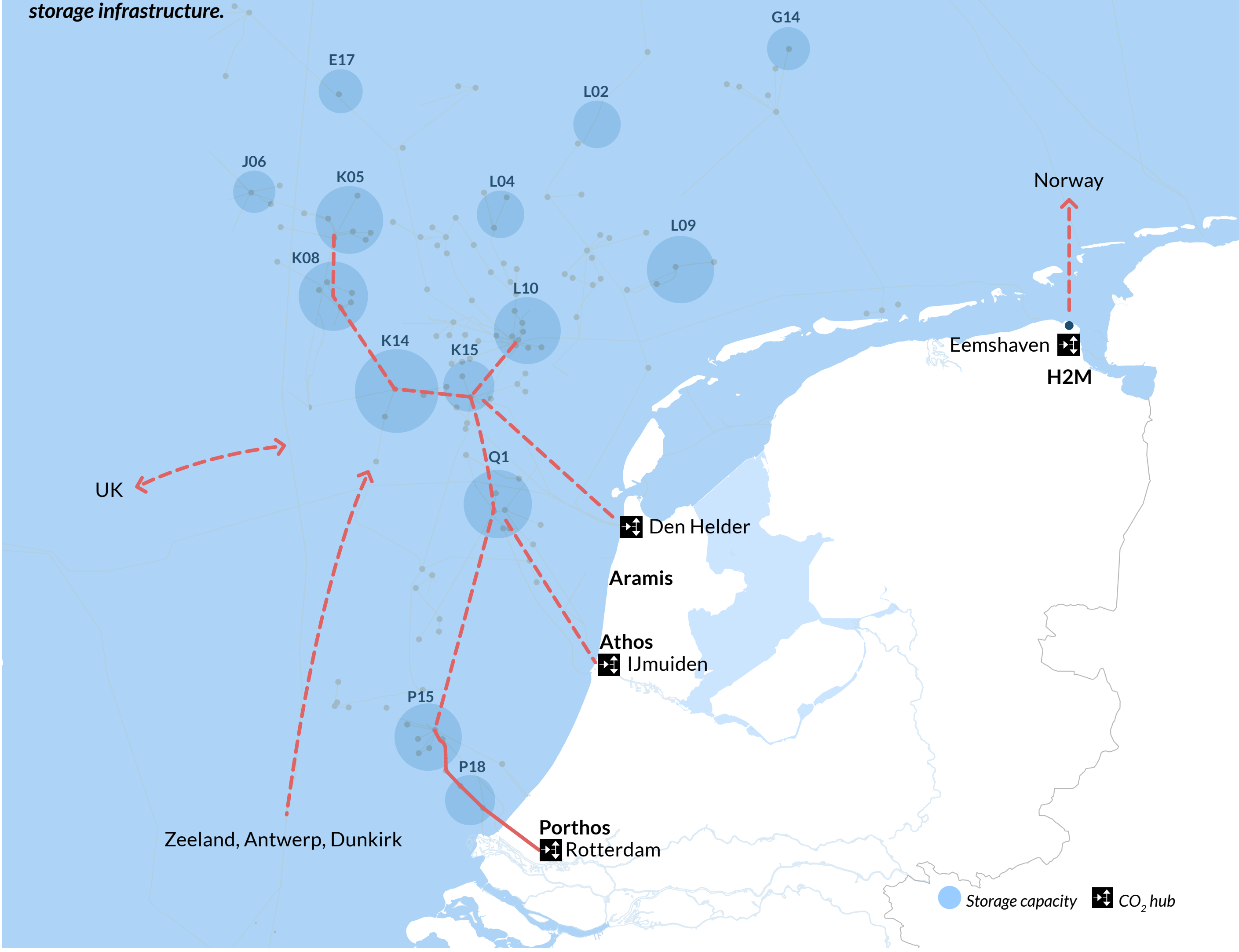
Offshore carbon capture and storage is also an important pillar in the future low-carbon energy system. The North Sea potential is vast: several tens of billion tonnes of CO_2 storage capacity in depleted hydrocarbon reservoirs and more than 100 Gt of storage capacity in saline aquifers. For the Netherlands this technical storage potential is 1.7 Gt CO_2.

Experience exists with all facets: capture, transport and storage in the Netherlands. Offshore storage is demonstrated with the Dutch K12-B project (0.02 Mt CO_2/yr), but at scale Norway is leading the way with Snøhvit (0.7 Mt CO_2/yr), and Sleipner (1 Mt CO_2/yr) storage projects.

