OFFSHORE **SYSTEM INTEGRATION** AS A **TRANSITION ACCELERATOR** IN THE NORTH SEA

TNO innovation for life

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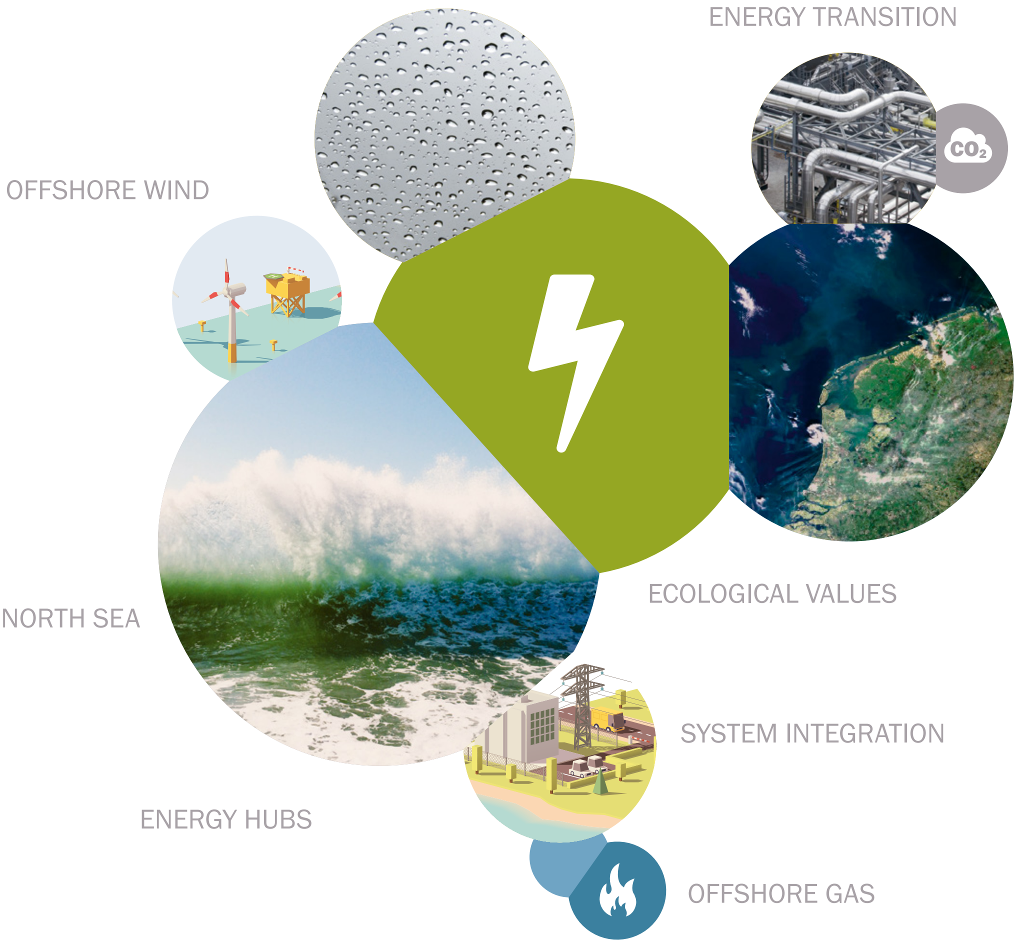

ENERGY TRANSITION
OFFSHORE WIND
CO2
NORTH SEA
ECOLOGICAL VALUES
SYSTEM INTEGRATION
ENERGY HUBS
OFFSHORE GAS

CONTENTS

INTRODUCTION

ONE OF THE BIGGEST CHALLENGES WE FACE AS A SOCIETY IS THE ENERGY TRANSITION: HOW ARE WE GOING TO ENSURE THAT IN 2050 AND BEYOND ALL DUTCH PEOPLE HAVE ACCESS TO SUSTAINABLE, AFFORDABLE AND RELIABLE ENERGY. PART OF THIS ANSWER MAY BE FOUND IN THE NORTH SEA.

The North Sea has traditionally been important for energy production in the Netherlands. A large proportion of our natural gas still comes from offshore platforms in the North Sea. This is going to change. The oil and gas industry is facing a serious decline in production, while offshore wind is emerging strongly. That offers opportunities. The presence of the extensive offshore infrastructure for conventional energy production may offer opportunities to accelerate the transition to sustainable energy sources such as offshore wind. The smart connection of offshore wind farms and gas infrastructure has the potential to seriously reduce CO_2 emissions, to make a fully sustainable energy system possible in 2050 and to drastically reduce the costs of the transition in the North Sea. We call this smart connection of energy networks ‘system integration’.

There are various perspectives on the role that system integration can play in the energy transition in the North Sea. These were collected through interviews and workshops with stakeholders, including wind operators, gas operators, sector organisations, government and NGOs. The insights obtained were used to outline a possible future scenario. This has been further developed so that there is a better understanding of how system integration could possibly speed up the energy transition and what the important decisions, opportunities and turning points are in this respect.

In the first chapter we discuss the preconditions for the energy transition in the North Sea along with the climate goals and their impact on the changing use of the North Sea, the challenges this brings with it and how system integration can contribute to this. Chapter 2 deals with the different options for system integration while Chapter 3 describes the new value chains for the energy transition in the North Sea: which system integration options will help to speed up the transition and which decisions will be needed in the short term. In chapter 4 we discuss the opportunities and turning points for realising system integration.

CHALLENGES FOR THE ENERGY TRANSITION

CLIMATE GOALS

THE ENERGY TRANSITION IS NECESSARY TO ACHIEVE THE CLIMATE TARGETS. These goals have been defined geographically at various levels, including global (United Nations 2015), European (European Commission 2016) and national level (SER 2013, Coalition Agreement 2017). Table 1 shows the climate targets at these different levels. Slowing down the global rise in temperature is the driving force behind the transition. Until recently, various objectives were often pursued to limit the rise in temperature, such as the share of renewable energy, efficiency in energy consumption and CO_2 emissions. By now, the most important parameter for 2050 is total greenhouse gas emissions, including CO_2, CH_4 and N_2O. From a Dutch perspective, the current climate targets for CO_2 emissions compared to 1990 emissions are a 20%, 49% and 80% reduction in 2020, 2030 and 2050 respectively.

In 2016, the share of renewable energy in the energy mix in the Netherlands was 5.9% and the reduction in CO_2 emissions compared to 1990 was 11% (CBS 2017). In order to achieve the climate goals set, substantial measures are needed to build up sustainable energy and to reduce CO_2 emissions on a large scale.
The North Sea is likely to play an important role in this transition. At present, the emphasis of Dutch energy production is still on land, with a share of 70% of conventional energy and 75% of wind energy. Due to declining gas production and a strong growth in offshore wind production, the role of offshore energy from the North Sea will continue to grow in the coming years.

CHANGING USE OF THE NORTH SEA

The ambition to achieve the climate goals may lead to a completely different use of the North Sea. Traditionally, the North Sea has been an important source of conventional energy from oil and gas fields. As a result of the energy transition, the offshore production of wind turbines is now developing very rapidly. Plans for the development of offshore wind are fixed until 2023, when five large wind farms of 700 MW each (EAE, TNO & ECN 2016) will have to supply a capacity of 4.5 GW. It follows from the coalition agreement (VVD, CDA, D66, CU

Paris-agreement		**Maximum rise in temperature**
	Ambition	1.5 °C
	Target	2.0 °C

EU Climate Action Plan	**CO_2**	**Sustainable energy (% total consumption)**	**Energy efficiency (% v. 2004)**
2020	20%	20%	20%
2030	40%	27%	37%
2050	80-95%		

National level	**CO_2 (reduction of emissions v. 1990)**	**Sustainable energy (% total consumption)**	**Energy efficiency**
2020	20%	14%	1.5% per year
2030	49%		
2050	80-95%		

TABLE 1: Summary of climate targets on a global, European and national level

2017) that the established capacity will amount to 11.5 GW in 2030. With the long-term targets for CO_2 reduction as indicated in Table 1, substantial growth is expected after 2023. Figure 1 shows the planned development of offshore wind in the Netherlands with scenarios of PBL (2018) for the period after 2023.

