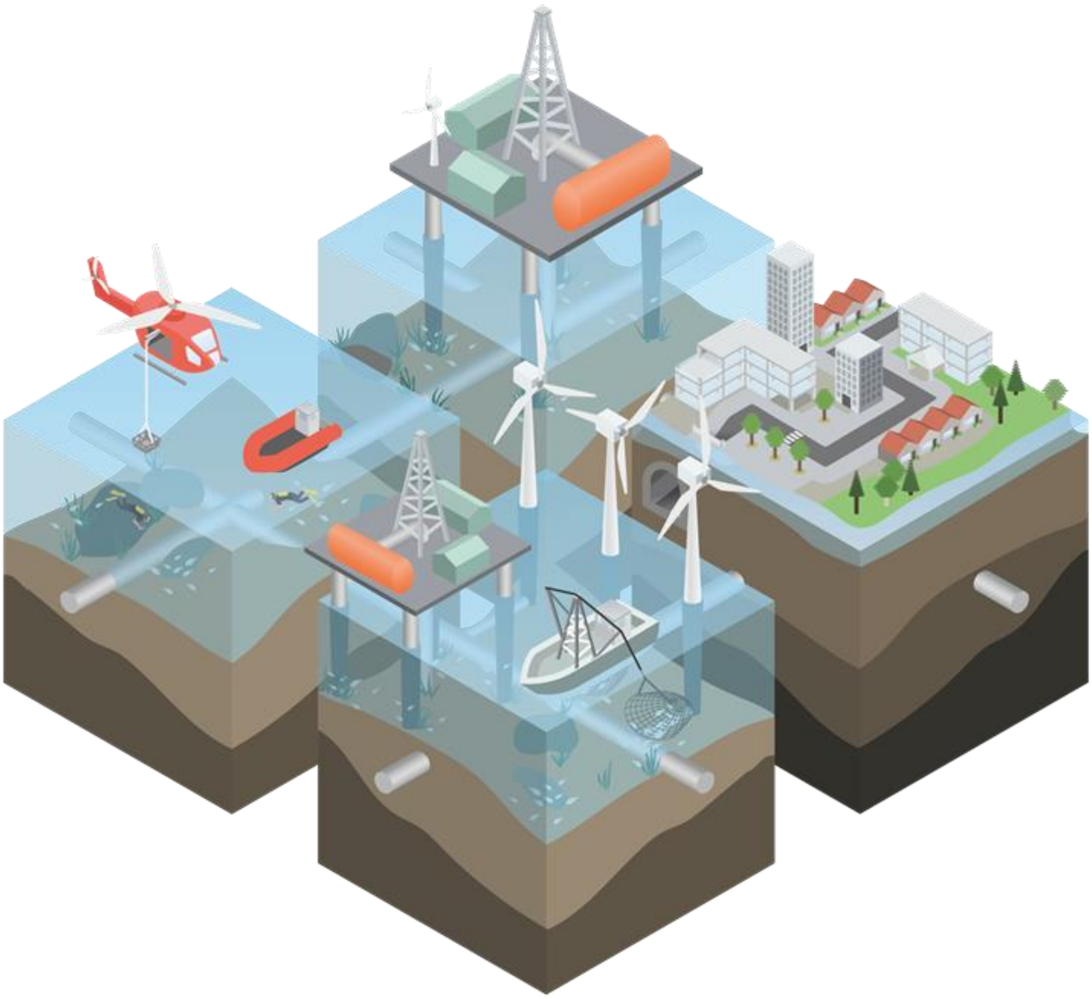
Synthesis paper NSE II

Hybrid offshore energy transition options

- The merits and challenges of combining offshore system integration options -

Project: North Sea Energy 2
As part of Topsector Energy



TNO, New Energy Coalition, university of groningen, Wageningen University & Research, Royal HaskoningDHV Enhancing Society Together

Executive summary

The North Sea will be a pivot in accelerating the energy transition that enables us to reach the targets of the Paris climate agreement. Reduction of offshore oil and gas production together with accelerated growth of offshore wind are two important trends for the coming decades.

These trends also pose new challenges to the offshore industry. First of all, offshore wind capacity growth will place a considerable burden on the spatial claim. Moreover, it bears the challenge that in periods of high wind electricity production the onshore grid cannot cope with the high volumes, resulting in grid congestion. This may already become a serious issue in the Netherlands before 2030. Secondly, the offshore oil and gas industry has the major challenge of re-using and decommissioning its offshore assets after production has ceased. Operators and the Dutch state have already reserved billions of euros for this endeavour for the coming decades.

Instead of addressing these two challenges separately, the creation of potential synergies among wind energy and oil and gas production offers room for mutual solutions. Specifically, the re-use of infrastructure for the offshore energy transition may enable achieving medium and long term climate goals and reduce its costs. Options for offshore system integration could then be explored to alleviate challenges arising from grid congestion, for instance via platform electrification and offshore energy conversion and storage (e.g. power to hydrogen; power-to-x).

The North Sea Energy program (NSE) investigates opportunities for climate synergies that arise when making smart connections between offshore wind energy and existing gas infrastructures. In particular, we assess various technical options that provide system linkage of offshore oil and gas infrastructures with those of wind energy. For these options the technical, environmental, societal, regulatory and economic feasibility has been explored. The analyses show that economically and environmentally meaningful options are on the horizon.

The North Sea Energy program[1] offers new perspectives on offshore system integration. The consequences for use of space, costs and benefits for the environment, the impact of system integration on different economic sectors and stakeholders, and the impact on the labor market are good examples.

In this phase of the programme the focus is on the case-specific perspective where three system integration options are combined (parallel or consecutive): platform electrification followed by power-to-hydrogen and CO_2 transport and storage. For three selected sites in the Dutch North Sea we have examined several research themes to discover the merits and challenges of offshore system integration from a technical, economic, environmental and regulatory perspective.

The research is supported by the Topsector Energy and received important contributions from companies EBN, TOTAL, NAM, TAQA and Loyens & Loeff.

[1] In parallel with the program an offshore power to gas pilot facility is being prepared that will demonstrate as first of a kind the offshore production of hydrogen via electrolysis on an existing oil and gas production platform.

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Offshore energy transition and the need for offshore system integration

Why is system integration in the offshore energy domain needed?
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. In this spirit, the Dutch ''Energieakkoord'' prescribes 14% of renewable energy by 2020, with a further increase towards 16% in 2023. In 2018 this has been updated with a draft Climate Agreement that is based on a reduction target for CO_2 emissions of at least 49% by 2030. A considerable share of the 48.7 Mt CO_2 reduction is foreseen to be reached by more offshore wind development and by implementing carbon capture and storage (CCS) with about 7 Mt CO_2 per year by 2030. Offshore wind is planned to grow from 4.5 GW in 2023 towards 11.5 GW in 2030.