Some important initiatives have been started in the Netherlands including Porthos, Athos, Aramis and H2M (see *Exhibit 13*). Combined these CCS initiatives in Netherlands target injection rates that sum up to 19 Mt/yr (+2/-5) in 2030 and increasing to 27Mt/yr (+6/-6) in 2050. Up to 100 PJ of blue hydrogen production in (mainly) the Rotterdam, Amsterdam and Eemshaven industrial clusters contributes 5-8Mt/yr.

In our energy system scenario, we see that in 2050 CCS is predominantly used in combination with waste-to- energy facilities, blue hydrogen production, bioenergy with CCS

Exhibit 13 Overview of carbon capture and storage initiatives in the Netherlands with indicative development of offshore transport and storage infrastructure.



(BECCS) and direct air capture (DAC). The deployment of such net atmospheric CO_2 removal options contributes to limiting global warming to 1.5°C but are prone to high uncertainty (IPCC, 2018).

The North Sea Energy modelling provides also a perspective on the challenge to reach the GHG reductions with a stringent cap on CCS towards 2050; we find energy system costs to be almost 4 billion euros per year higher than in our base scenario.

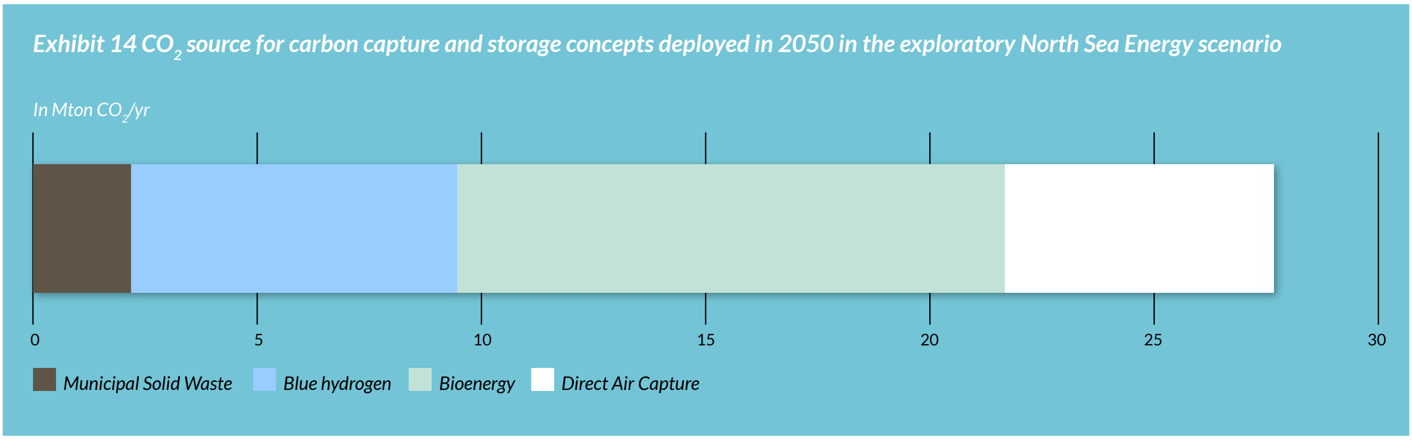
2.1.4 Platform electrification potential

Platform electrification is short term climate mitigation option with longer term value

Approximately 6% of produced natural gas offshore is consumed to operate the offshore facilities.[6] Electrification of gas platforms is a proven technology that allows for an alternative low-carbon energy source to operate the platforms and bring natural gas to shore. From technical perspective the electrification of offshore platforms could lead to savings of up to 1 megaton of CO_2 per year for the next decade. In a scenario where 10 platforms relatively close to the IJmuiden Ver offshore wind area are electrified within an offshore grid, fuel gas consumption could be reduced by 0.2 BCM (billion cubic meters) annually. By replacing the fuel gas with renewable electricity, an annual CO_2 reduction of up to 0.5 Mt could be realised. The business case for platform electrification is known to be very case specific, but results indicate a CO_2 price incentive with a ballpark range of 75 -100 €/ton CO_2 could under specific circumstances be sufficient to support a business case[7].