The presence of the oil and gas sector in the North Sea is slowly but surely decreasing due to depleting gas fields, low gas prices and rising operational costs. Figure 2 shows the predicted cessation of production (COP) of offshore gas installations under different gas price scenarios. This shows that the end of offshore gas production is foreseen between 2030 and 2050. This means cleaning up most of the current offshore oil and gas installations over the next 20 years: 156 platforms, 3,000 km of pipeline and 700 wells (EBN 2017). The cost of this reduction in the Dutch part is estimated at €3.7 billion, about 70% of which will be borne by the State, including EBN (EBN 2017). This amount does not include the cost of decommissioning the pipelines.

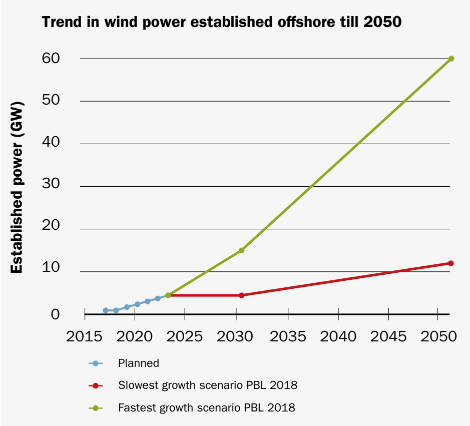


FIGURE 1: Development of wind capacity installed offshore up to 2050. The wind scenarios are already fixed until 2023, with an expected installed capacity of 4.5 GW being achieved (PBL 2018).

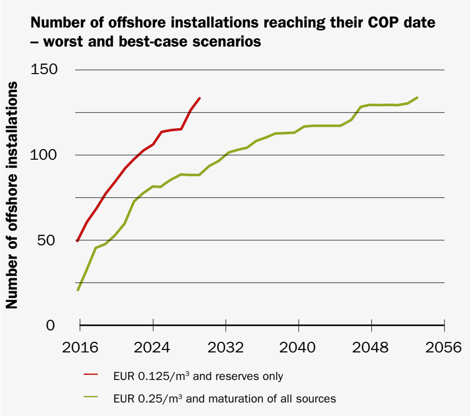


FIGURE 2: The number of offshore installations reaching its so-called Cessation of Production (COP). Cessation of Production is the moment that an installation is stopped from producing (EBN 2017). The prices mentioned are a best and worst case scenario for the gas price. From that moment on, the installation will be decommissioned within a reasonable period of time, unless there is reason to postpone it.

CHALLENGES FOR THE TRANSITION IN THE NORTH SEA

With the changing use, sustainable energy supply from the North Sea faces a number of major challenges. For example, the sea will become increasingly full with a large and growing offshore wind presence. This puts pressure on the spatial arrangement of the various user functions. In addition to offshore wind and gas, these include protected areas, fishing, military zones and shipping. In the most optimistic scenario, 60 GW of offshore wind capacity will already be installed in the Dutch part of the North Sea by 2050. This capacity takes up some 25% of the total space at sea (PBL 2018). The transition from gas to wind involves high costs not only for the aforementioned dismantling of platforms, pipelines and wells, but also for the construction of wind farms and the associated infrastructure for transporting the energy.

The long-term challenge is to ensure security of supply from the offshore wind sector to the Netherlands. At the moment, the capacity of the electricity grid is large enough to get the wind energy produced to land via a number of points. But if offshore wind rises to dozens of gigawatts of installed capacity, it is uncertain whether the current electricity grid can cope with such large amounts of energy. The stability of the grid may be jeopardised and there is a need for electricity conversion and storage among other flexibility options. In the coming years, there will be a growing need for options that can keep the electricity grid stable and offer flexibility for sustainable electricity production, possibly even before 2030 (PBL 2018). Energy conversion and storage are potential solutions.

SYSTEM INTEGRATION: INTEGRATED FRAMEWORK FOR ENERGY-ECOLOGY-ECONOMY.

The energy transition in the North Sea poses a number of major challenges in terms of the availability of space, costs and long-term security of supply. In order for the transition to succeed, an integrated approach is needed for energy production, food production (especially fishing) and conservation of ecological values (Natura 2000 areas). System integration of various functions in the North Sea could possibly contribute to this. Within this concept, the functions of use are combined in all sorts of ways so that they benefit from each other, together save space and costs, and accelerate the energy transition at sea. Moreover, an integrated approach creates solutions to problems that individual energy carriers cannot solve on their own. Cooperation between sectors and stakeholders is crucial in this respect.

OPTIONS FOR COOPERATION BETWEEN OFFSHORE WIND AND GAS

As two major players, the offshore wind and gas industries are the best placed to explore the possibilities for system integration in the North Sea for the first time. In the past, various studies have been carried out into concepts for cooperation by these parties, such as SIOE (TNO et al. 2016), SENSEI (EAE, TNO & ECN 2016), and Jepma & Van Schot (2017). Further studies are being undertaken within the North Sea Energy Program, the North Sea Wind Power Hub Consortium, the Reuse & Decommissioning Platform NexStep, and by the WEC Consortium (WEC 2018). These studies discuss the options for system integration between offshore wind and offshore gas. In this document, we will confine ourselves to introducing the various options. A detailed description and analysis of system integration options can be found in SENSEI (EAE, TNO & ECN 2016).

ELECTRIFICATION OF PLATFORMS

Under the current system, gas turbines and diesel engines provide power to the platforms. Conventional engines and turbines often have low efficiency and emit CO_2, nitrogen and sulphur oxides. Most of the energy is needed to compress natural gas. When electrification of a platform takes place, an electric motor replaces these turbines, whereby the electricity can come from land or be produced offshore. Electrification reduces the emission of greenhouse gases and other emissions such as NO_x and SO_x. It significantly increases the efficiency of the system and reduces the operational costs and own consumption of gas offshore. Electrification of offshore platforms can technically lead to savings of up to 1 megaton of CO_2 per year for the next decade (TNO et al. 2016).

There are three options for electrification of gas platforms:

1. *Connecting a gas platform to a coastal transformer station via submarine power cables*
   This is already happening on platform Q13a-A (Amstelveld) of Neptune Energy in the Dutch part of the North Sea and at various platforms in Norway. Different transmission technologies (AC/DC) are available for this purpose. The choice depends on the electricity consumption and the distance to the coast.

2. *Connecting a platform to an offshore wind farm*
   Electricity goes from a substation in an offshore wind farm to the gas platform (see Figure 3). During periods of low wind, electricity can be supplied from the coast as back-up via the offshore grid. Various gas producers are looking at this option in order to reduce their CO_2 and NO_x emissions.

3. *Connecting a platform to a large offshore grid*
   For large platforms and wind farms located far from the coast, the construction of an offshore grid is an attractive option. By using the same infrastructure for the different functions of use and for optional cross-border trade, it is possible to share the investment costs, operating costs and maintenance, as well as the benefits.

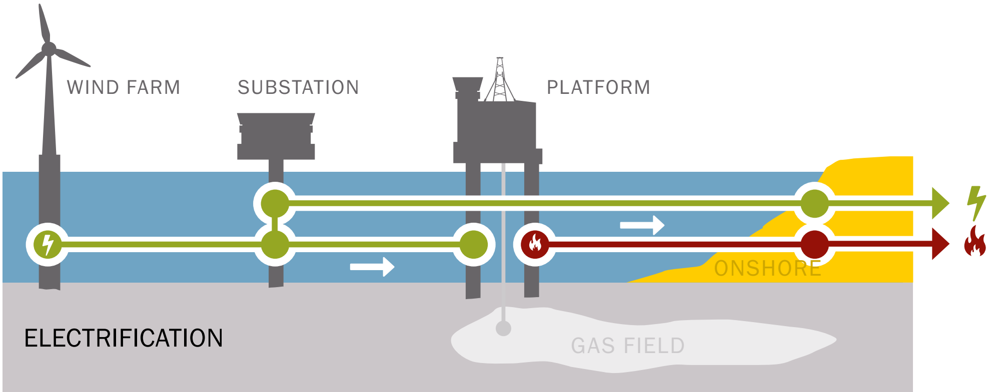


FIGURE 3: Diagram of the electrification of a platform via a wind farm.

