Integrated Offshore Wind and Hydrogen Production in the Northern Seas

An Expert Paper describing a Pathway to Scalable Renewable Energy Deployment

January 2026

HyNOS

Hydrogen Network Operators
of the Northern Seas

I. Executive summary

Europe's energy transition requires a balanced mix of electricity and molecules to achieve climate goals, energy security, and industrial competitiveness. Hydrogen will play a critical role alongside electrification, particularly for hard-to-abate sectors and for system flexibility. Offshore wind expansion in the Northern Seas offers vast renewable potential, but integrating large volumes of fluctuating electricity requires new solutions. Electrolysers can convert surplus renewable electricity into green hydrogen, reducing curtailment and supporting offshore wind growth. Furthermore, hydrogen provides advantages such as low-cost transport via pipelines, large-scale storage, and enhanced system resilience.

Initially, electrolysers will be located onshore at the landing zones of offshore wind energy; later, electrolysers will be located offshore close to the wind farms at **integrated wind areas**, creating even more system benefits and infrastructure cost reductions. To unlock this potential, governments must assign integrated offshore wind areas, design tenders that incentivize electrolysis at integrated wind areas, and mandate electricity-TSOs and hydrogen-TSOs to jointly execute an integrated offshore electricity and hydrogen network planning, providing both an electrical and hydrogen network connection to the offshore wind area. Coordinated action by policymakers, electricity-TSOs, and hydrogen-TSOs is essential to design and deliver a flexible, cost-effective, and decarbonized Northern Seas energy system for Europe.

II. Background and introduction

Europe's energy system is undergoing a profound transformation. To meet climate goals, reduce reliance on energy imports, and maintain industrial competitiveness, a balanced mix of electricity and molecules will be essential. It is not a matter of choosing one over the other — both are needed. **Electrification where possible, molecules where necessary**.

Hydrogen will play a key role in Europe's future energy system. By integrating hydrogen into the offshore energy planning, Europe can build an independent, resilient, sustainable, and cost-effective energy system.

HyNOS — Hydrogen Network Operators of the Northern Seas — is a collaboration of emerging hydrogen transmission system operators (H2-TSOs) from Northern Seas-bordering countries: Belgium, Denmark, France, Germany, Ireland, the Netherlands, and the United Kingdom. Together, these countries recognize the potential of on- and offshore hydrogen production and infrastructure as a pillar of Europe's energy transition.

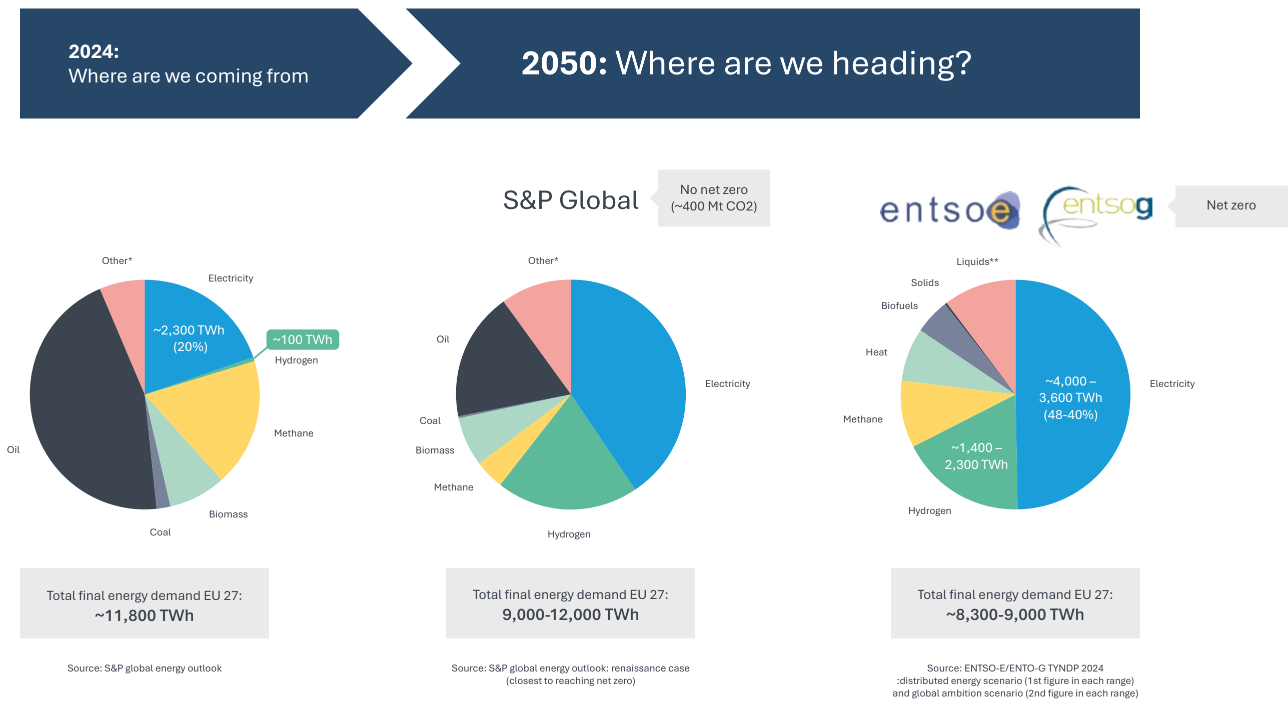
HyNOS aims to **build a shared understanding** of the benefits of hydrogen production – both on- and offshore - from the vast potential of offshore wind energy integrated in the electricity networks. This includes close coordination with electricity-TSOs (e-TSOs) in order to develop and plan integrated offshore networks, as well as active engagement with associations such as ENTSO-E, ENTSOG, and ENNOH. HyNOS also seeks an active dialogue with policymakers at the national and European level, for example through its contribution to the North Sea Energy Cooperation (NSEC)[1] and its Support Group 5 dedicated to the role of offshore renewable hydrogen and system integration.