For the longer term, an electrified production platform could also serve a strategic purpose within the energy transition. Some of these assets can be a stepping stone for more offshore system integration as combining system integration options. The most likely options being CCS and hosting power-to-x (e.g. hydrogen) conversion and/or as compression hub function for offshore produced hydrogen. For cases studied in the North Sea Energy program the business case for developing towards a CO_2 transport and storage hub were preferential over hosting power-to-x options in case of platforms.[7]

Exhibit 14 CO_2 source for carbon capture and storage concepts deployed in 2050 in the exploratory North Sea Energy scenario



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[6] NLOG, 2018 data, https://www.nlog.nl/selectiescherm-productie

[7] See for more details https://north-sea-energy.eu/

2.2

System value of offshore system integration

We need a portfolio of climate mitigation options to achieve an affordable energy transition

Offshore energy solutions and sector integration helps building a portfolio of climate mitigation options to achieve an affordable energy transition. According to the IPCC summary report 'pathways limiting global warming to 1.5°C require a wide portfolio of mitigation options and a significant upscaling of investments in those options'. The potential for low-carbon energy solutions offshore is proven to be large and could support a low-carbon future. With energy system modelling we have further assessed that it is very valuable to have a portfolio of options to keep the energy transition affordable. Modelling results suggest that offshore hydrogen helps to keep the total energy system affordable. Excluding solutions most often comes at a cost for society at the system level. In the Netherlands for example excluding or limiting the offshore wind option would incur much higher overall energy system costs towards 2050. Restricting CCS would incur system costs increasing with billions per year in 2050.

System value of offshore system integration reduce costs, time, emissions, space and capital

To unlock the value of the low-carbon energy potential it is needed to look and act across the borders of individual and existing sectors. Grasping the value requires integrated system thinking rather than sectoral optimization. Also sectors of the future should be included. In this way important resources can be saved and the value of the North Sea for many stakeholders could be enhanced: most relevant for the North Sea energy transition are time, space, emissions, and economics.

A good example is that offshore conversion of wind energy to hydrogen (or other energy carrier) and transport to shore could help keeping the cost down of the energy transition at the system level. As it could (partially) use existing infrastructure for production and transport also timelines for deployment could be shortened; i.e. offshore and onshore power grid extension with substations and power lines is known to have long lead and development times with several years to even more than a decade.[1]

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[1] Kamerbrief over gevolgen van het gebrek aan netcapaciteit voor duurzame elektriciteitsprojecten, 2019, tiny.cc/wcjflz

IPCC summary for policy makers on portfolio of mitigation options [1]

"Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (medium confidence)."

[1] Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C, 2018, p 17, tiny.cc/jqjflz

Most relevant for the North Sea energy transition are time, space, emissions, and economics.

Timing is also of the essence when deploying tens of GWs of offshore wind and perhaps other renewable energy sources over the next decades. A flexible and stable energy system is preferential for stakeholders across value chains in all offshore energy sectors. System integration offers flexibility to the energy system and results in more stable and better market conditions for variable renewable energy sources. This could prevent 'stop-and-go' investment cycles straining the offshore energy value chains; and delaying the energy transition.

Space is a critical element in the energy transition; both on- and offshore. As introduced in section 1.1, space is limited offshore. Synergies between sectors and countries often occur when physically coupling infrastructures. This sets that multiple functions of the energy system are to be spatially connected and could be spatially combined in an area. By combining various uses of the North Sea, the competition for space may be alleviated, which improves the balance between energy production, food production and ecological value. Other direct reduction of spatial claims may come from more efficient use of resources. A more flexible energy system helps to reduce curtailment[2] from variable renewable energy sources.[3] As curtailment is reduced, in theory also less installed capacity is required to meet the same energy needs; as there is lower loss of energy production. This in turn could reduce the spatial claims for offshore renewable energy.

Next to preferential economics the availability of space is also foreseen to become a decisive factor when developing both on- and offshore hydrogen production. Allowing offshore hydrogen production from offshore wind energy would in principle reduce the spatial claim onshore for electrolyser capacity; or in a full-electric scenario the footprint of high voltage stations and power lines. This should also be brought into perspective by comparing the even lower spatial footprint of blue hydrogen production.

All in all, we have found evidence that the portfolio of low-carbon energy solutions offshore in synergy support a fast low-carbon energy transition while balancing energy system costs and spatial impact of the transition (on- and offshore).

