Hydrogen Production from Offshore Wind and Hydrogen Infrastructure Development in Europe

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Summary

Offshore wind is positioned as one of the key energy supply sources in Europe's energy and environment strategy. According to the International Energy Agency, offshore wind power is expected to account for one-fifth of electricity supply in the European Union in 2040 (Sustainable Development Scenario).[1] Furthermore, the power generation cost of offshore wind has declined in line with the capacity expansion of wind power. Recent auctions have indicated that successful bid prices are now below $0.05/kWh (operation starts beyond 2025). Meanwhile, as a means to make best use of offshore wind resources, power transmission infrastructure development plays an important role. But hydrogen production is attracting attention in Europe as well for the same reason. The United Kingdom, Germany, the Netherlands and other North Sea countries have already started their efforts to promote hydrogen production with electricity from offshore wind. As for hydrogen transportation, which is another important issue to be considered in the hydrogen strategy, some European countries are planning to increase hydrogen blending ratios for gas pipelines as a short-term measure. They also have a plan to modify existing gas pipelines into those dedicated for hydrogen as a long-term strategy.

In Japan, offshore wind power generation projects were promoted after the enactment of the "Act of Promoting Utilization of Sea Areas in Development of Power Generation Facilities Using Maritime Renewable Energy Resources." However, constraints in grid connection capacity and the high cost of grid connection for offshore wind power are identified as the key problems for further development of offshore wind. In this regard, European experiences may suggest that hydrogen production with offshore wind power will be an option to avoid the grid interconnection constraints.

To achieve an 80% cut in greenhouse gas (GHG) emissions by 2050, Japan will have to low-carbonize the gas sector. It is necessary to accelerate policy discussion on how to transform the existing gas infrastructure to accommodate low-carbon gases including hydrogen.

[1] IEA, Offshore Wind Outlook 2019, https://www.iea.org/reports/offshore-wind-outlook-2019

1. Background

In December 2019, the European Commission released the European Green Deal aiming for net-zero greenhouse gas emissions by 2050.[2] In France and the United Kingdom, net-zero emissions by 2050 has already been legislated. Combining low carbon electricity with electrification of final energy consumption is one of the economical ways for GHG reduction. However, since not all the sectors could be electrified easily, CO_2-free hydrogen is getting more and more attention as a green substitute for fossil fuels in areas where electrification is difficult. Hydrogen production with renewable electricity can also absorb variable renewable energy's intermittency and ease its impact on the electric grid. It is for these reasons that hydrogen coupled with renewable energy is expected to be one of the key technologies to support a low-carbon society.

Offshore wind is positioned as one of the key energy supply sources in Europe's energy and environment strategy. From 2010 to 2019, offshore wind power capacity in Europe expanded about 6.5-fold (from 2,931 MW to 21,984 MW[3]). Meanwhile, the power generation cost of offshore wind continued to decline. From 2010 to 2018, the average offshore wind power generation cost decreased by 14% from $0.156/kWh to $0.134/kWh[4]. In some offshore wind auctions, the successful bidding price has dropped below $0.05/kWh (operation starts beyond 2025).[5] To make the best use of this low cost renewable resource, countries around the North Sea, which is the hottest spot of Europe's offshore wind development, are looking to using offshore wind for hydrogen production and have announced a number of feasibility studies and demonstration projects.

At the same time, how to develop hydrogen infrastructure to support the scaling up of the CO_2-free hydrogen[6] market, especially how to transform and utilize the existing gas infrastructure to accommodate hydrogen, has become one of the central issues in European countries' recent discussions on hydrogen development. This paper reviews the latest trends in offshore wind hydrogen production and hydrogen infrastructure development in 3 North Sea countries: the United Kingdom, Germany, and the Netherlands. And by studying the cases in these countries, this paper also looks at what the implications for Japan's offshore wind power and hydrogen development are.

[2] In December 2019, new European Commission President Ursula von der Leyen released the so-called European Green Deal seeking to achieve net-zero GHG emissions by 2050.
[3] IRENA, Renewable Capacity Statistics 2020, https://www.irena.org/publications/2020/Mar/Renewable-Capacity-Statistics-2020
[4] IRENA, Renewable Power Generation Cost in 2018, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf
[5] IEA, Offshore Wind Outlook 2019, https://www.iea.org/reports/offshore-wind-outlook-2019
[6] CO_2-free hydrogen includes green hydrogen from renewable energy sources and blue hydrogen from fossil fuels combined with CCS (Carbon Capture and Storage).