This paper is HyNOS' first expert contribution, building on internal knowledge and insights from recent relevant studies. It is intended as input for the North Sea Summit in Hamburg and the ongoing ministerial collaboration within NSEC. It outlines the strategic role of hydrogen in Europe's offshore energy future and offers specific recommendations for policy, infrastructure, and market design.

III. The role of electrons and molecules today and tomorrow

The energy transition in Europe has clearly begun — and is irreversible. Over the next 20 to 25 years, we aim to decarbonize our energy system, reduce dependence on energy imports, and maintain affordable energy for industries and households. As a highly industrialized continent, **Europe must navigate the energy trilemma** — balancing sustainability, affordability, and energy security.

Let us first remind ourselves **where we are coming from** — the facts — **and where we are heading** — the vision. Progress has already been made. Renewable electricity production, mainly from wind and solar sources, has grown rapidly in recent years. Although electricity makes up only ~20% of total energy use on average in the NSEC countries, half of that electricity already comes from renewable sources. The significant shift to renewable sources in the last decades has been driven by investments in and policy support of increasingly technologically and commercially viable large-scale wind and solar power generation. Yet 70-80% of today's energy system still relies on carbon-based molecules. Although the energy transition is underway, we must not lose sight of the bigger picture in which a large consumer base still includes hard-to-abate sectors such as aviation, shipping, heavy transport, steel, refineries, chemicals, and high-temperature process industries. These sectors require alternative pathways and policies to decarbonization. That reality calls for a broader strategy that goes beyond electrification alone.



* Includes solid waste, charcoal, ambient heat and net trade of electricity & heat
** Includes e-fuels such as e-kerosene, e-diesel etc.

FIGURE 1: FINAL ENERGY DEMAND (TWH) SCENARIOS PER ENERGY CARRIER IN EU27 BY 2050

A comparison of S&P Global estimates for 2050 and the TYNDP scenarios from ENTSO-E and ENTSO-G for 2050 shows that, in both scenarios (see figure above), molecules and electrons each play a crucial role in Europe's 2050 energy mix. In both scenarios also methane will still be part of the 2050 system, even in the net zero case, e.g. by consumption of bio-gases, natural gas consumption in combination with carbon capture and storage solutions, and e-methane solutions (e.g. clean hydrogen-based).

In both scenarios hydrogen will be an important energy carrier in the final energy mix, representing ~15-20% of total demand. In addition, hydrogen is expected to be required for the production of derivatives that fall under the methane and liquid fuel categories. In both scenarios, the supply of hydrogen is expected to be a mix of both domestic production and imports.

The bandwidth in scenarios require that policy-makers will provide guidance to consumers of renewable energy as follows:

- **Electrify where possible**: Governments should continue their efforts to incentivize production and consumption of renewable electricity. Renewable electricity offers the most energy- effective path to carbon neutrality.