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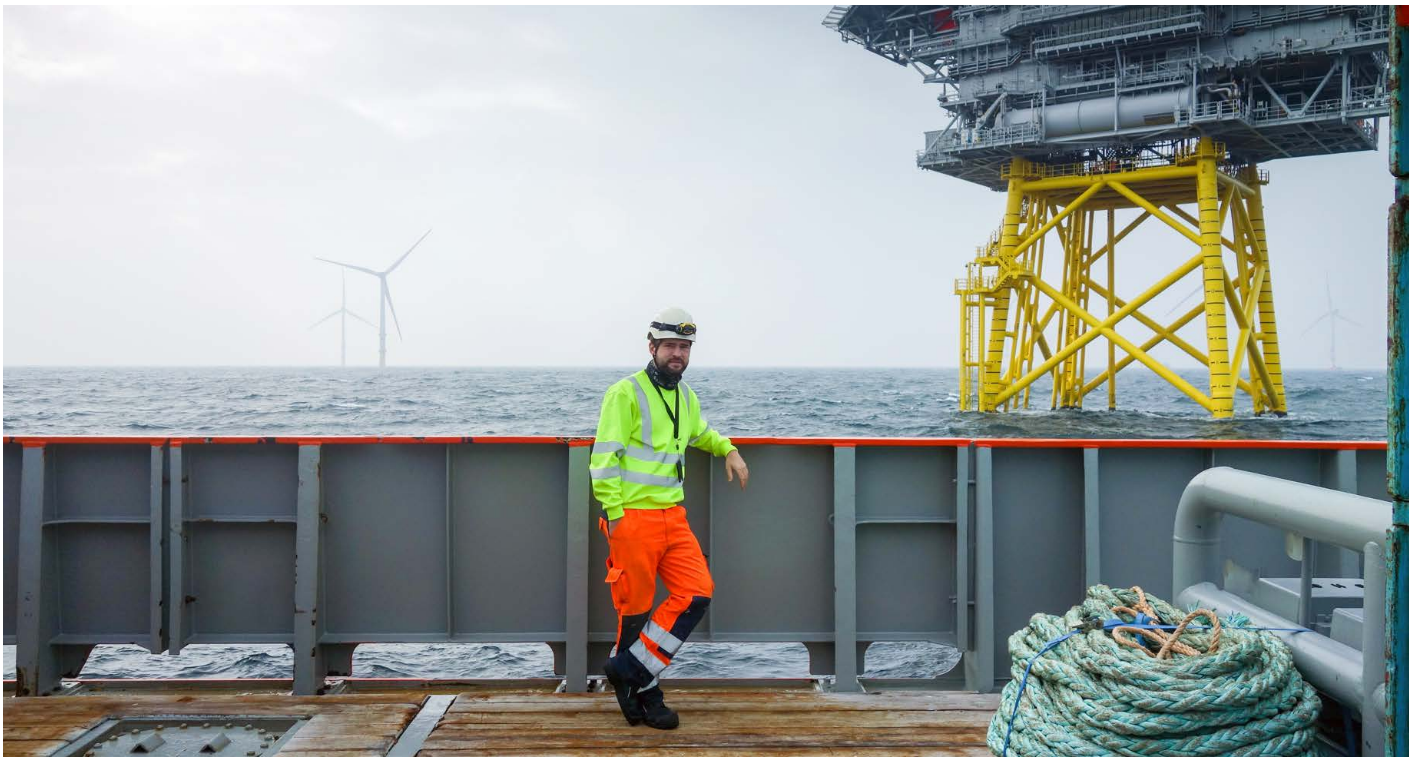
[2] 'Some or all of the turbines within a wind farm may need to be shut down to mitigate issues associated with turbine loading, export to the grid, or certain planning conditions.' https://www.wind-energy-the-facts.org/curtailments-7.html

[3] See also ESTMAP Public Project Summary www.estmap.eu



2.3

The need for coordination & collaboration

Coordination is prerequisite for designing an inclusive North Sea energy system balancing merits for ecology, economy and society

An important perspective has surfaced when assessing the portfolio of low-carbon energy solutions offshore. It has become apparent that on a system level there is much to gain from deploying the individual technologies and by combining them in an integrated system. We have found evidence for short- and longer-term CO_2 emission reduction, cost reductions on system level and for possible relief of the spatial claim for the energy transition. On the other hand, there are barriers that restrain market players from fast-tracking system integration options on the North Sea. Below we highlight key barriers/challenges to implementation and provide recommendations to remove or mitigate these. The central recommendation is that coordination is quintessential for offshore system integration to work and to provide value for economy, ecology and society.