2. European trends for hydrogen production with offshore wind and hydrogen use

2.1. U.K.

The United Kingdom has the world's largest offshore wind power generation fleet. By the end of 2019, installed offshore wind power capacity in the United Kingdom has reached 9,800 MW and its power generation accounted for around 10% of the country's total.[7] The country intends to further expand its offshore wind power deployment to 30,000-40,000 MW by 2030. Given that the United Kingdom has legislated net-zero GHG emissions by 2050, decarbonization of non-electricity energy demand will also be required and CO_2-free hydrogen is one of the answers. With these contexts, hydrogen production with offshore wind power naturally is one of the promising solutions for the country's long-term energy supply. Two examples of the government supported initiatives on offshore wind hydrogen production are: the Gigastack project and the Deepwater Offshore Local Production of Hydrogen (DOLPHYN) project.

The Gigastack project uses electricity from the 1,400 MW Hornsea 2 wind farm[8] (operation starts in 2022) for hydrogen production and the hydrogen will be provided to an oil refining facility.[9] The project is led by electrolyser system manufacturer ITM Power with partners including Hornsea Wind Farm developer and operator Ørsted, oil refiner Phillips 66 Limited, and energy consultant Element Energy. One of the Gigastack project's major objectives is to develop a large low-cost electrolyser stack (Table 1). After a feasibility study that ended in 2019, the project has entered its second phase, which includes the design of a 100 MW hydrogen production system and the development of a business case for green hydrogen in the United Kingdom.[10]

[7] Department for Business, Energy & Industrial Strategy, Wind powered electricity in UK, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875384/Wind_powered_electricity_in_the_UK.pdf

[8] The Hornsea Wind Farm covers four subsites for total capacity at 6 GW. Its construction started in 2018 and Hornsea 1 is already in operation. Completion of all the subsites is expected to be in 2028.

[9] https://investor.phillips66.com/financial-information/news-releases/news-release-details/2020/Industrial-scale-renewable-hydrogen-project-advances-to-next-phase/default.aspx

[10] Phase 2 received a 7.5-million-pound subsidy.

Table 1 Electrolyser system performance improvement and cost reduction targets in the Gigastack project

FCH 2 JU Multi-Year Annual Work Plan Targets		State of the Art (2017)	2020	2024	2030	Gigastack
KPI1	Electricity Consumption @ Nominal Capacity (kWh/kg)	58	55	52	50	54
KPI2	Capital Cost (£/kW)[1]	1,090	820	640	450	300-400
KPI3	Degradation (%/1,000hrs)	0.25	0.19	0.125	0.12	0.09
KPI4	Hot Idle Ramp Time (s)	10	2	1	1	<1
KPI5	Cold Start Ramp Time (s)	120	30	10	10	<30

1: Assuming €1.10/£
KP4 & KP5 shall be considered as optional targets to be fulfilled according to the profitability of the services brought to the grids thanks to the addition of flexibility and/or reactivity (considering also potential degradation of the efficiency and lifetime duration.

Source: Element Energy, Gigastack Bulk Supply of Renewable Hydrogen, January 2020[11]

The DOLPHYN project's focus is on long-term green hydrogen supply and is looking at hydrogen production with floating offshore wind power. As offshore wind development goes further, sites suitable for bottom-fixed wind farms (in shallow water areas where the water depth is up to 50-60 meters) will become more and more scarce, and floating wind farms (deep water areas where the water depth is more than 50-60 meters) need to be developed in the long term. The United Kingdom and other European countries are also working on the commercialization of floating offshore wind power generation. Since floating wind farms are usually far away from onshore, the DOLPHYN project is considering a system design with on-site hydrogen production (with a water desalination and electrolyser system installed on a 10 MW floating wind platform) (Figure 1) and using an undersea pipeline to bring hydrogen onto land.[12] The project will start with a 2 MW prototype platform (the U.K. government will provide a 3.12-million-pound subsidy to the project[13]) and partners of the project include: Environmental Resources Management Limited, Tractebel Engie, ODE and others. The DOLPHYN project has set a target to cut hydrogen production cost to 1.15 pounds/kg ($1.41/kg[14]) or less beyond 2030.

11 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866377/Phase_1_-_ITM_-_Gigastack.pdf

12 According to an economic assessment by the project partners, on-site hydrogen production combined with an undersea hydrogen pipeline is more economically efficient than onshore hydrogen production from electricity transmitted from offshore wind power farms because, in this case, the offshore wind farm is far from the coast and the power transmission cost is high.