- **Use decarbonized molecules where necessary**: Hydrogen and its derivatives — such as green ammonia, e-methanol, and synthetic fuels — offer realistic solutions to hard-to-abate and to hard-to-electrify industry sectors, and to locations with electricity grid constraints. In addition to the ramp-up of green hydrogen consumption, the consumption of biogases and low-carbon hydrogen does play a role in the transition strategy towards green hydrogen in some countries.

The energy mix does consist of multiple energy carriers today and in the future. **Energy policy** for the planning of this system requires a **holistic approach** — one that considers production, transport, and consumption across all energy carriers.

IV. Advantages of hydrogen in the future energy system

Hydrogen and its derivatives deliver decarbonized molecules to various industrial sectors. It serves as feedstock for production processes (e.g. refinery, chemicals, fertilizer production), as fuel for heavy transport and aviation (e.g. synthetic fuels) and as energy supply for some industrial high temperature processes. Renewable energy is required for the production of green hydrogen, and therefore global and regional energy prices will determine to what extent hydrogen will be produced domestically or imported.

The advantages of hydrogen as an energy carrier when produced in the domestic European energy system are:

- Hydrogen can be economically transported in large volumes and over long distances via pipelines [2]. Pipeline transport costs are significantly lower than other logistic routes required for imported hydrogen. Compared to transport of electricity, hydrogen pipelines transport is more economic and robust. In addition, hydrogen network operators have the possibility to optimize the assets by repurposing some of the currently used natural gas pipelines. This saves investment costs and construction time.

- Hydrogen, being a molecule, can be stored for shorter and longer time in large quantities, independent from the location of production and consumption. It contributes to the resilience of the overall energy system by providing flexibility to capture excess production of renewable electricity (dispatch to electrolysers) and the possibility to re-dispatch to electricity powerplants at times of excess demand. Large-scale hydrogen storage solutions are currently being developed in Germany and the Netherlands.

- Hydrogen contributes to the phase-out of fossil molecules which are predominantly imported by European countries. The increase of sovereign energy production makes Europe's energy system more resilient and less influential to some of the geo-political developments.

- As a flexible electricity consumer, large-scale electrolysers well-located in the electrical network, increase the utilization and the efficiency of electricity networks. This effect is a dominant driver for large-scale electrolysers in coastal areas, at the landfall of offshore wind power, where they avoid grid congestion and additional investments for grid reinforcements in the onshore network. Electrolysers located at sea at the offshore wind farm would in addition increase the degree of utilization of offshore electricity cables[3].

In addition to the advantages of hydrogen to society, it offers an additional investment opportunity to investors and developers in large scale renewables assets, such as offshore wind farms. Project developers with the option to sell both electricity and hydrogen produced by offshore wind farms are able to serve two markets, while limiting price and volume risks between the commodities and still harvesting the full potential of all wind energy produced.

In the following three sections, we explore further how European countries around the Northern Seas can practically implement their vision for an integrated energy system of both electricity and molecules, in particular hydrogen. First, we describe the expansion of offshore wind in the Northern Seas as a key driver for renewable energy, and how hydrogen supports and complements this wind build-out (section 5). Then, we highlight the strategic choices regarding electrolysis — where and how hydrogen should be produced (section 6). Finally, we introduce and elaborate on a new paradigm: integrated offshore wind areas, where electricity and hydrogen production are co-located at sea, offering new opportunities for system efficiency and market flexibility (section 7).

V. Offshore wind expansion in the Northern Seas and the role of hydrogen

The North Sea region stands out as a strategic asset for renewable energy production for Northwest Europe. It offers shallow waters with good wind potential, proximity to energy-intensive industries of northwestern Europe, and world-class port logistics. Europe also hosts leading wind turbine manufacturers and a robust supply chain supporting the wind energy industry.

Recognizing this potential, countries within the North Sea Energy Cooperation (NSEC) — together with the United Kingdom — committed at the North Sea Summit in Ostend (2023) to a joint ambition of reaching 300 GW of installed offshore wind capacity by 2050.