Current market failures hamper implementation of offshore system integration projects

There is one aspect that all offshore system integration options have in common: project initiators are struggling with building a sound business case to spur investments and get projects off the ground. This is what in economy is called a market failure. Ideally, investors or individuals allocate resources to options and pathways that would be most efficient or optimal from their and from societal point of view. Markets are not always designed and functioning for this outcome to materialise. This results in that technologies that are optimal from a broader societal perspective will not come off the ground because these investment decisions are based on project/plant-level business cases only. This leads to the fact that system integration options will not or too slowly become economically attractive to make the desired optimal contribution to the energy transition.

The most important market failures are:

- Investors do not include several relevant aspects from an overall socio-economic perspective (system costs/benefits, externalities, and macro-economic and geo-political impacts) into the value analysis, whereas such aspects would have had a positive impact on investment if included;
- Investors facing the traditional 'valley-of-death' in the evolution of a new technology, are not prepared individually to take all the risk of being the first-mover, among others because they fear by doing so to benefit competitors;
- Investors are afraid to invest in innovations of which they have insufficiently clear perspectives on their future prices and demand in the absence of a sufficiently developed market.

For the specific situation of the North Sea offshore energy system, without a serious and balanced set of policies and measures, offshore system integration will not come off the ground, much later off the ground, or will develop in a way that is suboptimal from the societal value perspective.

Progressing offshore hydrogen requires actions on regulatory framework

Earlier research already identified that the regulatory framework poses important challenges regarding the feasibility and development timelines for offshore system integration. The key challenges identified are:

1. The regulatory frameworks provide insufficient guidance on re-use of offshore gas infrastructure.
2. The current legal framework blocks offshore system integration as a fundamental revision of the wind energy at sea act would be necessary to connect offshore platforms to the offshore electricity network.
3. The current legal framework for electricity and gas provides no clear guidance on the market regimes for new infrastructure connections for system integration.

In this phase of the program we explored the existing regulatory challenges concerning the development of power-to-hydrogen offshore, and made recommendations on which legal changes are necessary to (i) overcome these legal challenges, and to (ii) stimulate the planning, production, transport and supply of green hydrogen offshore.

The analysis demonstrates that none of the analysed national regulatory regimes (the Netherlands, United Kingdom and Denmark) provide the legal certainty necessary to sufficiently support the conversion of wind energy to hydrogen at sea. This conclusion can be made for three reasons: first, it is questionable whether it is legally permissible to establish a connection between any part of the offshore electricity infrastructure and an existing offshore hydrocarbon platform; secondly, there is no specific authorisation procedure in place regulating the construction and operation of an electrolyser on an existing offshore hydrocarbon platform; finally, strict blending concentrations of hydrogen in the existing natural gas networks have been imposed at the national level.
The North Sea is increasingly characterised by new energy

uses, which require the deployment of a wide range of installations. Currently, legislation in place governs offshore hydrocarbon installations and offshore wind farms. However, it is difficult to ascertain which rules apply to power-to-hydrogen installations.

This shows that existing, related legal frameworks must be adapted to be made applicable to power-to-hydrogen. The recommendations are summarised in *Exhibit 15*. Given the challenges at hand it is advised that policy makers, stakeholders and researchers engage in further dialogue on the future regulatory framework governing the planning, production, transport and supply of hydrogen.

Establishing public awareness and effective stakeholder engagement will be central in a strategy towards offshore system integration on the North Sea

The energy transition is a social transition; possibly even more than merely a technical or economic transition. Understanding stakeholder awareness and perception provides the building blocks for effective stakeholder engagement strategies and thus contribute to societal embeddedness of offshore system integration technologies. In this phase of the program we have identified stakeholder perspectives related to platform electrification. Although more research is needed to come to definitive conclusions we have identified a methodology to map arguments that stakeholders use in favour or against platform electrification; and to which extent stakeholders agree and disagree on topics such as 1) Economic, 2) Technical, 3) Policy and regulations, 4) Communication and Stakeholder engagement, 5) System integration, and 6) Environment and nature. This also helps with the identification of possible

Exhibit 15 Recommendations on the national and European regulatory framework governing the planning, production, transport and supply of hydrogen.