An example of an electrified platform in the Dutch part of the North Sea is Neptune Energy's Q13a-A platform. It is located 14 kilometres from the coast, produces from the Amstel field and is electrified via a cable to the coast that is connected to the electricity grid of the municipality of The Hague. The estimated savings in CO_2 emissions are about 14,000 tons per year (Neptune Energy 2018).

POWER-TO-X OPTIONS

Power-to-X (PtX) is the general term for conversion of electricity to heat and gaseous or liquid energy carriers such as hydrogen, methane, ammonia, formic acid and methanol. Figure 4 shows examples of PtX, in which wind electricity is converted to hydrogen. Conversion to hydrogen can take place at different locations.

PtX is interesting to make sectors that cannot be (fully) electrified more sustainable and as one of the methods to make the energy system flexible. It offers added value because energy production and use can be decoupled. The use of PtX is interesting when there is a high supply of variable sustainable electricity.
The energy produced from the sun or wind can be converted into electricity and heat at a later stage. These energy carriers can also be used as feedstock in the chemical or transport sectors.

For offshore system integration, interest is currently being shown in the conversion to hydrogen, among other things. This conversion takes place via electrolysis, in which water is split into hydrogen and oxygen with the aid of electricity. Polymer Electrolyte Membrane (PEM) electrolysis seems to be the best option because it requires relatively little space and is most robust at varying loads.

A study by the New Energy Coalition (Jepma & Van Schot (2017)) has shown that the production of so-called 'green' hydrogen, made from sustainably generated electricity such as wind, is technically and economically feasible.

If desired, other products can also be made from hydrogen, which in many cases require CO_2, such as methane and methanol.

Hydrogen produced offshore can be transported to land in various ways. In the case of low production, the hydrogen is added to the natural gas network and then separated again on the coast. It is currently permitted to mix up to 0.5% hydrogen in the existing offshore gas grid. If hydrogen is produced at a high level, it may be attractive to build dedicated hydrogen pipelines or to reuse old gas pipelines for pure hydrogen transport.

Other PtX options to provide flexibility to the energy system are still in the pre-commercial phase. Examples are conversion of electricity into ammonia, formic acid and methanol as an energy carrier. In the long run, these may also be real methods of converting and storing electricity.

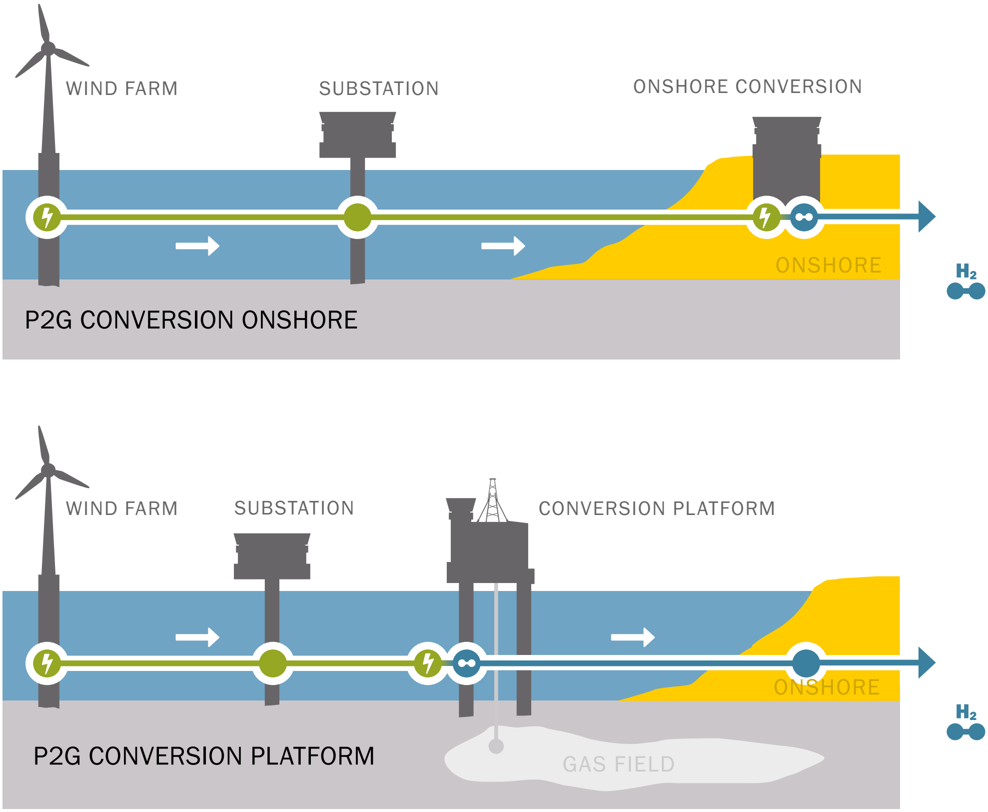
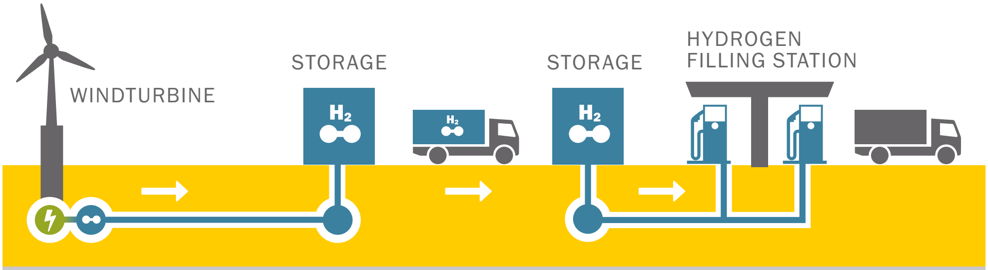


FIGURE 4: DIAGRAM OF POWER2GAS CONVERSION ONSHORE (UPPER) AND ON A PLATFORM (LOWER)

Hydrogen - grey, blue or green?
Hydrogen is mainly used as a feedstock for industry. The current use of hydrogen in the Netherlands is 800 kilotons per year (Berenschot & TNO 2017), most of which is produced and used in the Port of Rotterdam. Different types of hydrogen can be distinguished. Production is almost entirely carried out by cracking natural gas using various methods: grey hydrogen.
Of this, 80% is produced via steam methane reforming (SMR), the standard way for large-scale hydrogen production. Approximately 12.5 megatons of CO_2 are currently released as a result.
In the production of blue hydrogen, this CO_2 is captured and stored underground, which means that it is low in CO_2. For the future energy system, the focus is on the production of green hydrogen. This hydrogen is produced by electrolysis of sustainably generated electricity such as wind and solar energy. This is therefore a fully sustainable form of hydrogen production.



HYDROGEN MILLS

Hydrogen mill - Electrolysis in wind turbines
A consortium of hydrogen supplier HYGRO, wind turbine manufacturer Lagerwey and research institute ECN part of TNO is working on the development of the world's first hydrogen mill.
The aim is to test this mill at the Wieringermeer at the beginning of 2019. At the mill, with a capacity of 4.8 MW, the electrolyser is placed inside the mill so that far fewer components are needed. The hydrogen that will be produced by this project will be used as fuel (Hygro, Lagerwey & ECN 2017).

CO_2 TRANSPORT AND STORAGE

Carbon capture and storage (CCS) is the capture of CO_2 emissions by energy-intensive industry, followed by transport and storage in geological formations (IPCC 2005). Storage takes place by injecting CO_2 into porous rocks from, for example, (almost) empty gas fields or deep aquifers (saline formations) (see Figure 5).

According to the IEA scenarios (IEA 2013), CCS can achieve a contribution of about one sixth of the required CO_2 reduction in 2050, not only from electricity production, but also from the steel, cement and chemical industries. The scenarios predict CO_2 storage volumes in 2050 varying between 0 and 50 megatons of CO_2 per year (EBN & Gasunie 2010, Gasunie 2018, PBL 2017, PBL 2018). The coalition agreement 2017-2021 (VVD, CDA, D66, CU 2017) speaks of the ambition to have 20 megatons of CO_2 stored by 2030.