13 https://www.gov.uk/government/publications/hydrogen-supply-competition/hydrogen-supply-programme-successful-projects-phase-2#dolphyn

14 Cost of hydrogen production using natural gas combined with CCUS (carbon capture, utilization and storage) stands at $1.4-1.5/kg. (IEA, The Future of Hydrogen, https://webstore.iea.org/download/direct/2803)

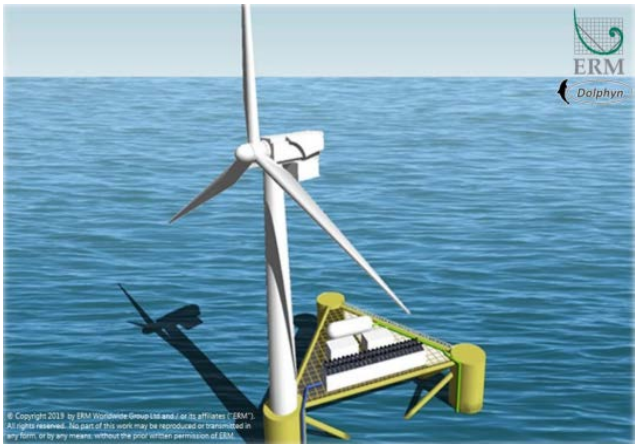

Figure 1 Floating wind farm platform designed for hydrogen production

Source: Department for Business, Energy & Industrial Strategy, Dolphyn Hydrogen Phase 1 Final Report, October 2019[15]

In the United Kingdom, CO_2-free hydrogen is perceived as a promising option for decarbonizing the gas sector. In 2018, heating demand accounted for 66% of the U.K.'s natural gas consumption (12% for the industry sector[16], 35% for the residential sector, 9% for the commercial sector and 10% for others).[17] Therefore, switching from natural gas to hydrogen to meet the heating demand will dramatically reduce natural gas consumption in the United Kingdom. To achieve the fuel switching, the United Kingdom has already kickstarted initiatives ranging from safety testing of consumer side hydrogen appliances to hydrogen infrastructure development.

For example, the Iron Mains Replacement Programme (IMRP)[18] which is already underway at present would save significant funding for hydrogen infrastructure development. In this programme, iron gas mains in the natural gas distribution grid is replaced with polyethylene (PE) ones (<7bar), which are suitable for hydrogen delivery. When the program is completed around 2031, about 90% of the gas distribution network in the United Kingdom is expected to be hydrogen ready[19].

Currently, the hydrogen blending ratio in natural gas pipelines is limited at below 0.1 vol% in the United Kingdom. As the first step to scale up usage of CO_2-free hydrogen, demonstrations are carried out to test the feasibility of higher hydrogen blending. One example is the HyDeploy project which is co-led by ITM Power and Keele University. In this project, the safety of 20 vol% hydrogen

15 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866375/Phase_1_-_ERM_-_Dolphyn.pdf
16 Including the energy conversion process in the industry sector
17 Gas (DUKES) (updated in July 2019), https://www.gov.uk/government/statistics/natural-gas-chapter-4-digest-of-united-kingdom-energy-statistics-dukes
18 This programme was implemented for safety considerations
19 https://www.icheme.org/media/11593/transitioning-to-hydrogen-report.pdf

blending to natural gas distribution pipelines and gas appliances without changes to these facilities is tested within the Keele University gas networks (this project was granted a special exemption from the Health and Safety Executive to the current hydrogen blend limit[20]). Like the HyDeploy project, the HyNET NW project also considers higher hydrogen blending into the existing gas infrastructure without replacement of the current gas appliances. At the same time, there are also projects focusing on the feasibility of switching from natural gas to 100% hydrogen such as the H4Heat project, H21 (H21 Leeds City Gate Project, H21NIC and H21 North of England) project, and the H100 project.

2.2. Germany

Germany has the world's second largest offshore wind power generation capacity (7,745 MW at the end of 2019) with a target of installing 15,000 to 20,000 MW offshore wind by 2030. Germany will phase out nuclear power by 2022 and coal-fired power by 2038 and is committed to renewable energy development, aiming to raise the country's renewable energy's share in the power generation mix to 65% by 2030.

In Germany, most of the wind farms are located in the north part of the country, while electric power load centers are in the south. Because of the constraints of north-south power transmission capacity, Germany proactively promotes the so-called Power-to-Gas (PtG) projects in which electricity from renewable energy is converted into hydrogen and the hydrogen can be used in various sectors. Since offshore wind farms are also in the north, further expansion of offshore wind will put more pressure on the already stringent power transmission limitations. Using offshore wind for hydrogen production is a possible solution to grid constraints and is gathering more and more attention.