National legislation

- Need for coordinated maritime spatial planning of the North Sea ensuring that cross-country synergies are not lost.
- Need to remove legal barriers to connect existing offshore hydrocarbon platforms to any part of the offshore electricity infrastructure. Consider to introduce a definition or separate legal regime governing the electricity cables establishing such connections.
- Necessity to clarify what rules that apply to the construction and operation of an electrolyser on an existing offshore hydrocarbon platform. Need to consider sector-specific legislation governing the authorisation procedure of power-to-gas or to provide guidelines clarifying the applicablility of existing licences and/or permits to the development and operation of power-to-gas facilities offshore.
- Need to remove legal barriers to the injection of hydrogen into the existing natural gas system. Consider to adapt admixture limitations of hydrogen in secondary legislation to concentrations that are proven to be technically feasible and safe.

↔

European legislation

- Necessity to clarify the interplay between the electricity- and gas legislation with regard to definitions and ownership regimes for power-to-gas.
- Need to harmonise gas quality standards specifying admissible levels of green gases in the natural gas system, including admixture levels of hydrogen.
- Need to ensure that green hydrogen receives the necessary support to be successfully integrated into the energy sector: (i) include power-to-gas in guidelines on governmental support (ii) clarify the applicability of guarantees of origin to converted energy, and (iii) harmonise rules on network tariffs for energy storage in the electricity system.
- Need to clarify the application of environmental and safety law to power-to-gas.

concerns that stakeholders have with deploying system integration options. A key result and recommendation is that stakeholder awareness of offshore system integration, in this case platform electrification, is rather limited and needs to be improved. Also, the technologies and concepts for which stakeholder perspectives are assessed should be broadened.

An inclusive approach is then required as next step to come to an effective and fair strategy to deploy low-carbon energy solutions on the North Sea. Practically this suggests engaging stakeholders in the establishment of a long-term roadmap, joint fact-finding activities, scoping of research and requesting feedback on Research, Development and Innovation (RD&I) results.

Inclusive and integrated design of North Sea energy system is needed balancing merits and challenges for ecology and environment

Next to techno-economic evaluations and public engagement research the North Sea Energy program also includes the ecology and environment perspective on offshore system integration. We combine methodologies of life cycle perspective and location-based (strategic) environmental assessment to better understand the merits and challenges of offshore system integration.

Exhibit 16 Legal assessment energy islands

A legal assessment of a sand-based energy island under Dutch jurisdiction shows that the current situation leaves a tremendous lack of clarity for those seeking to develop a functioning energy island.

Exemplary is the absence of an adequate definition of a sand-based energy island being an 'artificial island, installation or structure'. This is very relevant as international law (UNCLOS) omits 'artificial islands' from an obligation to be removed once abandoned or disused.[1] Another barrier could be a 10-year limit for certain permits under the terms of the Water Act. Forthcoming policy framework for artificial islands thus should provide some sector-specific legislation or provisions related to energy islands to improve clarity.

[1] Article 60 (3) UNCLOS tiny.cc/xtjflz

This phase of the program has added a quick-scan of environmental challenges and benefits for energy islands. The construction and operation of an island in the North Sea is expected to have several negative environmental impacts. But at the same time, an island on the North Sea could have benefits. Ecological values could benefit, when the island is designed well. The determination of the ecological and environmental effects of offshore energy islands is not straightforward, which results in a delicate balance between positive and negative effects. We foresee that successful implementation of offshore energy islands may only work if we find a way for nature-inclusive design and valorising the benefits for ecology. Costs are mostly quite comprehensible/ easy to determine, but how to assess the value of the benefits?

Coordination is essential for roll-out of new energy infrastructure and fostering strategic legacy infrastructure

Strong coordination from a central authority or group of authorities on both the national as international level would help capturing the value that we described in the previous sections on system level. A good example is the electrification of platforms. A coordinated and cross sectoral power grid offshore will enable cost and emission saving and will support future innovations for deep climate change mitigation. In this phase of the program we explored the value of a shared offshore power grid for a larger number of platforms in three scenarios: 'Electrification', 'CO_2-storage' and 'Electrification +

CO_2-storage'. These scenarios vary in the number of platforms connected (6 to 13) and the system integration option(s) implemented at the platform (platform electrification and/or CO_2 storage). The joint developments and coordinated roll-out results in all scenarios in a reduction of cable investment costs; per platform these are 54-66% lower for a power grid compared to individual connections to the platform. This leads to an investment cost reduction of 21-26 million euro per platform. However, negative effects due to increased complexity of an offshore power grid should be considered. With an increasing number of platform operators the complexity of the cooperation will increase.