At the moment, the implementation of CCS projects has been delayed, partly due to the discontinuation of the Rotterdam Storage and Capture Demonstration (ROAD) project. There are storage facilities for a number of gigatons, particularly in the Dutch offshore sector.

CCS is important for system integration because it can use the existing gas infrastructure for transport and storage, and electricity is needed on platforms to compress and condition CO_2. In the total energy consumption of the North Sea, it must also take into account possible competition between permanent storage of CO_2 and the future cyclic storage of various gases, including hydrogen, as a contribution to a flexible energy system.

CCS also plays an important role in the production of so-called blue hydrogen, which is produced by decomposition from natural gas to hydrogen and CO_2. In order to make this production low in CO_2, it is necessary to capture and store the CO_2 produced. One of the most famous blue hydrogen projects is the Statoil-Nuon Vattenfall-Gasunie initiative to make the Magnum power station at Eemshaven energy neutral by storing captured CO_2 during hydrogen production underground in Norway. A second initiative for blue hydrogen is planned in the Rotterdam Harbour (the H-vision project).

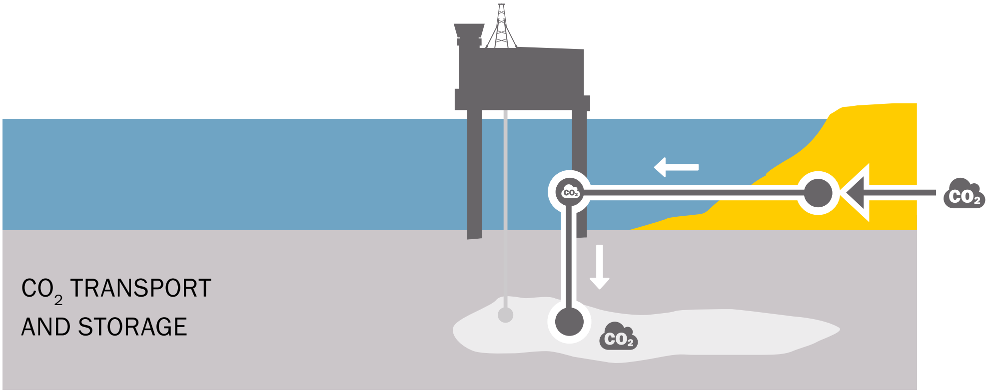


FIGURE 5: Diagram of CO_2 transport and storage

Magnum, a hydrogen-fired power plant
Statoil, NuonVattenfall and Gasunie are working together to convert NuonVattenfalls Magnum power station in the port of Eems (Eemshaven), which is currently running on gas, into a power station running on blue hydrogen. This will lead to a reduction in CO_2 emissions of four million tons per year. The hydrogen is produced via so-called Steam Methane Reforming, after which the CO_2 produced in this process will be stored in Norway. The production of hydrogen is therefore low in CO_2.

GAS-TO-WIRE

Gas-to-Wire (GtW), or Gas-to-Power as it is also known, is the conversion of gas into electricity (Figure 6). On offshore platforms, conversion takes place using gas turbines and fuel cells or techniques that use pure oxygen for combustion (oxyfuel technology). Combining it with CCS reduces CO_2 emissions in the process (Figure 6). GtW is an option when gas fields are remote from the existing gas infrastructure but near an electrical network or transformer station. Another possibility is to apply GtW to so-called marginal or near-produced gas fields where it is no longer economically viable to use the existing gas infrastructure for exploitation. Finally, GtW in combination with Power-to-Gas (PtG) may be interesting to enable stable electricity supply during periods of low wind. In high winds, wind energy is converted into synthetic gas and stored. In times of little wind, this gas can be converted back into electricity via GtW.

Setting up GtW systems requires investments in grid connection and the possible conversion of existing offshore platforms to make GtW possible. These costs can be limited by using existing offshore wind transmission systems or GtW facilities that are easy to move and reusable, such as floating facilities. At present, this technology is still in the pre-commercial phase, but there are already initiatives to market GtW as a service in combination with CCS.

ENERGY STORAGE

Energy storage involves storing energy in different forms and on different scales, above or below ground. Well-known forms are the storage of electricity in batteries, CAES (compressed air energy storage) and the storage of gases such as natural gas and hydrogen in salt caverns or empty gas fields. The capacity required for this strongly depends on the application of storage, for example balancing or seasonal storage. For system integration, one of the possible applications is to offer flexibility 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 on platforms, caverns or empty gas fields. Figure 7 shows examples of offshore energy storage. Jepma & Van Schot (2017) studied several scenarios for the conversion of surplus wind energy to hydrogen or other gases, including storage on different space and time scales.