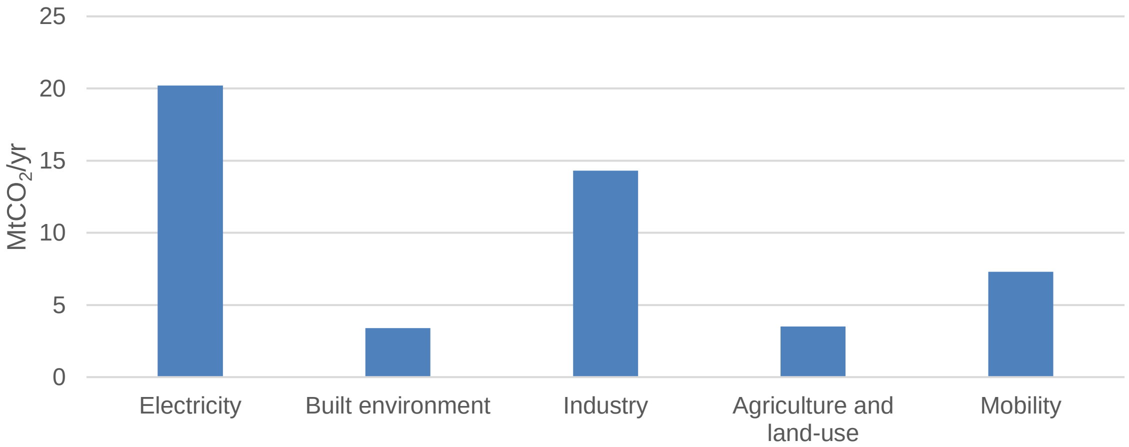


Figure 1 Sectoral CO_2 reduction targets for 2030 in the Netherlands' draft climate agreement[2]

Offshore sustainable energy, most dominantly offshore wind, and CCS will thus have a very important contribution to the accelerated growth of a low carbon and sustainable energy supply in the Netherlands. Next to wind energy the North Sea hosts several important (economic) activities, including oil and gas production, fisheries, sand and shell extraction, shipping, areas for military use, nature reserves, and recreational activities. The area thus has an important economic and environmental function for the Netherlands' economy; and there is competition for space.

Space is an important limiting factor for offshore energy production. In future scenarios up to 26% of the Netherlands Continental Shelf is 'used' by offshore wind[3]. The spatial claim of offshore hydrocarbon production and transport is considerably declining in the same period; although CCS and offshore hydrogen production and transport would likely involve re-use of oil and gas infrastructure and thus a part of the spatial claim remains.

Strong offshore wind deployment also has the challenge according to the PBL study (2018) that new landing points are difficult to realise and that in periods of high wind electricity production the onshore grid cannot

[2] Ontwerp van het Klimaatakkoord, 2018,
[3] PBL in De toekomst van de Noordzee – PBL 2018 recently has performed spatial scenario analyses for the North Sea (Netherlands Continental Shelf -NCP). With regards to energy production the study anticipates in the most ambitious scenario an offshore wind growth towards 15 GW installed capacity in 2030 and 60 GW in 2050.

cope with the high volumes, i.e. grid congestion. This already may become a serious issue before 2030. Offshore system integration could be one of the options to alleviate this situation, for instance via platform electrification and offshore energy conversion and storage (e.g. via power to hydrogen; power-to-x).

The offshore oil and gas industry has the major challenge of re-use and decommission of its offshore assets after production has ceased. Offshore operators and the Dutch state, via EBN, has already reserved billions of euros for this endeavour for the coming decades. Re-use of infrastructure for the offshore energy transition may reduce costs of achieving medium and long term climate goals.

The decline of gas assets on the one hand, and the build-up of offshore wind assets on the other hand, offers an opportunity where system integration between these two may be of added value to accelerate the energy transition at the North Sea. There are various system integration options that could enable and accelerate this transition, including (see also Figure 2):

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

These options may jointly lead to an accelerated growth to sustainable energy production at the North Sea by:

- Reducing the CO_2 emissions during the transition phase between these energy systems.
- Enabling the production and transport of large amounts of wind energy to shore by partly transporting in the form of green molecules (e.g. hydrogen);
- Reducing the societal costs of decommissioning of the fossil energy infrastructure on the one hand, and the build-up of the new energy infrastructure on the other;

Re-use of existing gas infrastructure (both pipelines, platforms and depleted fields) may open the route towards a North Sea scenario for energy production at reduced costs and making use of the potential of green molecules (e.g. green hydrogen) to play a major role in our new energy system. By combining various uses of the North Sea, the competition for space may be reduced, which improves the balance between energy production, food production and ecological value.

What has been achieved so far and what is the goal in this phase of the TKI North Sea Energy programme?

In the first phase of the TKI North Sea Energy programme the consortium has mainly focused on assessing the business case of offshore system integration options in isolation and assessing their added value to the energy transition. This assessment included: platform electrification, power-to-gas on offshore platforms and in wind turbines; offshore and onshore conversion of natural gas to hydrogen and CO_2 for subsurface storage; offshore natural gas to wire; and offshore energy storage using batteries.

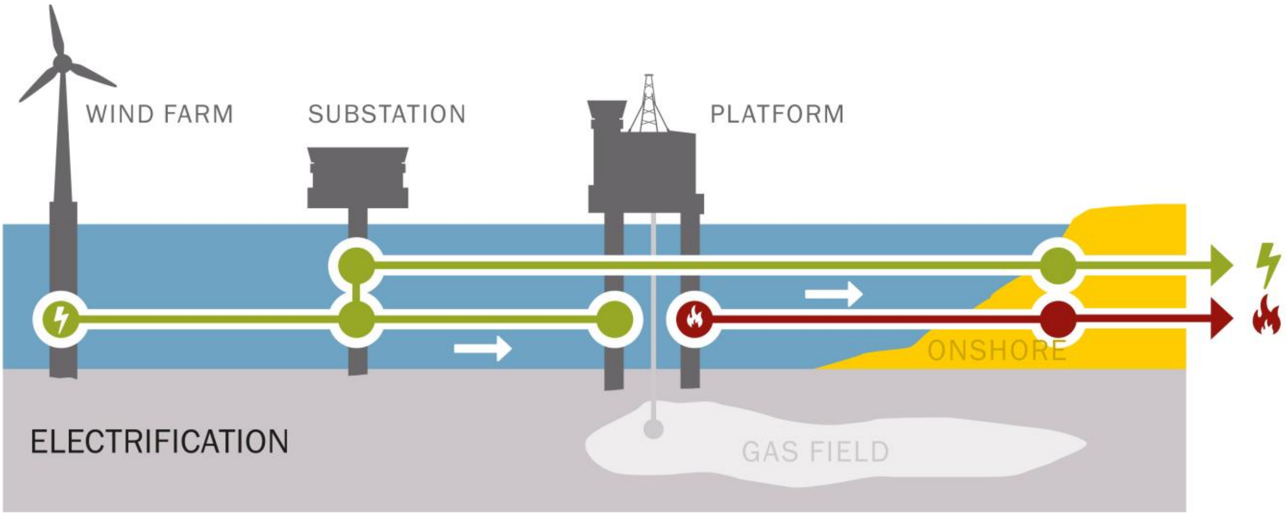
The research has also provided perspectives on the role of system integration options in energy landscape of the future, on macro-economics, environmental benefits of platform electrification and on the impact of system integration options on the human capital agenda. Also, a public and online North Sea Energy Atlas has been published as part of the first project[4]. The public results of the NSE1 project are summarized in a synthesis paper 'Klimaatwinst door systeemintegratie op de Noordzee'.[5]