In 2019, oil refiner Raffinerie Heide launched the Westküste 100 project in the northern German state of Schleswig-Holstein in cooperation with partners including Thyssenkrupp, EDF (Germany), Holcim Germany (a cement company), Open Grid Europe (OGE), Ørsted, Thüga Aktiengesellschaft (an investment company), the Heide Region Development Agency (a local government development organization) and Stadtwerke Heide (a local government-owned utility), etc. The project plans to produce carbon-neutral synthetic jet fuel from green hydrogen (hydrogen produced from renewable energy) and CO_2 captured at a nearby cement plant.[21] Green hydrogen will be produced with surplus electricity (electricity that otherwise would be curtailed) from the nearby offshore wind farm. For the initial phase of the project, a 30 MW electrolyser system will be installed within the 5-year project period.[22] Based on experiences from the initial phase, the electrolyser capacity might further be scaled up to 700 MW, and more applications of green hydrogen are also under consideration.

[20] https://www.itm-power.com/news/hydeploy-uk-gas-grid-injection-of-hydrogen-in-full-operation
[21] Framework of the project can be found at https://www.westkueste100.de/
[22] https://www.heiderefinery.com/en/press/press-detail/cross-sector-partnership-green-hydrogen-and-decarbonization-on-an-industrial-scale/

Because of the power transmission constraints and the increasing demand for CO_2-free hydrogen, hydrogen production with offshore wind is expected to further increase in Germany. In the National Hydrogen Strategy published in June 2020 it is mentioned that the framework for harnessing offshore wind for green hydrogen will be further developed.[23]

In terms of hydrogen infrastructure, utilization of existing natural gas infrastructure is given high priority in Germany. Germany allows hydrogen to be blended into natural gas pipelines at the ratio of 2 to 10 vol%[24] (differed by region) and there are already a number of demonstrations of blending hydrogen into natural gas pipelines. Projects of producing carbon-neutral synthetic fuels (such as methane and liquid fuels) from green hydrogen and CO_2 (as in the abovementioned Westküste 100 project) are also being carried out. Carbon-neutral synthetic fuels can not only contribute to CO_2 emission reduction but the utilization of such fuels does not require major changes to existing infrastructure or energy appliances.

Existing natural gas networks will also play a central role in the development of hydrogen infrastructure for the long term. At the Gas 2030 Dialogue, which was set up by the Federal Ministry for Economic Affairs and Energy (BMWi)[25] to consider the future development of gas infrastructure, how to handle hydrogen in the current gas networks is one of the key topics. The first draft report from the Dialogue suggests that hydrogen network development should be coordinated with the scaling up of hydrogen demand and dedicated hydrogen networks for industry and transportation sector users in some regions will be needed. It also emphasizes that existing natural gas infrastructure (including pipelines and storage facilities) should be utilized for developing hydrogen networks (for example the retrofitting of natural gas pipelines for hydrogen delivery).

In response to such government policy, FNB Gas, a group of gas transmission pipeline operators in Germany, has released a hydrogen network vision including dedicated hydrogen pipelines totaling 5,900 km (Figure 2). Of the hydrogen network vision, 90% of the hydrogen networks will be pipelines or storage caverns converted from existing natural gas infrastructure (retrofit). In May 2020, FNB Gas announced the H_2 Startnetz 2030 plan which is a proposal for a 1,200 km hydrogen grid in northern Germany by 2030 (1,100 km converted from existing natural gas pipelines and 100 km of new hydrogen pipelines). Investment requirement for the 1,200km hydrogen network is estimated to be around 660 million euros (1% increase of pipeline fees[26]). FNB Gas is also going to incorporate hydrogen into its new Gas Network Development Plan 2020-2030 and has conducted studies on mapping future hydrogen supply and demand (the distribution of domestic PtG facilities, hydrogen

[23] Federal Ministry for Economic Affairs and Energy (BMWi), The National Hydrogen Strategy, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

[24] IEA, Limits on hydrogen blending in natural gas networks, 2018, IEA, Paris https://www.iea.org/data-and-statistics/charts/limits-on-hydrogen-blending-in-natural-gas-networks-2018

[25] December 2018

[26] FNB Gas, https://www.fnb-gas.de/media/h2-startnetz_2030_mit_erlaeuterung.pdf

import terminals, and hydrogen end use facilities).