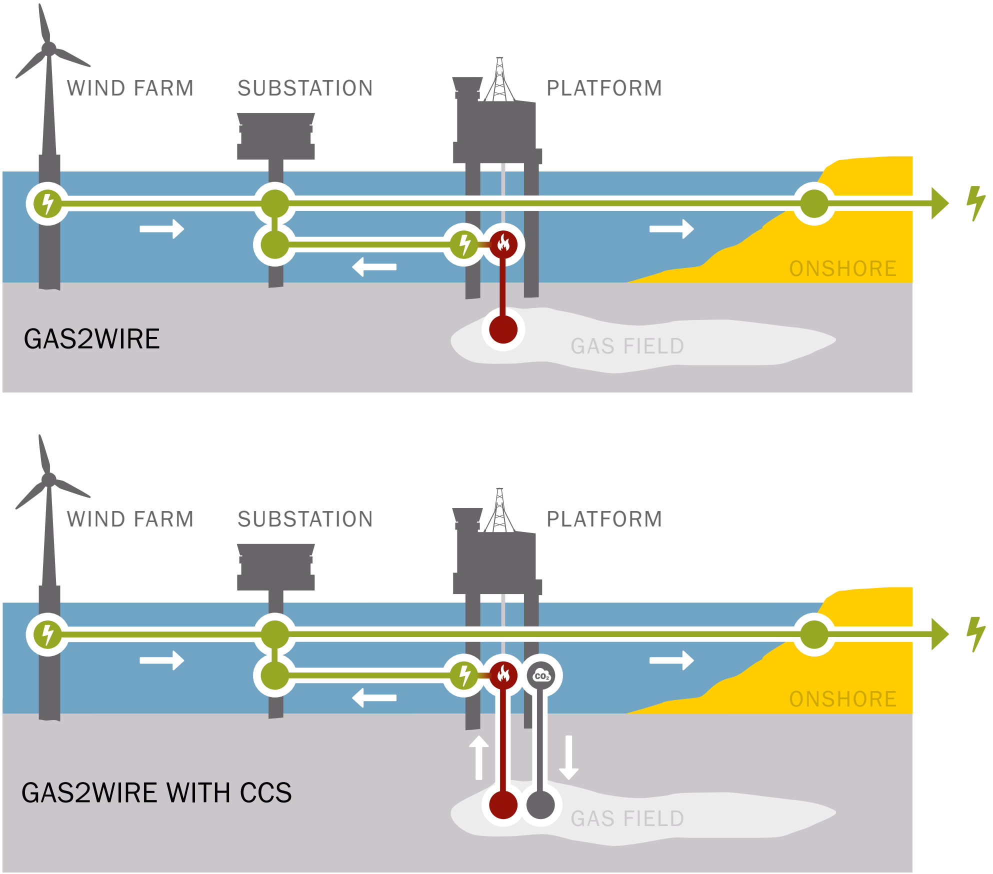


FIGURE 6: DIAGRAM OF A) GAS-TO-WIRE AND B) GAS-TO-WIRE WITH CCS

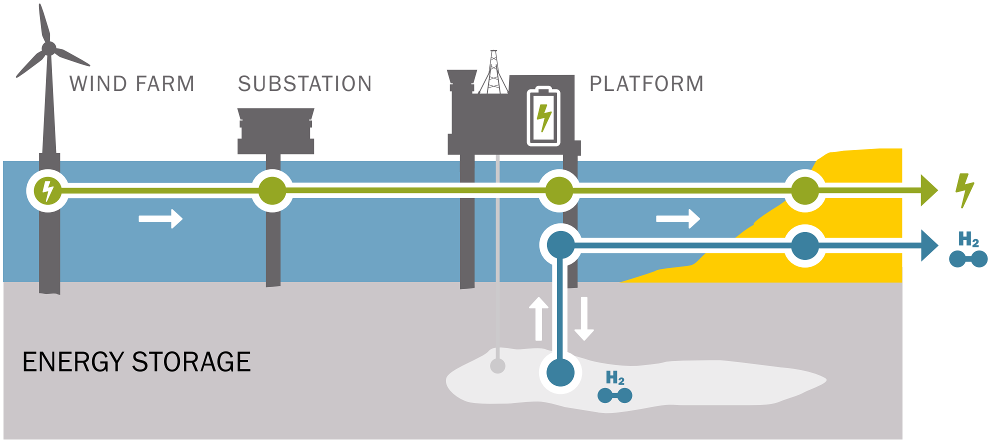


FIGURE 7: DIAGRAM OF FORMS OF OFFSHORE ENERGY STORAGE

NEW VALUE CHAINS

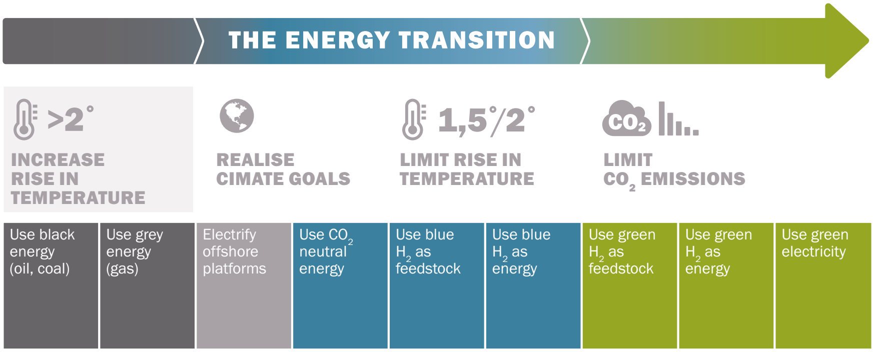


FIGURE 8: Different forms of energy in the energy transition.

The transition model

In addition to energy saving, the climate targets call for the development of sustainable sources of energy and a sharp reduction in CO_2 emissions. To make this possible, a transition is needed from the use of black, fossil to green, sustainable energy. In order to provide insight into this transition, a model for the energy transition has been developed (Figure 8), which shows the various options for achieving the climate goals in the energy transition. The model offers four types of energy, which are ranked according to their CO_2 emissions. This involves energy supply in various forms: as a source of heat or electricity, or as a feedstock for products.

The four types of energy are:

1. Green energy - produced entirely from sustainable sources such as sun, wind, biomass and geothermal energy.
2. Blue energy - low CO_2 energy from fossil fuels. Reduced CO_2 emissions through capture and storage.
3. Grey energy - extracted from natural gas; releases CO_2, but less than with coal and oil.
4. Black energy - extracted from oil and coal and high CO_2 emissions.

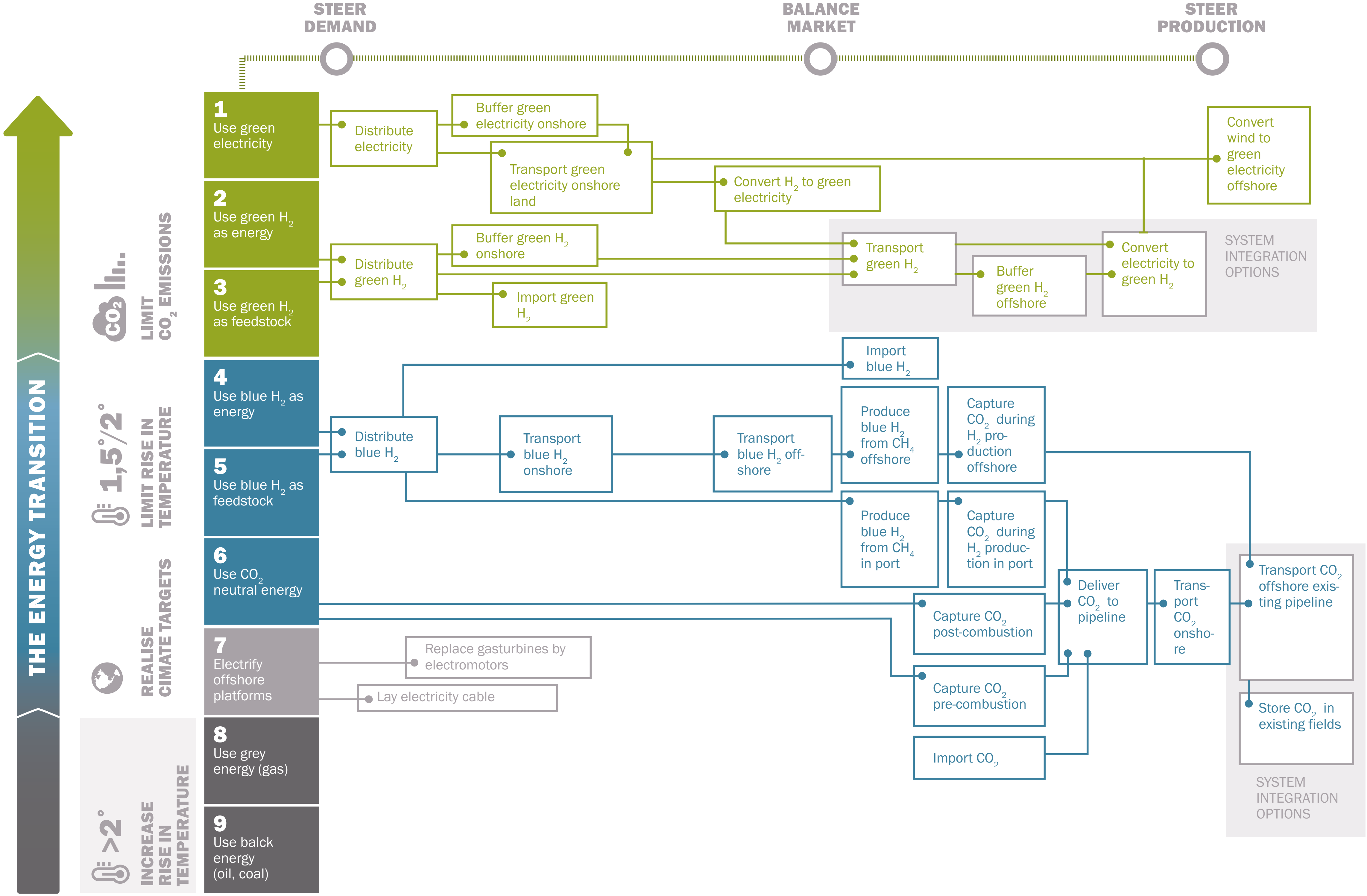
VALUE CHAINS FOR ENERGY TRANSITION IN THE NORTH SEA

At the request of the RVO, at the end of 2017 TKI New Gas, TNO and Hennemann & Hartkamp launched an initiative to gain insight into how system integration in the North Sea can accelerate the energy transition. This involved a large number of stakeholders in offshore systems integration, including wind operators, gas operators, industry associations, government and NGOs.

In two workshops, value chains were developed for possible new energy carriers within the energy transition. In addition, the role of system integration in accelerating the energy transition for these various energy carriers was determined.