The complexity of above-mentioned coordination is that careful planning would take into account offshore wind capacity coming online, gas production horizons and transport needs for offshore assets, time lag between reservoirs coming available for storage and CO_2 infrastructure roll-out. All factors mentioned, and more, are also subject to uncertainty and sometimes confidentiality, making it even harder to find optimal coordinated solutions.

A second example, and much related, is the coordination of a transport and storage plan for CO_2. Currently, there is no orchestrated roadmap on carbon capture and storage. Instead we see rather separated commercial development projects being initiated in the Netherlands. In countries around us, notably in the UK, Norway and Ireland, similar development projects are underway. A longer-term vision on the development of transport and storage infrastructure should be developed that aligns and integrates ongoing commercial CCS initiatives in the Netherlands and the wider North Sea region. Such an "international CCS infrastructure outlook" should explore (and exploit) synergies to reduce total system cost.

A third example would be a hydrogen infrastructure outlook across the North Sea area. This should include spatially explicit deployment pathway(s) for on- and offshore hydrogen infrastructure. For key infrastructure components this should map likely production locations, onshore and offshore pipelines (existing and new), hydrogen shipping, storage (surface and subsurface), and demand centres with anticipated developments.

Establishing coordination per topic/technology on a shared offshore power grid, a CCS infrastructure outlook and a hydrogen infrastructure outlook is already a considerable task. The key challenge to unlock the full potential of the low-carbon energy options is to bring those actions together on national and international level and work towards an integrated approach, for example a North Sea Energy Infrastructure Outlook.

Exhibit 17 Artist impression of an offshore energy island *(source Bilfinger Tebodin)*

2.4

Conclusions and outlook

Unlocking the vast potential of the North Sea for the energy transition will create system value but requires strong coordination

The North Sea area is destined to become a pioneering region for the European energy transition towards a climate neutral economy by 2050. In the North Sea Energy program, a consortium of a large number of partners strives towards making this reality.

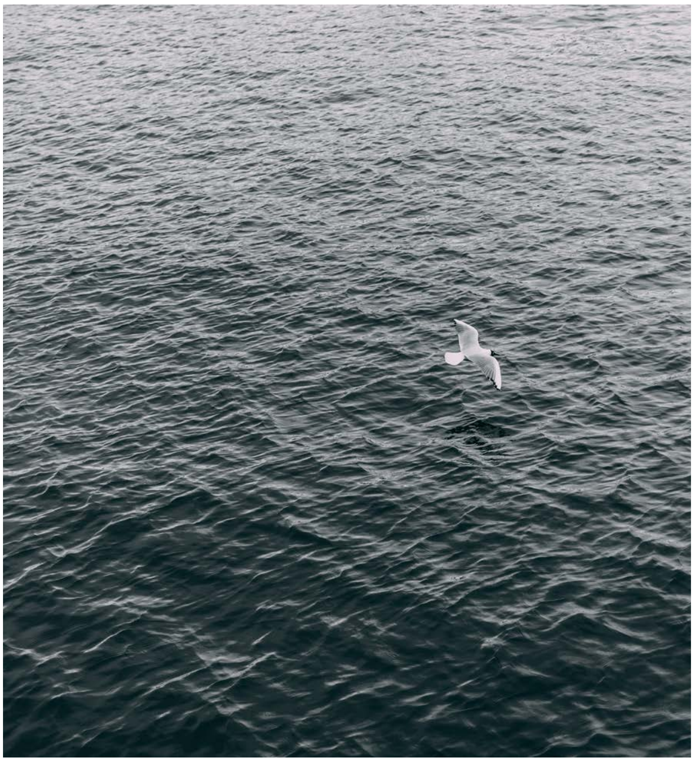
The findings of this phase of the program prove that the North Sea holds vast potential to deploy low-carbon energy solutions towards 2050, including: offshore wind, carbon capture and storage, offshore hydrogen production transport and storage, energy islands and energy storage.

Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO_2 emissions, use space more efficiently, enable & accelerate the energy transition and reduce cost for society. And the results show that we need a portfolio of climate mitigation options to achieve an affordable energy transition. Excluding options from the portfolio increases the cost of the energy transition significantly; up to billions per year in 2050 depending on the choices made. Unlocking low-carbon energy potential of the North Sea thus requires integrated system thinking rather than merely sectoral optimization.