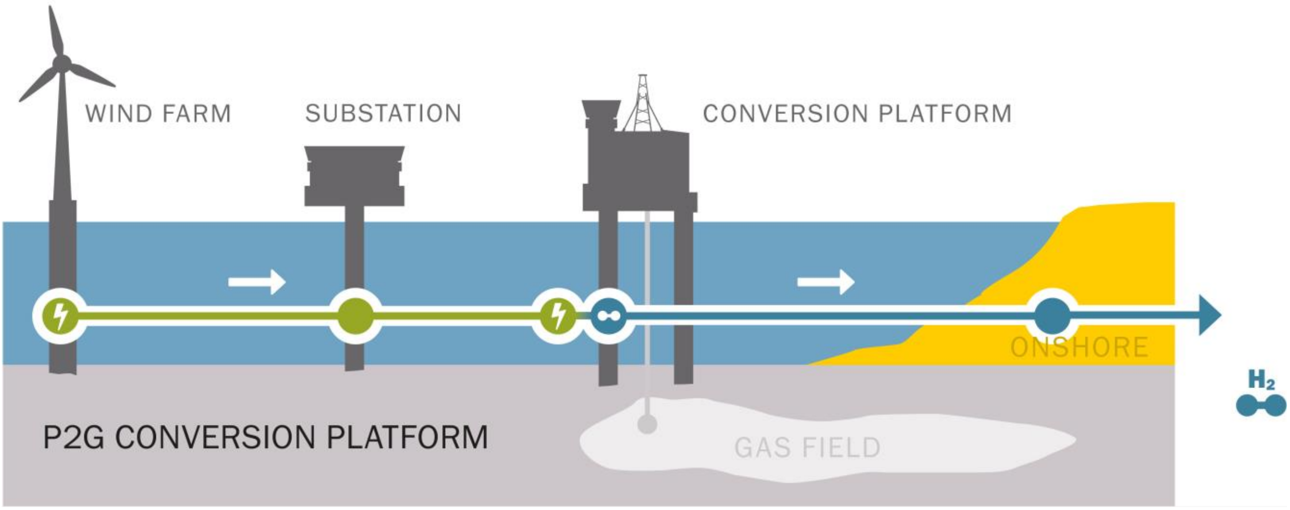
In this report the second phase of the programme is summarized. In this phase of the programme the focus has shifted towards a more case-specific perspective where three system integration options are combined (parallel and/or consecutive): platform electrification followed by power-to-hydrogen and/or CCS.

[4] https://www.north-sea-energy.eu/atlas.html
[5] http://www.north-sea-energy.eu/results-year-1.html

For three selected offshore sites we have examined several research themes to discover the merits and challenges of offshore system integration from a technical, economic, environmental and regulatory perspective.

Reading guide
This report starts with a summary of the techno-economic assessment, followed by a deep-dive into work performed on the screening and ranking of offshore subsurface assets. In the section environmental performance of offshore system integration the three system integration options are reviewed on their environmental merits and challenges using established and new approaches. In the section on the regulatory framework of offshore system integration three key challenges are identified and discussed. The general conclusions are summarised in the final section.





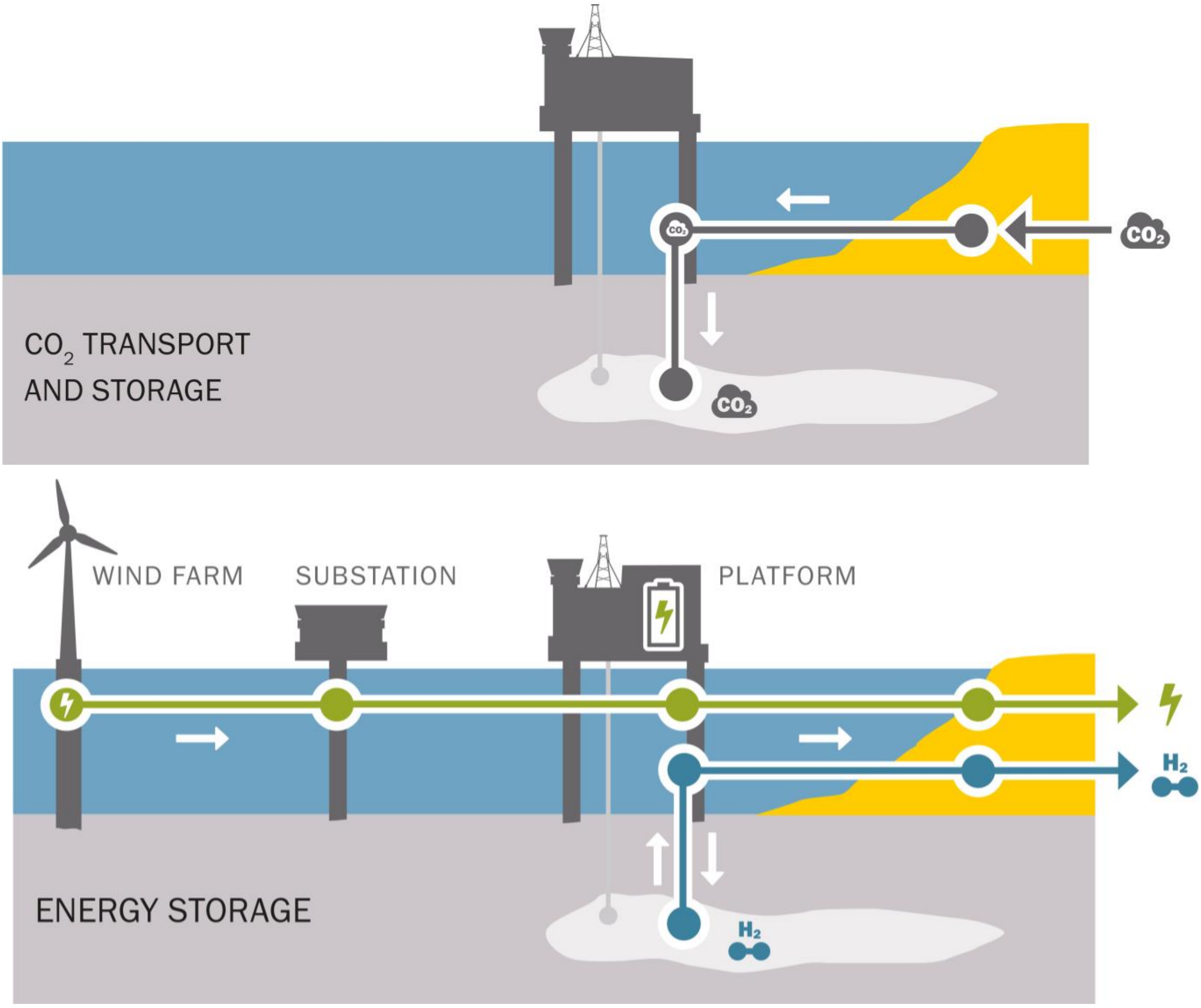


Figure 2 Offshore system integration options

The value and challenges of combining offshore system integration options

Platform electrification is a stepping stone for offshore Carbon Capture and Storage and Power-to-hydrogen

In earlier studies it was already concluded that system integration options are interlinked in space and time[5,6]. The most clear example stipulated is that platform electrification could be an important stepping stone for a larger offshore electricity grid that could facilitate:

- CO_2 transport and storage;
- Power-to-gas and power-to-x;
- Gas to wire;
- Energy storage.