In order to create focus within the value chains, it was decided to focus primarily on offshore energy generation as a producer. Since

FIGURE 9



STEER DEMAND
BALANCE MARKET
STEER PRODUCTION
THE ENERGY TRANSITION
LIMIT CO_2 EMISSIONS
1,5°/2°
LIMIT RISE IN TEMPERATURE
REALISE CIMATE TARGETS
>2°
INCREASE RISE IN TEMPERATURE
1 Use green electricity
2 Use green H_2 as energy
3 Use green H_2 as feedstock
4 Use blue H_2 as energy
5 Use blue H_2 as feedstock
6 Use CO_2 neutral energy
7 Electrify offshore platforms
8 Use grey energy (gas)
9 Use balck energy (oil, coal)
Distribute electricity
Buffer green electricity onshore
Transport green electricity onshore land
Convert H_2 to green electricity
Convert wind to green electricity offshore
Distribute green H_2
Buffer green H_2 onshore
Import green H_2
Transport green H_2
Buffer green H_2 offshore
Convert electricity to green H_2
SYSTEM INTEGRATION OPTIONS
Import blue H_2
Distribute blue H_2
Transport blue H_2 onshore
Transport blue H_2 offshore
Produce blue H_2 from CH_4 offshore
Capture CO_2 during H_2 production offshore
Produce blue H_2 from CH_4 in port
Capture CO_2 during H_2 production in port
Deliver CO_2 to pipeline
Transport CO_2 onshore
Transport CO_2 offshore existing pipeline
Store CO_2 in existing fields
Capture CO_2 post-combustion
Capture CO_2 pre-combustion
Import CO_2
SYSTEM INTEGRATION OPTIONS
Replace gasturbines by electromotors
Lay electricity cable

industry is a major consumer with 46% of the energy consumption in the Netherlands (EBN 2017) and the Port of Rotterdam and Moerdijk industrial cluster is a leader with 20%, the value chains have been worked out for this area as a user. This method can also be used to develop value chains for other clusters (e.g. Groningen, Delftzijl, Amsterdam, IJmuiden) and users (e.g. agriculture, fisheries, mobility, households). The assumptions for the design of these value chains are as follows:

1. Offshore wind will grow strongly in the future, from 700 MW per year now to a minimum of 1 GW per year from 2023.
2. The current market for hydrogen as a feedstock comprises 800 kilotons (Berenschot & TNO 2017), half of which is in the Port of Rotterdam.
3. The new energy system needs both molecules (hydrogen) and electrons (current). The current ratio of 80%/20% will shift in favour of electrons in the future.
4. The new energy system is subject to fluctuations in production per day, per season and over the years.

SYSTEM INTEGRATION AS A TRANSITION ACCELERATOR

Figure 9 shows the value chains that have been developed with the options for system integration as shaded blocks. Such an option arises when added value can be created from the existing oil and gas infrastructure by reusing it after conventional oil and gas extraction has ceased.

The most important opportunities for system integration that have been identified as transition drivers by the various stakeholders are

1. Production of green hydrogen on existing platforms and transport via existing pipelines
2. Storage of green hydrogen in existing fields and pipelines.
3. CO_2 transport and storage in existing fields.

The main objective is to achieve and accelerate a transition to a sustainable energy supply with green electricity and green molecules from offshore wind.

1. Production of green hydrogen on existing platforms and transport via existing pipelines

The production of green hydrogen from wind energy on existing platforms is one of the accelerators towards sustainable energy supply. Conversion of electricity into green hydrogen is an opportunity to offer flexibility to the energy system in addition to demand and production control, storage and transport.

Hydrogen can be produced on platforms using electrolysers and subsequently transported to shore through existing pipelines. Green hydrogen can then onshore be used as feedstock for industry, as a direct energy source, or be converted back into electricity, but also temporarily stored. Offshore wind scenarios show that from 2030 onwards a large amount of electricity will become available for the production of green hydrogen. In addition, there is already an existing feedstock market for hydrogen, which is expected to remain intact. In order to produce green hydrogen offshore, research is needed into how this relates to alternatives such as the production on land or the import of green hydrogen. Although offshore conversion is more complex than onshore conversion, it also has a great advantage. The transport costs of energy in the form of molecules are considerably lower than in the form of electrons. It also needs to be made clear how the hydrogen market is going to develop, both in terms of use, volumes and market specifications.

In addition, hydrogen faces a number of technical challenges for both production (conversion efficiency, stability, scale) and transport (integrity of pipelines, compression) that require research. It is also unclear whether hydrogen production is best used as a peak-shaver for excess electricity or whether it should run continuously. For very large-scale green hydrogen production, well above 100 MW, the capacity of offshore platforms is too small because of the space required for electrolysis. For this reason, alternatives such as energy islands are expected to be needed in the long term. All this suggests that there is sufficient time to realise offshore production of green hydrogen. But in order to achieve this on a large scale by 2030, a step-by-step demonstration and scaling up is critical. Figure 10 provides a rough outline of the action plan to achieve large-scale production of green hydrogen at sea. In the very short term (2018), decisions are needed on research into the technical questions concerning production and transport, followed by decisions to stimulate green hydrogen production by means of SDE+ subsidies or via a bottom in the CO_2 price. Next, choices for the locations of the platforms and the scaling up of offshore Power-to-Gas pilots on small (1-5 MW), medium (20-50 MW) and large (200-300 MW) scale in 2019, 2020 and 2025 respectively will be discussed in order to achieve large-scale offshore production of green hydrogen in 2040. As long as grey hydrogen production is allowed and the CO_2 price remains too low, green hydrogen production will only be possible by introducing additional market incentives.

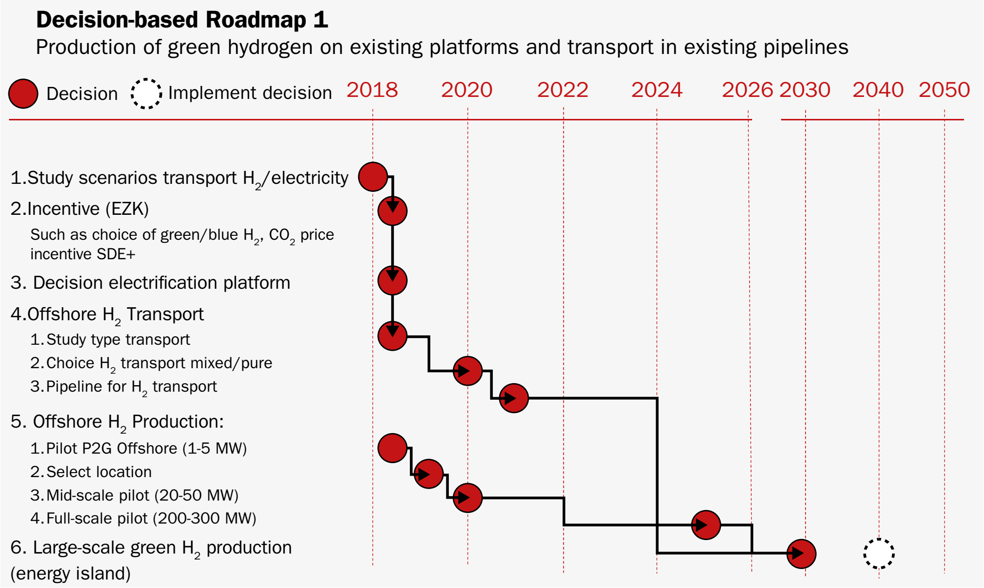


FIGURE 10: Decision-based roadmap for the production of green hydrogen on existing platforms and transport via existing pipelines

The most important cost reduction must come from scaling up and further technology development.

North Sea Wind Power Hub

The North Sea Wind Power Hub consortium, consisting of TenneT (the Netherlands and Germany), Energinet (Denmark), Gasunie and the Port of Rotterdam, is investigating the possibilities of creating one or more energy islands on the Dogger Bank in the middle of the North Sea. These so-called Power Link Islands are intended to become the breeding ground for large-scale wind production and also form the link between the various North Sea countries. One of the important goals of the Power Link Islands is the large-scale production of hydrogen via Power-to-Gas, which can then be transported and (temporarily) stored. Transporting energy with hydrogen as an energy carrier is one of the possible solutions to get large quantities of wind energy to land.

2. Storage of green hydrogen in existing fields and pipelines

The future sustainable energy system not only has fluctuations in demand but also in production with a larger share of sustainable sources of energy. These variations occur over days and seasons due to the changing supply of electricity from wind and sun. Flexibility within the energy system can be achieved through demand and production control, conversion, storage and the expansion of transport capacity. The storage of green hydrogen, on which the emphasis is placed, is therefore one of several options for achieving flexibility.

Hydrogen storage is possible on land as well as at sea. Reuse of pipelines and empty fields may save costs when stored at sea. For storage in pipelines, hydrogen is either blended into the current natural gas network or stored in pure form when the pipelines are no longer in use for the transport of other gases. In addition, hydrogen can be stored in larger quantities in empty gas fields and salt caverns.