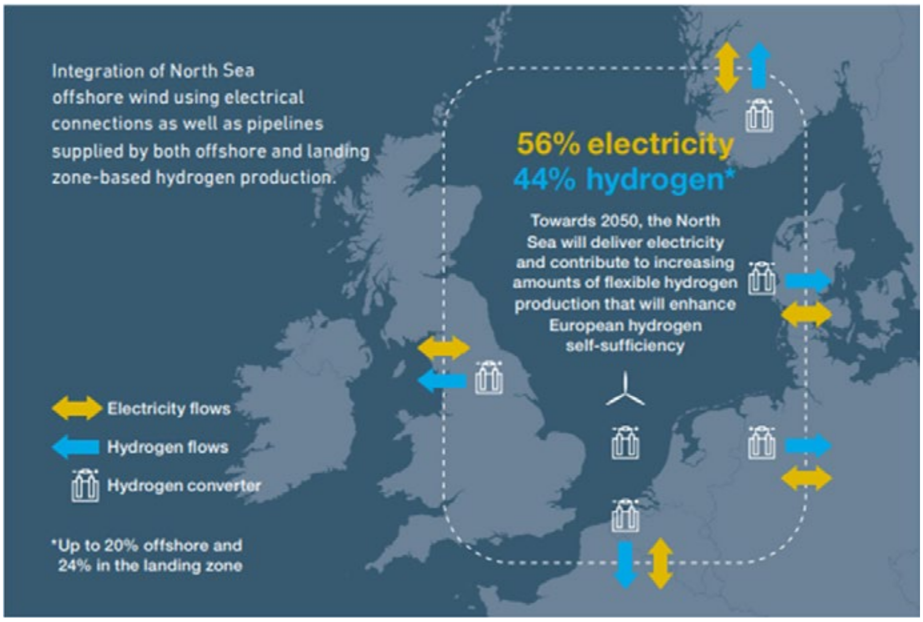


FIGURE 2: DISTRIBUTION OF ELECTRICITY AND HYDROGEN AT FULL INTEGRATION OF NORTH SEA OFFSHORE WIND IN 2050 (NSWPH)

The North Sea Wind Power Hub consortium (NSWPH)[4] has provided a very comprehensive overview and different analyses for the integration of large volumes of weather-dependent renewable energy volumes into the European energy system. As wind power build-out capacities increase, periods of curtailments become more frequent, especially in times of high electricity generation (windy days offshore) coinciding with low (onshore) electricity demand. In these situations, surplus electricity yields could be converted into green hydrogen at low cost: Hydrogen production from offshore wind energy can beneficially use excess renewable energy and thereby increase operating hours for wind turbines. One of the last reports that NSWPH produced, is the Pathway 2.0 Study[5]. This study incorporated more granular wind data and showed more specific options of flexibility that large-scale hydrogen production could provide to the energy system.

A very relevant, insightful main conclusion is that, when building out North Sea wind capacity to 300 GW in 2050, the optimally configured energy system could transport 56% of the energy to the onshore electricity grid and convert the remaining 44% into hydrogen, either produced offshore or in the coastal areas.

VI. Electrolysis: where and why

Electrolysers convert renewable electricity into green hydrogen. Although the basic principle for electrolysis is known for more than hundred years, developments to increase electrolysis efficiencies, optimize balance of plant options, improve manufacturing technology and scale up of production volumes are of interest since recent years. Along with these recent developments comes the questions about the optimal location for electrolysers - their location plays a critical role in the efficiency and cost of the overall energy system.

The general principle for the electrolysers location should be: Electricity used for hydrogen production should be converted as close to the renewable energy source as costs and infrastructure allow, thus reducing electrical infrastructure cost and prevent electrical energy transport losses.

Most of today's electrolysers are built either close to a strong existing electrical grid connection and/or at the site of the hydrogen offtaker ('behind the fence''). These early projects, often realized by integrated value chains between producers and consumers, range from 10 MW to 100 MW electrolysis capacity. They support the start and scale-up of green hydrogen consumption, the electrolyser supply chain and confirm business and market models.

Regional and national onshore hydrogen networks are expanding and do allow future electrolysis projects to be located more distant to offtakers. Electrolyser locations can then be governed by its proximity to renewable energy sources or at other geographically favourable locations in the electricity network.

As the build-out of offshore wind energy evolves, the optimal electrolyser locations gradually shift from onshore more towards offshore to increase proximity to the renewable energy source as shown by the NSWPH Pathway 2.0 study. Some large-scale electrolysers with direct connections to offshore wind farms are being planned or currently realized in the coastal areas, where wind farm electricity lands. Connections to the hydrogen onshore infrastructure are also realized at these coastal locations.