The working hypothesis in this phase of the North Sea Energy programme was that combining system integration options (either in parallel or consecutive) on an offshore platform improves the business case and lowers overall energy system costs. The first part of this hypothesis was tested by analysing the techno-economic possibilities and limitations of different development scenarios for three operating platforms: K5, K14 and P15. All scenarios contain at least a combination of platform electrification with power-to-hydrogen and/or CCS; and differ on the timeline of introducing one or more of these system integration options.

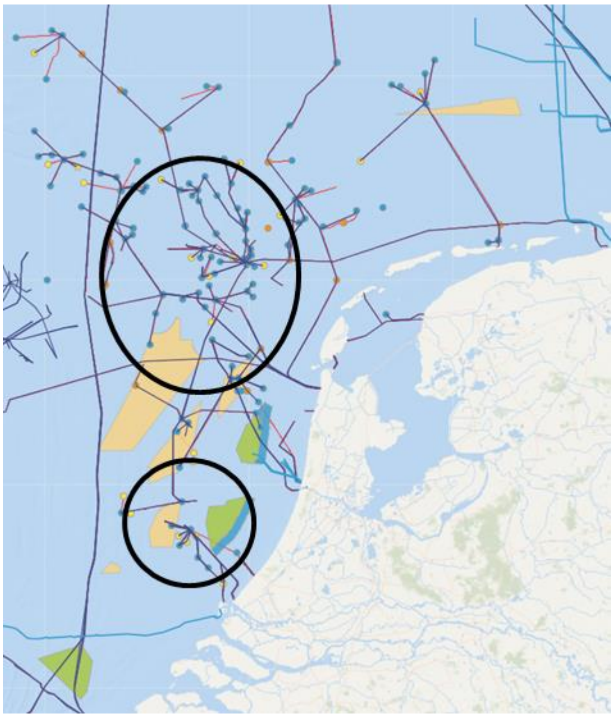


Figure 3 Study area North Sea Energy 2

[6] SENSEI Strategies towards an efficient future North Sea energy infrastructure 2016

The results confirm the insights from NSE1 that electrifying a platform can be a sound investment if savings on fuel gas and CO_2 emissions compensate the high cable and platform conversion investments, in addition to the lost (or delayed) earnings that result from production downtime during the refurbishment period. With positive and sustained market incentives for CO_2 reduction (i.e. a high CO_2 price in this study) and increasing gas price scenarios this could be the case, but this is very much case specific. The number of years to earn back the investment varied highly from one platform to the other.

Some aspects are very important for a positive business case. For example, the time horizon for gas production is of high importance. Furthermore, adding a new purpose to the offshore platform after conventional and electrified production of natural gas can have a positive effect on the business case. The power cable needed for electrification supports the re-development of the platform towards a CO_2-hub or hydrogen production platform. The net present value for the platform operators seems to improve when implementing CCS and/or hydrogen compared to continuing with business as usual, being conventional natural gas production until a given decommissioning date.

Transforming a platform (cluster) into a CO_2 hub proofs to be a sound business opportunity if the offshore operator could limit CO_2 transport investments and receives a CO_2 transport and service fee[7] of at least 2 to 8 €/ton CO_2. It should be noted that project risks and margins are not valued within these calculated fees and that these results depend strongly on the volumes assumed to be transported and stored. CCS profits namely significantly from economies of scale: a higher volume of CO_2 stored results in an improved business case. Major assumptions with regard to the offshore CCS option are that the CO_2 volumes are constant and stable over the years, CO_2 storage does not interfere (any longer) with oil & gas production, reservoirs offer sufficient storage capacity and will be filled up to 80%, and that wells and existing infrastructure can be re-used for CO_2 injection.

Hydrogen production offshore showed a less profitable investment scenario. The business case to produce green hydrogen on the platforms with the help of electrolysers turned out to strongly depend on the price to be received for the hydrogen, the average electricity price paid to produce hydrogen, and the operating hours of the electrolyser. Moreover, in some cases large-scale hydrogen production would not be possible at all due to the size and weight restrictions of the current platforms. This would require an additional investment from the operator to build a new platform for the electrolyser, which in turn increases the specific costs of producing hydrogen significantly. Under the assumptions that (i) no new platform needs to be built, (ii) the selling price of green hydrogen would not differ too much from bulk grey hydrogen market prices, assumed at €2 / kg, and (iii) hydrogen admixed to natural gas would only generate the gas price, there was no business case for offshore hydrogen production for all scenarios. Hydrogen production would generate a business case, though still a fraction of the CCS option, if hydrogen selling prices would increase to levels ranging between 3 to 5 €/kg. Such a future price level could possibly be achieved under greener policy scenarios towards the use of hydrogen in the energy system and / or if positive externalities of offshore hydrogen production in terms of savings on the (wind) electricity infrastructure would be internalized (see also results of NSE 1).

Enhancing circularity of offshore assets improves the business case
The results indicate that the highest value of offshore system integration from offshore operator perspective is in re-using the subsurface assets as much as possible. This includes the pipelines, wells and reservoirs. This explains the positive value for CCS as it uses most or even all of the asset: wells, reservoirs, platforms and pipelines. Here the existing platform is the enabler for this re-use of assets. In general, the wells and reservoirs are the limiting factors determining the capacity and volume of transported and injected CO_2; and thus revenue. This is somewhat different when refurbishing a platform to a H_2-hub. In this option the platform

[7] This should not be mistaken with a CO_2 price. The CO_2 price under the Emission Trading Scheme (ETS), or other incentive should be high enough to also cover the costs of CO_2 capture and onshore CO_2 transport.

dimensions and new investments in offshore deck space determine the capacity for H_2 production and compression, and thus the revenue[8].

Regarding pipelines it is clear that re-use of assets has clear benefits for the business case. For CO_2 transport this translates in much lower investments, tens of millions of euros and more, or several euros per ton of CO_2 transported and stored. For the offshore production and transport of hydrogen results show that re-using the pipelines is almost a necessity given the relative weak business case and low overall revenues due to the inability to achieve economies of scale for offshore H_2 production. Offshore energy islands may significantly alter this picture. This topic is part of ongoing research in NSE 3 in 2019.