There is still little insight into the technical and economic possibilities for storing large quantities of green hydrogen. With the assumed accumulation of electricity generated by wind in the North Sea, a large amount of electricity will become available for the production and storage of green hydrogen.

Figure 11 shows which decisions are needed for the storage of green hydrogen. As in the case of production, there is sufficient time to investigate and realise offshore storage. Market research into storage needs is the crucial first step for the coming year. Another important aspect to consider is legislation on hydrogen storage, for example in empty fields, or on the percentage that can be added to the existing gas system. That is now 0.5%, but in

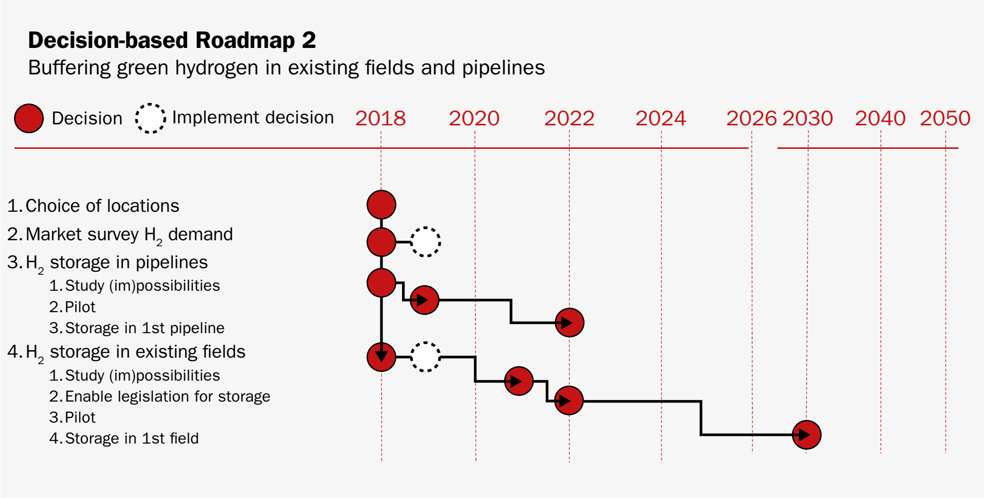


FIGURE 11: Decision-based roadmap for buffering of green hydrogen in existing fields and pipelines

Germany it is 10%. Furthermore, there are many technical questions concerning the storage of hydrogen in empty fields and the transport in existing pipelines. In order to allow storage in pipelines, decisions on pilot projects to achieve operational storage in 2022 are needed in 2019. For storage in existing fields, there should be a decision for operational large-scale storage in 2030 by 2022.

3. CO_2 storage in existing fields

Reuse of existing pipelines, platforms and empty gas reservoirs for CO_2 capture and storage helps to speed up the energy transition. A great deal of research has already been done into the (im)possibilities of CCS and many roadmaps and scenarios are available, including EBN and Gasunie (2010) and The Rotterdam Climate Initiative (2010). EBN and Gasunie are currently working on an update of the CCS roadmap.

How much storage is needed?

Providing flexibility through storage is one of the options to enable a large-scale wind scenario in the North Sea. The question that arises is how much storage capacity is needed. By comparison: 10 GW of wind capacity, an estimate of the planned capacity in 2030, will deliver ~315 PJ/year which equals ~9 bcm of hydrogen gas when all wind electricity is converted. This means that a few small gas fields would suffice for the needed buffering capacity.

CCS is already technically possible, but not yet financially feasible. In order to make this possible, a number of decisions are needed, in particular on the financing of an initial small-scale storage facility, the postponement of the completion of infrastructure, electrification of suitable platforms and, most importantly, the introduction of a minimum price for CO_2 (see Figure 12). These decisions are all (partly) the responsibility of the Ministry

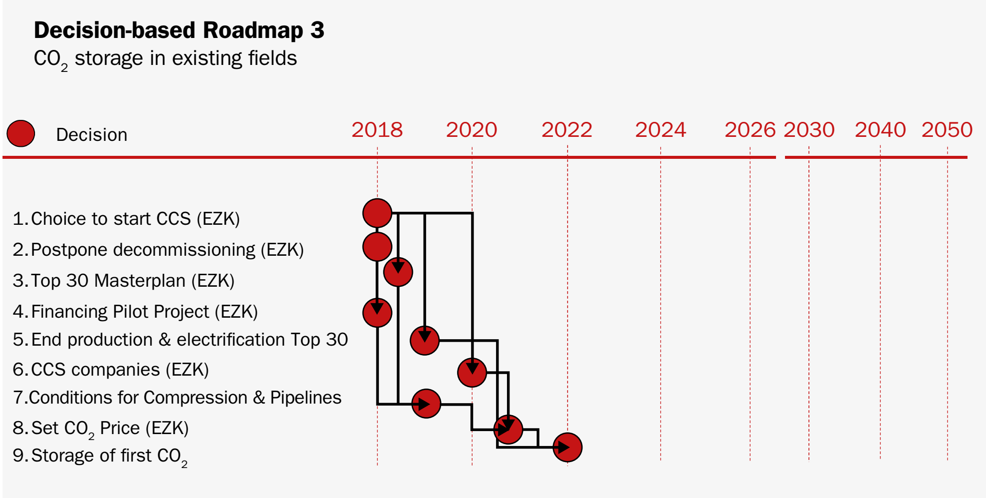


FIGURE 12: DECISION-BASED ROADMAP FOR CO_2 STORAGE IN EXISTING FIELDS

of Economic Affairs and Climate. Rapid decision-making will make it possible to store CO2 under the North Sea from 2022 onwards, particularly in a number of empty fields near the coast of South Holland.

OTHER SYSTEM INTEGRATION OPTIONS THAT DO NOT ACCELERATE THE TRANSITION

1. Electrification of platforms - springboard for the transition

Electrification of existing platforms contributes to the energy transition in the North Sea, but does not count as a transition accelerator. Indeed, electrification in itself does not ensure a transition to sustainable sources of energy or the reuse of existing capacity, but rather a reduction in emissions (CO_2, NOx, particulate matter) from existing platforms. However, platform electrification does have a prominent role to play in enabling the production of, for example, green hydrogen on existing platforms and the storage of energy or CO_2 in existing infrastructure. It provides energy for and contributes to reducing emissions from the facilities needed to make this possible. For this reason, electrification of platforms that can play a role in the production and storage of hydrogen and storage of CO_2 is considered a springboard in the transition.

2. Production of blue hydrogen from existing infrastructure

Blue hydrogen can be produced offshore from fossil sources on existing platforms, followed by storage of CO_2 produced. As with electrification, this does not accelerate sustainable energy production in the North Sea, but it does reduce CO_2 emissions.

Blue hydrogen production is important for the energy transition for two reasons. Production can help to build up a hydrogen infrastructure and market until green hydrogen production is competitive. At the same time, it can accelerate the rollout of CO_2 transport and storage infrastructure by connecting more CO_2 sources.

However, the production of blue hydrogen offshore is much more expensive than on land and lacks the advantage of low transport costs compared to methane. In addition, the Port of Rotterdam already has infrastructure available on land for this purpose. The production of blue hydrogen therefore has a role to play in the transition, but the question is whether this should be done offshore.

3. Offshore production of electricity from gas
Gas-to-Wire (GtW) converts gas directly into electricity. If the CO_2 is captured and stored in a gas field during this process, it is referred to as low-CO_2 electricity. This process does not contribute to accelerating the energy transition. In a sense, GtW is even delaying the transition, because it makes it possible to extract fossil energy that was not previously economically viable. An economic advantage of GtW is that it makes more efficient use of the existing offshore infrastructure for electricity transmission. With CCS, GtW is a business model to deliver low-carbon energy, but not an accelerator or springboard for the transition.

OPPORTUNITIES AND TURNING POINTS

IN THE PREVIOUS CHAPTERS WE DISCUSSED VARIOUS OPTIONS FOR SYSTEM INTEGRATION AND THEIR POSSIBLE CONTRIBUTION TO THE TRANSITION TO A SUSTAINABLE AND FLEXIBLE ENERGY SYSTEM. A number of turning points around this issue need to be addressed if offshore system integration is to become a reality. In this chapter we present an overview of the opportunities and turning points around offshore system integration, insofar as these have not yet been discussed in previous chapters.