Two examples of projects with offshore wind powering electrolysers located at the coastal landing zone

Shell's HH1 electrolyser project, currently under construction in the Rotterdam harbour area, will get its power from the Dutch offshore wind farm Crosswind, which is developed by Shell and ENECO. Hydrogen will be used by Shell in its refinery in Rotterdam.

The Dutch offshore wind farm Oranjewind developed by Total Energies and RWE will power Air Liquide's Elygator electrolyser in Rotterdam that will produce green hydrogen for the refinery of Total Energies in Antwerp.

As the next step of the development, electrolyser locations will evolve directly at the offshore wind farms since they are able to create significant system benefits and can help to reduce costs for the build out of the energy system as NSWPH Pathway 2.0 study and other recent studies are indicating. Wind farms especially at the more remote locations in the North Sea, for example search areas 6-7 in the Netherlands and zone 4 and 5 in the German EEZ are candidate locations for such offshore electrolysers. Offshore location allows for more efficient use of electrical infrastructure.

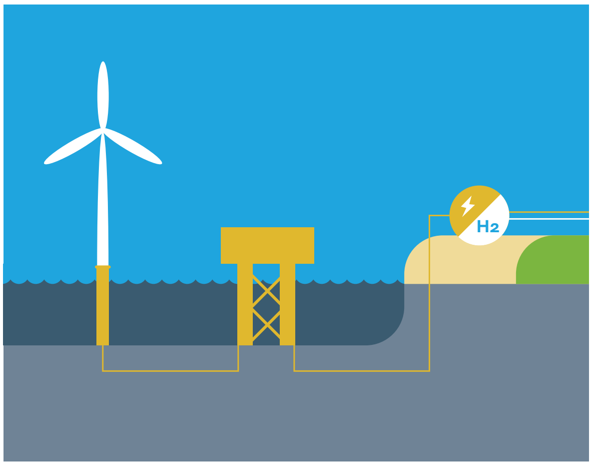


FIGURE 3: COASTAL ZONE ELECTROLYSER, POWERED BY OFFSHORE WIND FARM, CONNECTED TO HYDROGEN PIPELINE

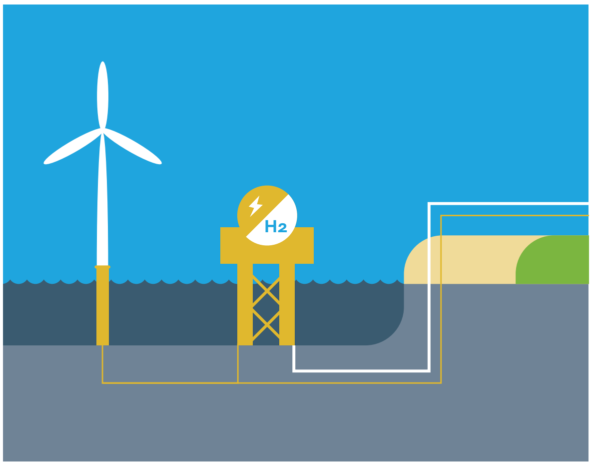


FIGURE 4: OFFSHORE PLATFORM-BASED ELECTROLYSER CLOSE TO THE OFFSHORE WIND FARM, CONNECTED TO OFFSHORE PIPELINE

VII. A new paradigm: co-located wind and hydrogen in integrated offshore wind areas

The expansion of offshore wind energy in the Northern Seas introduces a new paradigm in energy system design: integrated wind areas with wind turbines and electrolysis plants co-located offshore, and with a combined electricity and hydrogen infrastructure connection.

The integrated wind area hosts both wind turbines and electrolysers before the point of electrical grid connection. This gives wind farm operators the possibility to optimize electricity and hydrogen production at the wind farm. Furthermore, the electrical grid connection allows the use of wind energy from other offshore wind farms as well as renewable solar energy from onshore for conversion into hydrogen. The hydrogen produced will be transported to shore via an offshore hydrogen pipeline that is integrated into the onshore hydrogen network.