The technical feasibility of re-using assets is obviously an important pre-requisite for the business case results presented above. A technical screening assessment has been performed indicating that re-using the pipelines for the transport of CO_2 and H_2 seems technically feasible at the moment. Initial recommendations for re-using pipelines for CO_2 are reducing impurities in the CO_2 to a minimum, evaluation of applying crack arrestors and coatings, study risk of CO_2 and pipeline material/component interactions, review equipment involved in the transport process to be operated bi-directionally, and CO_2 static load and flow assurance studies.

Space, timing and coordination are key pre-requisites for a sound business case
The combination of CCS and hydrogen production may compete for space on the platform and for use of the infrastructure for compression, transport and storage. A very important limiting factor is the space available on the platform. In the studied scenarios this proofed to be much higher for offshore hydrogen production than for CO_2 storage. Adding floorspace offshore is highly costly (e.g. adding a new platform at tens of millions of euros) and this is also a key factor determining the feasibility of the scenario that includes hydrogen production.

An exploratory study on the required equipment and its space and weight dimensions is performed. For electrification large and heavy transformers are the main concern. The total required deck space is 4-7 40-feet containers, depending on specific electrification requirements of the platform. Producing H_2 requires the largest space requirements of the three options: up to 20 40 ft containers for 100 MW of electrolyser capacity (including auxiliary equipment and utilities). For CCS it is assumed that one of the main components, i.e. compression, is placed onshore and that offshore heating of the CO_2 is not needed, thus there is limited impact on required deck space offshore. The availability of space on the platform is under these assumptions not likely to become a limiting factor.

CCS and H_2 might be in competition for re-using subsurface assets (see next section) and pipelines. For pipelines the re-use of the WGT and Local pipeline sections (see Figure 4) was studied. In theory both can be applied to transport CO_2 and H_2, but likely not simultaneously. Re-routing and re-connecting existing natural gas evacuation pipelines (or sections) may also free up pipeline sections for CO_2 and H_2 transport. Coordination between offshore stakeholders is imperative regarding natural gas transport forecasts and CCS and H_2 scenarios such that the value of existing pipeline sections for offshore natural gas transport followed by transport of CO_2 and/or H_2 is better understood.

Coordination regarding platform electrification could yield important cost reductions for operators and thus improvement in the overall business case. An exploratory case study was performed on a shared power infrastructure between K14 and K5 going to wind farm Hollandse Kust Noord. The results indicate that both direct and alternating current variants are feasible, but with their own merits and disadvantages related to transmission losses, dimensions, reactor and transformer configurations and equipment dimensions. Additional studies are required for a detailed specification of components, control and for grid compliance.

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[8] In this phase of the NSE programme the business case for offshore hydrogen storage, and thus the value of re-use of reservoir and well assets, is not taken into account.

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.

Figure 4 Natural gas pipelines on the Netherlands Continental Shelf

Energy transition offshore requires a delicate balance between coordinated strategies and customized individual solutions

The challenge with coordinating offshore system integration is best to be visualised by an already difficult 4D puzzle (i.e., both in space and in time) that has shifting puzzle pieces. The offshore assets, the puzzle pieces, are unique. The platform dimensions, linked wells, reservoirs and pipelines are one of a kind with their own history, shareholders and predictions. The optimized business case for these offshore assets are also very much case specific. This would suggest for a highly individual approach to find the optimal strategy within the offshore energy transition. Were it not to the fact that coordination of efforts is suggested to result in high cost reductions for both individual operators (as shown in NSE2) as for the overall energy system (as shown in NSE 1 results and to be further studied in NSE3[9]). The endeavour for the next phase of the NSE

[9] This includes studies on a shared power infrastructure in place, coordinated CCS roll-out and an coordinated H2 offshore grid deployment.

programme is to find this balance between reducing overall energy system costs and acceptable business cases for individual solutions for offshore assets.

The role of the subsurface in offshore system integration

The role of the Dutch subsurface in the future energy system will change considerably. The conventional role as stable supplier of commodities like natural gas will slowly fade and is likely to be replaced by a role that can be described as ‘subsurface as a service’. The subsurface will not likely be only supplying commodities, but more and more services like CO_2 storage and energy storage to accommodate the energy transition and deep emission reduction pathways with CCS and large shares of variable renewable energy technologies (such as wind and solar).

Depleted fields will be very important assets for offshore energy transition: CO_2 storage and energy storage

Subsurface fields form one of the important assets when it comes to re-use of existing gas infrastructure. On the one hand offshore fields are at this moment mostly targeted for permanent storage of CO_2. On the other hand, subsurface storage of hydrogen is currently considered as one of the potential options to store energy at a large-scale, besides storage of e.g. compressed air and heat. The figure below shows the variability of production of wind energy in Germany. Buffering energy in the subsurface via hydrogen storage could deliver important strategic and balancing services to the future energy system.

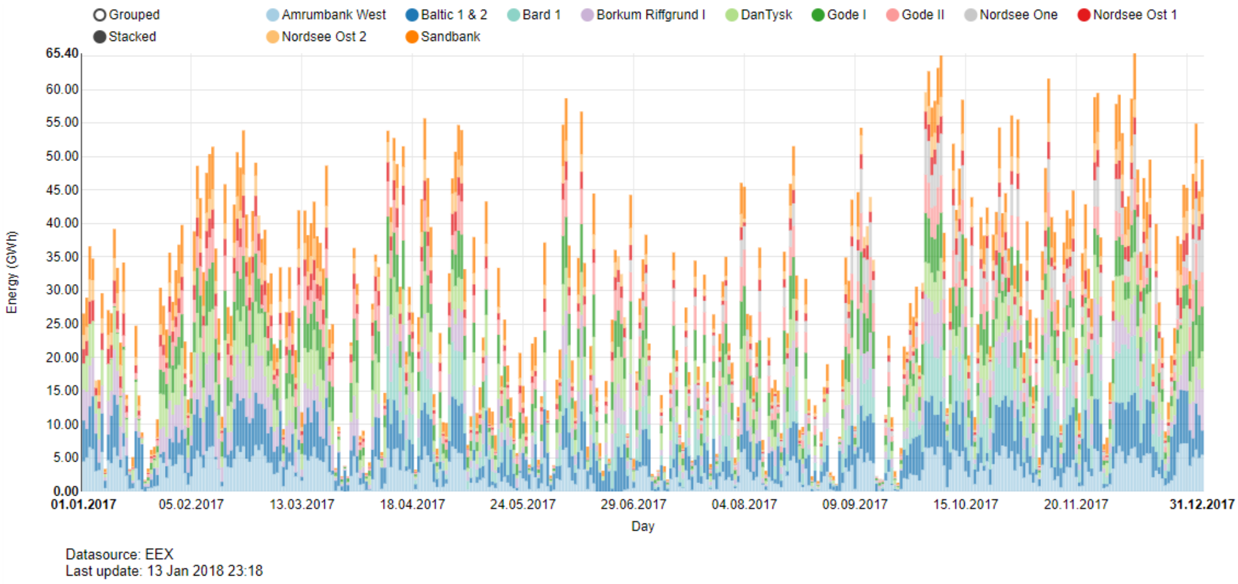

Figure 5 Variability in wind production in Germany in 2017 (Fraunhofer, 2018)[10]