OPPORTUNITIES

Reuse of existing infrastructure to enable future scenarios

The greatest opportunity that offshore system integration offers is a cost reduction in the construction of offshore wind production and the phasing out of offshore gas production. There is a future scenario in which large amounts of offshore wind power (12 to 60 GW in 2050) will be installed at larger distance offshore. Within each of the future offshore wind scenarios, an important role for hydrogen as an energy carrier is foreseen. Existing infrastructure can play an important role in this respect in the form of the reuse of pipelines for (hydrogen) gas transport, the storage of energy in the form of gas in existing pipelines and empty gas fields, and platforms as a location for hydrogen production in the transition phase to energy islands. This gives system integration the flexibility it needs to make large-scale sustainable energy production cost-effective and fit into the energy system.

Urgency

The previous chapter reveals that system integration may offer opportunities to accelerate the energy transition. The first decisions to make systems operational will be necessary in the very short term in order to achieve the climate goals. In addition, the availability of existing infrastructure is a crucial factor in view of the rapidly approaching phasing out of oil and gas infrastructure in the North Sea. This urgency offers an opportunity to take steps towards the transition in the short term, but at the same time requires a great deal of effort because the period of time required to achieve this is relatively short.

Momentum - electrification of certain platforms as kick-start

An important opportunity that arises to enable system integration is the momentum that is currently being created around the electrification of platforms. Electrification has already been realised for a platform close to the Dutch coast with a power supply from land and is now the use of offshore wind energy is being investigated as a real option for electrification. In addition, the use of transport and storage of CO_2 in empty gas fields offshore has been in the spotlight for many years. A new CCS roadmap is being developed in which suitable offshore locations for storage are discussed in the scenarios. These platforms also need to be electrified for the conditioning of CO_2 for injection and transport.

Whereas electrification has now outgrown the research phase, Power-to-Gas is currently in the spotlight when it comes to R&D. There are a large number of initiatives to bring PtG from the lab into practice, such as the TKI-funded research programme North Sea Energy Program of TNO and the New Energy Coalition, the Reuse & Decommissioning Platform NexStep of EBN and NOGEPA, and the North Sea Wind Power Hub Consortium of TenneT, Energinet, Gasunie and the Port of Rotterdam.

TURNING POINTS

Hydrogen of the future - supply and demand
In this document, we have outlined a scenario in which green hydrogen production can make an important contribution to the energy system of the future. Of course, this scenario depends on a number of developments that are intended to make this production cost-effective. For example, the development of hydrogen demand will largely determine when and where this production starts. Currently, hydrogen consumption in the Netherlands is around 800 kilotons, produced entirely on land from natural gas.

The main users of this hydrogen are refineries, other chemical industries and producers of fertilisers and ammonia. The Rotterdam industrial cluster accounts for about 50% of current hydrogen consumption. This may provide an opportunity to use the energy generated by offshore wind directly on land, both in the form of sustainable electrons (electricity) and molecules (hydrogen). In this way, the need to strengthen the onshore transmission grid could be limited.

Whether the market demand for hydrogen remains the same or grows depends on a large number of developments within industry, mobility and households. Choices for our energy carriers of the future will help to determine the scale of green hydrogen production at sea. In addition to future scenarios, there are also spatial and technical issues that determine whether, when and where sustainable hydrogen production facilities should be set up. For example, the availability of compact and efficient electrolysers and fresh water is one of the technical conditions for producing significant amounts of green hydrogen on platforms. In addition, as already mentioned, the construction of offshore energy islands is very likely to be necessary in order to achieve the necessary hydrogen production in 2050.

CO_2 in the North Sea
CO_2 capture and storage offshore has been the focus of attention for many years and a large number of scenarios for the rollout of CCS are available. This abundant information, combined with experience from this field, offers an opportunity to bring system integration closer. For example, technical knowledge about CO_2 transport and storage can be used to further investigate transport and storage for hydrogen. In addition, the scenarios for CO_2 storage capacity can be used to test and set up the availability for hydrogen storage. When making scenarios, it is important to know that cyclic hydrogen storage and permanent CO_2 storage also compete with each other when it comes to storage space.

A field that has been put into operation for the permanent storage of CO_2 is no longer available for the temporary storage of hydrogen. The same applies to the use of existing pipeline infrastructure for the transport of CO_2 or hydrogen. In addition, a scenario of accelerated availability of green hydrogen as a feedstock for industry offers opportunities to reduce the need for hydrogen production in combination with CO_2 storage. For this reason, it is necessary to coordinate the plans for these different forms of storage in order to arrive at optimum scenarios for the energy system.

The CO_2 price is both an opportunity and a turning point. In chapter 3 the CO_2 price was already mentioned as one of the most important factors to put the different options for system integration into practice. At the moment, the price of CO_2 is less than EUR 10 per ton. This makes both electrification and

CO_2 storage, the two most important factors for growing to hydrogen production in the North Sea, economically unfeasible. This can be made possible, for example, by the introduction of a price floor for CO_2 emissions by the government or by increasing the price within the Emissions Trading Scheme (ETS) by withdrawing market rights.

Legislation and regulations
Legislation and regulations on the various options for system integration can form a barrier in the transition to the new energy system. A great deal of work in this area is already available from the CATO research programme (CATO 2017) on the transport and storage of CO_2. With regard to hydrogen, DNV GL concludes in a study into the possible introduction of hydrogen in the Dutch onshore gas network that transporting 100% hydrogen is technically possible, but that current regulations can lead to major problems for large-scale hydrogen transport (DNVGL 2017). Adequate solutions for this are of great importance for the success of offshore system integration, but also for the role of system integration in the energy transition in general.

Who will organise the energy system of the future?
One of the major challenges within a large-scale issue such as the energy transition in the North Sea is who is going to organise the energy system of the future. Because the North Sea is used intensively for various purposes, including energy production, food supply and transport, the design of this new sustainable energy system involves a large number of stakeholders, all of whom have their own roles and interests in the design of this new system. As described in chapter 1, the design of the energy system of the future requires an integrated approach in order to arrive at an optimal scenario for the entire North Sea. This requires a much broader view than a purely business perspective on system integration. Dealing well with any conflicting interests determines the success of system integration and the energy transition in the North Sea.

For system integration, time is added as a determining factor, emphasising the urgency of action once again. The period in which infrastructure must be reused is short due to the imminent phasing out of the gas infrastructure. Determined action is needed in the very short term to seize the opportunities offered by system integration. The next ten years will be crucial for the development of the North Sea as a sustainable energy source for the Netherlands and for determining whether we can make use of the value offered by system integration in the coming decades.

FINALLY

This document shows that offshore system integration may offer opportunities for the transition from the old to the new energy system in the North Sea. This integration could possibly lead to a cost reduction in the phasing-out of oil and gas installations on the one hand and the build-up of offshore wind capacity on the other. At least as important is the fact that it enables a sustainable energy scenario in the North Sea. System integration can potentially make a major contribution to the landing of large quantities of wind energy through the production, transport, conversion and storage of green hydrogen. To take advantage of this opportunity, it is necessary to accelerate the construction of offshore wind energy in such a way that sufficient electricity is available for conversion to green hydrogen to meet the required storage capacity.

Successful offshore system integration requires social business cases in which not only the industrial value of the installations in the North Sea is taken into account, but also the value for society as a whole. If only financial incentives are involved, there is a chance that this will lead to sub-optimal scenarios for the design and use of the North Sea. There is a risk that installations and infrastructure with an important hub function for the new energy system will be lost.

There is therefore a strong need for systems thinking, so that in 2050 and beyond there will be room for economic use of, food production on and preservation and improvement of the ecological values of the North Sea. In this way, the Netherlands can set an example for the other North Sea countries in their transition to a sustainable energy system.

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Ellen van der Veer
Joris Koornneef
Rene Peters

CONTACT
Rene Peters
ENERGY
Location Delft - Leeghwaterstraat
rene.peters@tno.nl
☎ 088 866 6340

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