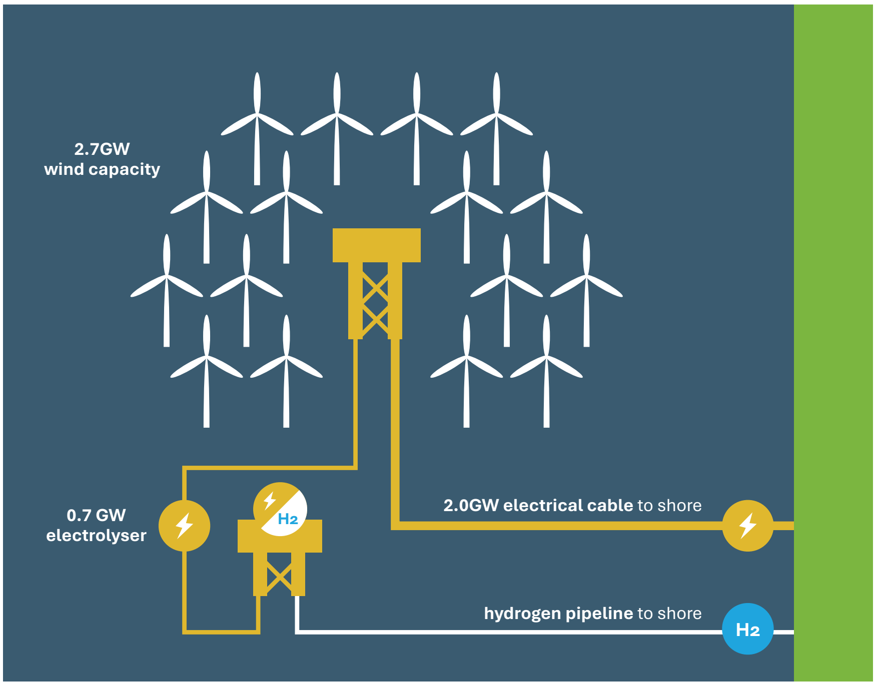


FIGURE 5: CONCEPT OF INTEGRATED WIND FARM OF 2.7 GW WITH 0.7 GW OVERPLANTING

The design of integrated offshore wind farms with a connection to both electricity and hydrogen infrastructure is an important steppingstone for the development of the North Sea energy system because it provides the possibility to increase the wind capacity of a wind farm with substantial "overplanted" wind turbines that exceed the electrical grid connection capacity and offers the opportunity for hydrogen production.

In the illustration of figure 5, the wind park has an electrical grid connection capacity of 2 GW and the overplanted capacity of the wind farm is 0.7 GW. The hydrogen produced by the offshore electrolyser will be transported to the offtakers.

Several studies[3 6] have shown that integrated wind areas with offshore electrolysers converting a certain portion of the energy into hydrogen with connections to both the electrical grid and an offshore hydrogen pipeline, provide better overall economics compared to full electricity generation.

The three main benefits of integrated offshore wind areas with dual infrastructure connections are:

- It offers wind energy developers an additional business opportunity and a derisking scenario to their investments. Energy can be exported either as electricity or as hydrogen, depending on demands and electricity prices.
- Society will benefit due to decreased need of direct subsidies on the long-term, as well as by enabling utilization of a larger wind potential.
- In case of overplanted wind farms investments in electrical transmission infrastructure will be reduced while achieving a higher degree of infrastructure utilization, hence contributing to overall energy system savings.

Designs and studies for offshore electrolyser platforms.

In the recent years several design studies have been done by commercial parties or as research project. Concept studies varied from electrolysis directly at the wind turbine (Siemens H2Mare project[7]) or at offshore platforms with capacities of up to 500MW, either on one single platform or multiple 120-200 MW platforms. Some developers even work on artificial energy island concepts as a possibility to reduce overall systems costs. A study shows[8] that PEM electrolysis technology qualifies better for offshore application compared to Alkaline technology. Assessments of saltwater consumption and treatment and brine exhaust were done. All design concepts include offshore-electrolysers, desalination, gas treatment equipment, compressors, balance of plant, among other things, and are based on a modular approach which can be scaled up.

Concept of a 4 x 180MW offshore electrolysis cluster

Even though concepts and design for large-scale offshore electrolyser plants are available, those designs and concepts are not ready for implementation yet. First demo-projects are needed to mature technologies and gather operational experience before scaling-up.

VIII. Tender design for integrated offshore wind areas

To deliver the benefits associated with integrated wind areas, policymakers will have to tailor tenders that will attract sufficient bids from project developers. Tenders shall support developers to competitively bid for direct electricity production and conversion into hydrogen for a part of the production and provide incentives for the contribution to the resilience of the energy system.