Whereas storage of CO_2 has been intensively studied over the past decades and still is (Porthos project, Athos project, CATO programs, etc.), storage of hydrogen is the new kid on the block when it comes to large-scale storage. In *Ondergrondse Opslag in Nederland – Technische Verkenning* (EBN & TNO 2018), storage of hydrogen, CO_2 and compressed air were studied for the onshore and near-shore area. CO_2 storage is currently only considered in the offshore part of the Netherlands. Hydrogen storage and Compressed Air Energy Storage are considered in most scenarios to be deployed onshore in caverns, though a scenario exists where hydrogen could potentially be stored in depleted gas fields in the near-shore areas around Rotterdam and IJmuiden. Whether offshore storage of hydrogen is a viable options remains an open question.

[10] https://www.energy-charts.de

A newly developed subsurface screening tool will help identifying ranking strategic subsurface assets for H_2 and CO_2 storage
For that reason, a start was made with a technical subsurface screening tool to screen for various asset re-use options, also in the offshore portfolio. This screening tool is aimed to give a first-order estimation of relative ranking of various reservoirs in a portfolio for re-use for CO_2 storage and hydrogen storage. The tool is based on an expert-based multi-criteria analysis. This means that experts can put their own scoring and relative weight to the various criteria for re-use. The tool has been applied to two field cases to see how the reservoirs in the portfolio of these clusters technically rank for re-use for CO_2 storage and hydrogen storage.

The re-use criteria that are considered most important are well status, buffer/storage capacity, injectivity, reservoir availability and containment/risk management effort. The fact that the exercise is expert-base has pros and cons. It does reflect the strong experience and knowledge base present within the different operators and enables them to tune the screening towards important case-specific considerations. On the other hand, choices in weighing and scoring indicators may vary strongly between different portfolios and users, which may reflect in variations in relative ranking for the same portfolio. The results so far are mostly consistent, though variations due to specific weighing choices are present.

Another challenge is the foundation of various criteria related to hydrogen storage. As was also reflected in the *Ondergronde Opslag in Nederland – Technische Verkenning*, hydrogen storage in depleted gas reservoirs needs a better understanding of engineering requirements and molecule-reservoir fluid-reservoir rock interaction. To successfully screen the Dutch portfolio for storage of hydrogen in gas fields, several questions need to be answered in the field of, amongst others, containment, work gas-cushion gas ratios, well status and injectivity.

When combining the screening of reservoir portfolio with storage scenarios as in the earlier mentioned study, an important question arises. Will the subsurface storage demand in the offshore part of the Dutch North Sea be significant enough to cause competition between CO_2 and hydrogen storage? As can be obtained from CO_2 storage plans and roadmaps, it is most likely that CO_2 storage will start within near-shore reservoirs close to the large CO_2 sources like Rotterdam and IJmuiden. However, if volumes will appear to be this large that hydrogen storage will be needed in depleted gas fields, we may have filled up suitable near-shore reservoirs permanently with CO_2. Therefore, it is important to earmark potentially suitable fields for hydrogen storage, both onshore and offshore.

Improving and applying the tool on the portfolio of subsurface assets will shed light on the strategic value for both CO_2 and H_2 storage
Technically screening the subsurface for CO_2 and hydrogen storage is a way to understand which reservoirs are relatively more suitable for either one or the other forms of storage. This could serve as quick way to set first-order boundary conditions for techno-economic analyses, like was described in the previous section. An important next step would be to improve the foundation of various criteria, mainly for hydrogen storage. That will help to take the step to a technical screening of the full Dutch offshore portfolio, identifying important clusters for both CO_2 and hydrogen storage.

Environmental performance of offshore system integration

The combination of life cycle perspective and location based strategic environmental assessment is of high value for understanding the merits and challenges of offshore system integration
In the first phase of the North Sea Energy programme a life cycle assessment (LCA) was performed to compare the environmental performance of gas produced in the Dutch North Sea with and without electrification of platforms. As the name suggests an important characteristic of LCA is that it takes into account the complete life cycle of a product (cradle-to-grave) from resource extraction to waste treatment.

The focus regarding environmental performance was on the emissions of greenhouse gasses and NOx, which were compared for 1 m^3 of natural gas produced[11]. It was assumed that the ten platforms with the highest fuel consumption are electrified and are powered with mainly electricity from nearby wind farms.

The analysis showed an environmental benefit of gas produced with electrification over the reference without electrification. Per m^3 produced, greenhouse gas emissions were reduced by about 25% and NOx emissions by about 40%. This indicates that emissions of about 500,000 tons of CO_2-eq could be prevented per year. For NOx emissions, this reduction potential would be about 2000 tons per year.

Earlier analyses on the environmental life cycle performance of CCS indicates that CCS reduction depends on the application and sector in which the technology is implemented (e.g. power or industry). For the power sector results show a decrease in greenhouse gas emissions for the whole chain of 47-84%[12].

Detailed analyses on the environmental life cycle performance of offshore hydrogen production will be performed as part of the NSE3 programme in 2019, but it is already suggested by earlier studies that green hydrogen will reduce the CO_2 footprint of hydrogen production significantly[13],[14].

This environmental perspective has been enriched and the scope has been widened with a strategic assessment of environmental impacts of system integration options[15].The analysis provides a first indication of the type and extent of a broader set of environmental impacts related to system integration at the North Sea. However, compared to LCA analysis this method has more a comparative and qualitative approach.

Offshore energy transition and reduction in CO_2 emissions has clear environmental synergies but also trade-offs
In the strategic assessment a framework is prepared based on the *People, Planet, Profit* approach. The impacts of the three system integration options are described accordingly and the extent of the impacts is scored on a seven-point scale ranging from strongly positive (+ + +) to strongly negative (- - -) impact. The system integration options are then first assessed as stand-alone options. This is followed by an assessment of the different system integration scenarios (combination of options) per case study. The environmental performance for the individual system integration options is summarized in Figure 6 - Figure 8.

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[11] 'North Sea Energy II D4.1: Life cycle assessment of platform electrification', 2018
The analysis encompassed the entire Dutch North Sea under 2014 conditions.
[12] Corsten et al. 'Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature', 2013
[13] Simons, Andrew & Bauer, Christian. Life cycle assessment of hydrogen production. 2011
[14] Bhandari, Trudewind & Zap. Life Cycle Assessment of Hydrogen Production Methods – A Review 2012
[15] 'North Sea Energy II D.2 - 'Strategic Assessment of Environmental Impacts of Offshore system Integration Options'2018

For all three system integration options it shows that during the construction or conversion phase activities will take place with an pressure on the environment. These include additional ship movements and construction works that will 'disturb' or have a moderate impact on most of the environmental aspects. Negative impacts, were mitigation measures need to be investigated, are expected to impact nature (- -), sound (- -) and cultural heritage and archaeology (- -). Cable or pipeline laying is expected to disturb local flora and fauna, generate under water sound, and could impact objects of cultural or archaeological value. In addition, for the CCS and green hydrogen production options negative impacts could be expected due to handling of toxic waste related to refurbishment of the platforms.