To unlock the potential and value on energy system level strong coordination and collaboration are essential. We identified that successful removal or mitigation of some key barriers is needed, including current market failures and regulatory challenges. The Netherlands share the North Sea with neighbouring countries and it is therefore also required to align on national and international level to plan and facilitate the roll-out of new energy infrastructure while fostering strategic legacy infrastructure. The recently concluded Dutch North Sea agreement provides a logical starting point for such coordination and collaboration. On an international level the Political Declaration of North Seas Countries Energy Cooperation provides a basis for further actions.

On the North Sea we need to find a delicate balance between different use functions. Nature and food production, and its stakeholders, are important pillars next to the energy transition. The road ahead requires designing and adopting an inclusive stakeholder engagement approach and nature-inclusive design strategies to come to an effective and fair energy transition strategy. Such inclusive and integrated design of the energy system in the North Sea area allows then the balancing of merits for ecology, economy and society as well as their boundary conditions.

> The North Sea area is destined to become a pioneering region for the European energy transition.



Outlook: fast track from idea to commercial projects

The coming decade is critical for laying the foundation for the future energy system on and around the North Sea. For some concepts, positive business cases are possible on the short term (e.g. platform electrification and CCS), but this requires clear and sustainable market signals. For other concepts, such as offshore power-to-hydrogen, power-to-x and hydrogen production on energy islands, a favorable business case most likely appears post-2030. To arrive at commercial projects in time these technologies and concepts need to be tested and demonstrated. The coming decade is thus pivotal for deploying first full-scale or pre-commercial projects and demonstrate concepts with business cases beyond 2030.

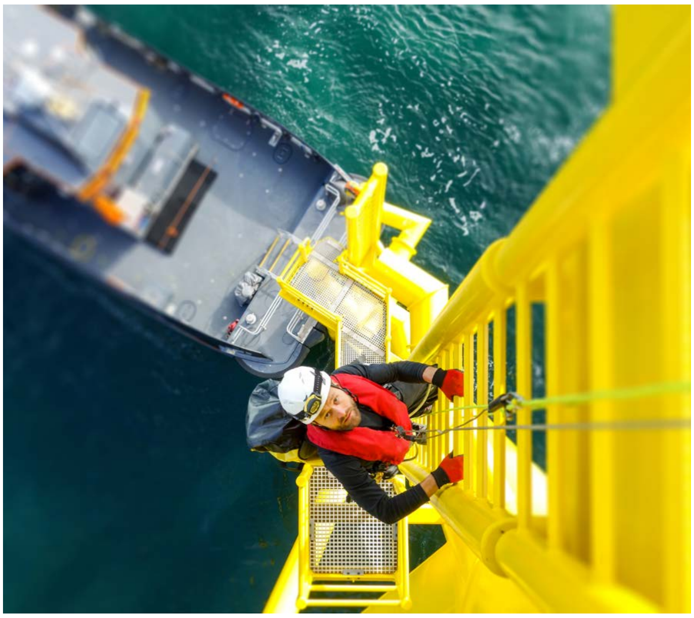
In the next phase (2020-2021) of the North Sea Energy program therefore a focus will be placed on the identification of North Sea Energy Hubs where system integration projects could be materialized and further developed. This includes system integration technologies strategically connecting infrastructures and services of electricity, hydrogen, natural gas and CO_2. A fit-for-purpose strategy plan per hub and short-term development plan will be needed to fast-track system integration projects, such as: offshore hydrogen production, platform electrification, CO_2 transport and storage and energy storage.

We will develop a roadmap for offshore system integration at the North Sea towards 2050. This will integrate the multidisciplinary results generated in all phases of the North Sea Energy program. It will include practical timelines to develop system integration projects over time and assess whether synchronization of investment agendas in infrastructure developments or transformation yields barriers that need to be resolved.

We will strive towards co-creation of knowledge and collaborative development of future action pathways to deliver concrete system integration projects/pilots and demonstrations as a spin-off from the next phase of the program.

In the North Sea Energy program we will transfer knowledge in the national and international domain. International synergy is very important for offshore system integration opportunities. Therefore international expansion of the program and coupling with offshore system integration initiatives outside the Netherlands is a key target for the next phase of the program.

We will develop transition pathways for offshore system integration at the North Sea towards 2050.



For access to publications and background information please visit: https://north-sea-energy.eu/

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