In current tender designs for pre-investigated wind farms in countries like Germany and the Netherlands offshore electricity grid access to connect the wind farm and provide the ability to reach onshore consumers is warranted. Within the tender for an integrated offshore wind area, a warranted connection to an offshore H2-pipeline is necessary and would allow the project developer to propose a suitable bid. The access to the offshore hydrogen pipeline assures the developer that onshore hydrogen consumers can be reached.

The recent slowdown in awarded offshore wind tenders across North Seas countries have resulted in revisions of future **tender frameworks**. One of the incentives that is considered to be implemented with the purpose of minimizing financial risk, is a system of Contract for Difference (CfD). Through CfDs project developers will have a long-term price warranty for a part of their wind energy production, next to production volumes covered in long-term power purchase agreements with individual customers.

While defining offshore wind tender models that include hydrogen production (integrated wind farm tenders), the impact of a proposed CfD-scheme on the volumes of hydrogen production needs to be carefully assessed. According to the definition of RFNBO-qualified hydrogen the source of its renewable energy may not be subsidized.

Contract for Difference schemes are considered subsidy schemes and may therefore, under current REDII and REDIII regimes, make volumes of hydrogen produced at integrated wind farms less attractive since they would not qualify as RFNBO-conform hydrogen.

Recent offshore wind-tenders with electrolysers in the Netherlands

In the past three years, the Dutch Enterprise Agency (RVO)[9] has issued and awarded offshore wind tenders, that included non-financial criteria. The bidders were called to propose options to support the integration of wind energy into the Dutch energy system.

For the tenders Hollandse Kust West VII tender (760 MW awarded in 2022), Hollandse Kust Noord V (700 MW awarded in 2024) and the Ijmuiden Ver-beta tender (2GW awarded in 2024), the bidding consortia included electrolysers.

IX. Unlocking the offshore H2 potential: required policies and regulation

H2-TSOs have started to develop and implement hydrogen networks on the mainland, connecting producers and importers with offtakers. In the future, those H2-TSOs will design and construct offshore pipelines that connect electrolysers located in coastal areas as well as offshore. For that development, we recognize that there are several items that require attention and further elaboration.

These are:

a) Mandate for joint electricity and hydrogen network and interface planning

North Seas e-TSOs and H2-TSOs, as organized in their collaborative groups OTC and HyNOS and supported by their associations ENTSO-E and ENTSOG/ENNOH, need a clear mandate by the TEN-E regulation for integrated electricity and hydrogen network planning. This will improve the planning process based on guidance of policy makers and other relevant stakeholders, within the countries as well as in the offshore region. ENTSO-E's future Offshore Network Development Plans shall increasingly include scenarios with offshore electrolysis plants.

In addition, connection concepts and grid codes need to be developed for offshore integrated projects including electrolysers that will be connected to the electrical grid. Designing and planning of interface concepts and codes requires alignment with all involved stakeholders and need sufficient lead-time.

Realization of integrated wind farms beyond 2035 implies that alignment and requirement processes need to start already today. TSOs and their associations need to initiate the processes pro-actively and give guidance to policy makers.

b) Large-scale electrolysers in coastal areas are part of the offshore system

Governments realize that the benefits of an integrated offshore wind energy system start with the realization of electrolysers at locations where vast amounts of renewable electricity lands, often the coastal areas. Integrated planning for both energy vectors hence starts with planning of coastal electrolysers and their dual network connections.

c) Assign integrated offshore wind areas and a corresponding tender design

Governments must assign integrated wind areas for combined production of electricity and hydrogen. Developers shall be supported by policies and warranted infrastructure access to be able to issue competitive bids for wind farms combining electricity and hydrogen production.

Offshore wind and hydrogen developers should be involved as key stakeholders in the design process of those tenders. Incentives need to be defined to realize offshore electrolysis projects. Support mechanisms (e.g. CfDs) to support offshore wind energy shall be tailored such that it also supports the production of RFNBO-compliant hydrogen.

d) Enabling and incentivizing demo and pilot projects for offshore electrolysis

As design studies for offshore electrolyser platforms have demonstrated, installation of large-scale offshore electrolysers is feasible, but financial and operational risks of an offshore industrial process plant need to be further assessed and mitigated. Demonstrator or pilot projects are a steppingstone to further de-risking, mature, and corresponding incentives for realizing such pilots are required.

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