Electrification

The main difference in the operational phase for the electrification option is that conventional power equipment (gas or diesel generators) has been replaced by electrically-powered equipment. This has an expected positive impact on air emissions (+ +), mainly CO_2 and NOx. Due to electrification, the use of fossil fuels for gas production is altered to the supply of energy from sustainable sources. The impact on sustainable energy use is therefore scored positive (+ +). Further positive impacts are expected related to operational safety and the reduction of traffic movements and sound. Minor negative impacts are expected related to operation of the power cable.

CO_2 transport and storage

The most important reason to start CCS is to reduce CO_2 emissions. As shown in LCA-literature CCS reduces the life cycle greenhouse gas emissions. Trade-offs are that during the operational phase the CCS option scores a negative (- -) impact for operational safety as it is assumed that the reference situation is a mothballed platform, which means that there are no safety risks at all and maintenance is not required. The platform will be back in production and therefore risks will be present again, although it should be noted that these are smaller for operation with electrical installations. In case the platform is manned, operations take place 24/7, which results in daily operational safety risks, and a negative score (- -). In case of an unmanned platform, the platform will occasionally be visited for maintenance. The risks for operational safety are lower and therefore scored moderately negative (-). All other environmental impacts during the operational phase of CCS score moderately or are considered neutral. No positive effects are indicated, but it should be noted that CO_2 capture is explicitly out of scope in this assessment as the focus is on offshore part of the CCS chain. This explains that no positive impacts are shown in Figure 7.

Offshore hydrogen production

During the operational phase the green hydrogen production option scores a positive (+ +) impact for the aspect sustainable energy use. Sustainable energy from wind farms or specific wind turbines will be used to produce green hydrogen. Fossil fuels will not be used any longer. Furthermore, this option scores a negative (- -) impact for operational safety using the same approach and reasoning as for CCS above. Only moderate effects are expected related to *electromagnetic fields,* which could negatively impact the flora and fauna (*nature*). These effects are caused by cables transporting electricity required to produce green hydrogen. Further, by-products are produced from desalinated and filtered seawater (demi water) for electrolysis. It is not clear where these by-products will be disposed or collected and transported from the platform. Disposing these by-products back into the seawater may be an option. Therefore, both the salinity and 'waste' concentration can increase locally. It may be expected that the local increase of salinity is of insignificant proportions compared to the large North Sea, but it could have a moderately negative impact (-) on the *water quality* and therefore on flora and fauna (*nature*). On the other hand, disposal of the 'waste' (consisting of plankton etc.) could have a moderately positive effect (+) on the *water quality* and therefore on *nature*.

		Electrification			
		Construction		Operation	
	Theme	Cable/ pipeline	Existing platform	Cable/ pipeline	Platform
Planet	Nature	- -	-	-	0
	Seabed	-	0	0	0
	Water quality	-	-	0	0
	Underwater sound	- -	-	0	+
	Air emissions / Smell	-	-	0	++
	Electromagnetic fields			-	
	Materials and waste	-	- -	0	+
People	Landscape and light	0	0	0	0
	Cultural heritage and archaeology	- -	0	0	0
	Sustainable energy use	-	-		++
	Traffic (ship movements)	-	-	0	+*
	Operational safety			0	++**
Profit ability	Other spatial uses	-	0	-	0

** In case of an unmanned satellite platform (+) and neutral (0) in case of a manned platform.*
***In case of an unmanned satellite platform (++) and moderately positive (+) in case of a manned platform.*

Figure 6 Environmental performance of offshore platform electrification

Legend

+++	Strongly positive impact, the development has clear added value
++	Positive impact, clear improvement compared to the reference situation
+	Moderately positive impact, no significant improvement
0	No impact / Neutral
-	Moderately negative impact, no disrupting effect
- -	Negative impact, mitigation measures should be investigated
- - -	Strongly negative impact, effect is outside of the judicial framework
	No impact possible

		CCS			
		Construction		Operation	
	Theme	Cable/ pipeline	Existing platform	Cable/ pipeline	Platform
Planet	Nature	- -	-	0	-
	Seabed	-	0	0	0
	Water quality	-	-	0	0
	Underwater sound	- -	-	0	0
	Air emissions / Smell	-	-	0	-*
	Electromagnetic fields				
	Materials and waste	-	- -	0	-
People	Landscape and light	0	0	0	-
	Cultural heritage and archaeology	- -	0	0	0
	Sustainable energy use	-	-		-
	Traffic (ship movements)	-	-	0	-
	Operational safety			-	-**
Profit ability	Other spatial uses	-	0	-	0

** As the scope of this study covers the offshore environmental impacts, onshore impacts are not included. Therefore, the positive impact of the CO_2 capture onshore is not included in the assessment.*
***In case of an unmanned platform (-) and negative (--) in case of a manned platform.*

Figure 7 Environmental performance of offshore CO_2 transport and storage

		Green hydrogen production			
		Construction		Operation	
	Theme	Cable/ pipeline	Existing platform	Cable/ pipeline	Platform
Planet	Nature	- -	-	-	-
	Seabed	-	0	0	0
	Water quality	-	-	0	0*
	Underwater sound	- -	-	0	0
	Air emissions / Smell	-	-	0	0
	Electromagnetic fields			-	
	Materials and waste	-	- -	0	-
People	Landscape and light	0	0	0	-
	Cultural heritage and archaeology	- -	0	0	0
	Sustainable energy use	-	-	++	++
	Traffic (ship movements)	-	-	0	-
	Operational safety			-	-**
Profit ability	Other spatial uses	-	0	-	0

Figure 8 Environmental performance of green hydrogen production

New method maps ecological synergies and pressures due to the re-use of offshore assets
As part of the strategic analysis a focus was applied on better understanding the consequences of different system integration options for marine life. This part of the study[16] introduces a new framework for semi-quantitative risk predictions for ecological impacts. This enables ranking and comparing environmental pressures and impacts resulting from different system integration activities. For these activities, environmental pressures are appointed to sub-activities involved in the production phases, transition phases and the final decommissioning of infrastructure. For these pressures, the ecological impacts on marine benthos, fish, birds and marine mammals are semi-quantitatively scored. Moreover, the applied screening methodology also enables a structured assessment of cumulative effects in relation to lined-up offshore system integration activities.

The results show that platform electrification has no significant negative or positive effect on marine benthos, fish, birds and marine mammals. For both CCS as green hydrogen production lower impacts are expected compared to gas production. Only during transition phases for the infrastructure, an overlap of activities may result in a temporary higher impact level.

[16] 'North Sea Energy II - Screening impacts of offshore infrastructures on marine species groups: a North Sea case study for system integration Deliverable D.1.

System integration: a stress test for the regulatory framework?

This phase of the programme has also shed the first light on the legal barriers and drivers for offshore system integration. Several aspects have been included:

- The international legal framework in relation to offshore energy activities
- The current Dutch legislation in place pertaining to offshore hydrocarbons production, wind energy activities, CO_2 storage and hydrogen production;
- An overview of the possible barriers and drivers in realizing an integrated and hybrid offshore energy system.

The analysis of the international law of the sea has highlighted that coastal states in principle have the jurisdiction to regulate offshore hydrocarbons production, wind energy production, carbon dioxide injection and storage, as well as hydrogen production in their territorial seas and exclusive economic zones (EEZs). The execution of these activities should however always take place with due regard for the rights of other users of the sea. To prevent unnecessary interference with especially the right of navigation of other states, detailed international rules for the decommissioning of disused platforms have been developed. Given the shallow depth of the North Sea and the light-weight platforms used, all platforms on the Dutch continental shelf will have to be removed once they become disused. Internationally, it is however acknowledged that when a platform performs a new legitimate use it cannot be considered as disused and can consequently stay in place. For pipelines, no international decommissioning obligation exists.

The review of current Dutch legislation has focused on the legislation applicable to the above mentioned energy activities. An important observation in this respect is that not all onshore legislation automatically applies in the EEZ and on the continental shelf. Only legislation that explicitly states so is applicable offshore. With regard to energy activities, the applicable legislation includes the Mining Act, the Water Act, the Wind Energy at Sea Act and segments of the Electricity Act and of the Gas Act. An analysis of these acts, *grosso modo* highlighted three sets of legal barriers to system integration.

1. The regulatory framework provides insufficient guidance on the re-use of offshore infrastructures
A first legal barrier pertains to the regulatory framework for the placement, operation and decommissioning for offshore infrastructures. This framework is first of all fragmented in that hydrocarbons extraction and carbon dioxide storage are both regulated by the Mining Act, whereas the placement and removal of infrastructures for hydrogen production is only regulated by the Water Act. This makes re-use an especially complex and challenging issue when a transition is made from hydrocarbons to hydrogen production. Secondly, the Mining Act is strongly focused on removal and only provides little guidance on re-use after the original hydrocarbons activities on a platform are ceased. The lack of thought given on re-use as an alternative to removal during the drafting history of the Mining Act is especially pressing when a transition is made from hydrocarbons to hydrogen production, but also when for example a temporal gap exists between the original activity and the new activity. In the latter case, issues such as how long the infrastructure can be left in place between two activities, how certain the re-use should be to allow for an exception from the removal obligation, who should take responsibility for the infrastructure during such mothballing period and how to prevent the removal of infrastructures which could be used at a later stage are largely unaddressed. The Minister is however aware of the fact that the current regulatory framework does not facilitate re-use and is therefore planning amendments to the Mining Act on this issue.

2. The current legal framework for the offshore electricity network blocks offshore system integration
Secondly, there is the issue of offshore electricity consumption. For all system integration scenarios, the offshore consumption of electricity plays a pivotal role. The offshore electricity network operated by TenneT could function as a source of electricity for offshore platforms, but unfortunately the current legal framework blocks this potential. The current regulatory framework found in the Electricity Act only allows for the

connection of offshore wind parks to the network. The entire technical and market design of the offshore grid is moreover solely aimed at the transport of renewable electricity to shore. To be able to connect offshore platforms to the network a fundamental revision of the Electricity Act would be necessary.

3. The current legal framework for electricity and gas infrastructure provides no clear guidance on the market regimes for new types of infrastructure for system integration

Thirdly, there is the issue of the applicable legal market regimes to offshore pipelines and cables. For the existing types of pipelines and cables, the Electricity Act and the Gas Act provide rules on market issues such as third-party access and tariff setting. The technologies discussed under the header of system integration would however involve new types of pipelines and cables, such as hydrogen pipelines and electricity cables between wind parks and offshore installations. Since these pipelines and cables do not fit any of the existing typologies found in the Electricity Act or Gas Act, it is unclear what the applicable market regimes for these types of infrastructure would be.

Conclusions

For three selected sites in the Dutch North Sea we have examined several research themes to discover the merits and challenges of offshore system integration from a technical, economic, environmental and regulatory perspective.

The results indicate a clear merit in lining-up offshore system integration options. The business cases for offshore platform electrification followed by refurbishment of the platform to offer a CO_2 transport and storage function is quite positive under scenarios where the CO_2 reduction incentive is strong and when the transport and storage operator receives a sustainable fee for its services. Platform electrification followed by hydrogen production offshore showed a less profitable investment scenario. Overall the results indicate that the highest value of offshore system integration or lowest costs are achieved when also re-using the subsurface assets (wells, reservoirs and pipelines) as much as possible and when sharing infrastructure to reach economies of scale for the offshore power grid and the transport of CO_2 and H_2.

The challenges are to be found in the high initial investments and the uncertainty for a sustainable business case under current market conditions. Technical challenges identified and reviewed are offshore deck space and weight limitations for the system integration options (mostly for H_2 production and compression) and the issues with converting existing pipelines for natural gas transport to CO_2 transport pipelines.

Regarding the subsurface perspective, a start was made with a technical subsurface screening tool to screen for various re-use options. This screening tool could give a first-order estimation of relative ranking of various reservoirs in a portfolio for re-use for CO_2 storage and hydrogen storage.

The environmental perspective shows that offshore energy transition and reduction in CO_2 emissions has clear environmental synergies, but also has trade-offs. For all three system integration options the construction or conversion phase activities will take place with an pressure on the environment. During operation of the options there are expected to be strong positive impacts on air emissions and climate, sustainable energy use and operational safety. However, some alternatives also show trade-offs related to operational safety, nature and electromagnetic fields. For most of the screened negative environmental impacts no disrupting effects are expected and for some negative impacts mitigation measures are advised to be investigated in a full strategic environmental assessment. The results from a more focused assessment regarding marine benthos, fish, birds and marine mammals show that platform electrification transition has no significant negative or positive effect. For both CCS as green hydrogen production lower impacts are expected compared to natural gas production.

Finally, the regulatory perspective clearly indicates three challenges for offshore system integration:

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

NSE II results and deliverables

Work Package A

A.	– Techno-economic scenarios and economic impact of offshore energy system integration options at case study areas

Work Package B

B.	– Regulatory framework: barriers or drivers for offshore system integration

Work Package C

C.	– Screening of optimum re-use of the subsurface

Work Package D

D1.	– Environmental performance of offshore energy - potential impacts of the presence of offshore energy infrastructure on benthic species, fish, birds and marine mammals
D2.	– Strategic Assessment of Impacts of Possible System Integration of Oil & Gas and Wind Energy for the case study area

For access to publications and background information please visit:
https://www.north-sea-energy.eu/results-nse2.html