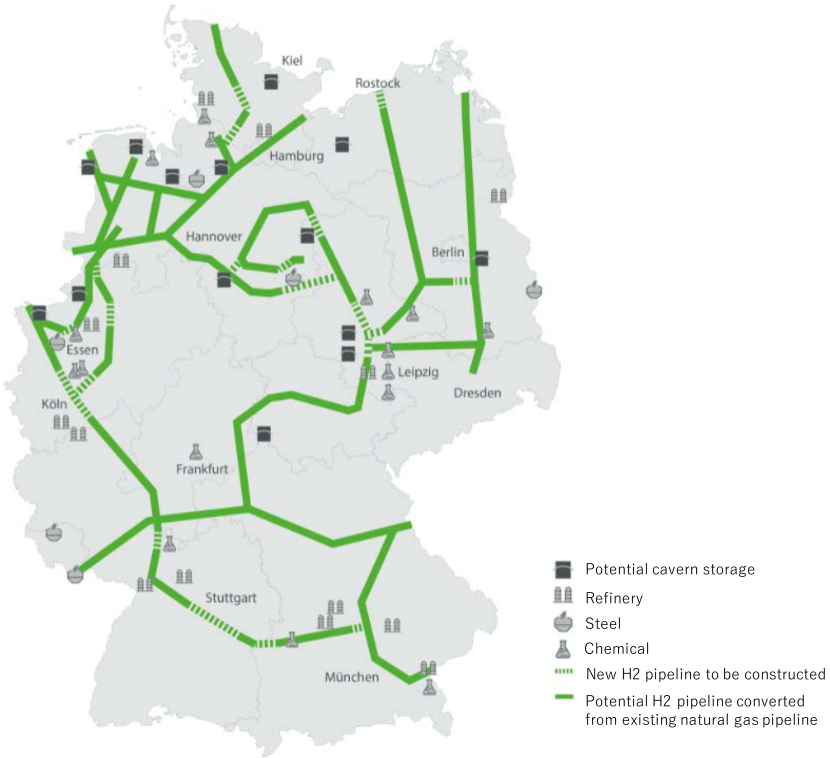

Figure 2 Hydrogen network vision

Source: FNBGas[27] (Modified by the author)

Demonstrations on building a hydrogen network using existing gas infrastructure have already begun. One of such efforts is the GET H2 Nukleus project,[28] led by BP, RWE, chemical manufacturer Evonic, and gas pipeline operators Nowega and OGE. The project seeks to build a green hydrogen production facility (a 100 MW electrolyser system using wind power) in Lingen, Lower Saxony States, northwestern Germany, and use a 130 km pipeline to deliver the green hydrogen to chemical facilities and oil refinery plants in Gelsenkirchen, Westphalia State. The pipeline is expected to start operation by the end of 2022. Most of the pipeline will be from existing natural gas pipeline retrofitted to handle 100% hydrogen with a small part of new hydrogen pipeline.

2.3. Netherlands

The Netherlands has set a target of cutting GHG emissions by 49% from the 1990 level by 2030 and as one of the efforts to achieve the target the country also decided to legislate a plan for

[27] https://www.fnb-gas.de/fnb-gas/veroeffentlichungen/pressemitteilungen/fernleitungsnetzbetreiber-veroeffentlichen-karte-fuer-visionaeres-wasserstoffnetz-h2-netz/

[28] GET H2 Nukleus project https://www.get-h2.de/en/get-h2-nukleus/

phasing out coal-fired power generation by 2030. At the same time, the Netherlands will halt its domestic gas production (shut down the Groningen gas field) by 2022. Gas produced at the Groningen gas field is the so called low-calorie gas with a nitrogen content of 14%.[29] Pipelines and end use appliances for the low-calorie gas are different from those for high-calorie gas (for example, gas imported from Russia). With the shutdown of the Groningen gas field, substitutes for the low-calorie gas will be needed and hydrogen is perceived as one of the promising options. The Dutch government, though accepting blue hydrogen (hydrogen from fossil fuels combined with CCS) for short-term use for economic reasons, plans to use mainly green hydrogen in the long term and positions hydrogen production with electricity from offshore wind as one of the key technologies for its future energy supply.

By the end of 2019 the Netherlands has about 1,118 MW of offshore wind power generation capacity and the country is looking to raise the capacity to 11,500 MW by 2030. To bring down green hydrogen production cost, the country has also set a target for electrolyser systems installation. According to the Climate Agreement published in June 2019, the Netherlands is going to install 3,000 to 4,000 MW electrolyser systems by 2030.[30]

Under the environmental and energy context, hydrogen production with offshore wind power is getting more and more attention in the Netherlands, not only from the government but also from energy companies. Oil giant Shell Netherlands, Dutch gas grid operator Gasunie and Groningen Seaports have jointly launched one of the world's largest green hydrogen projects, the NortH2 project, planning to install a 3,000-4,000 MW[31] electrolyser system by 2030. The project is going to use electricity from offshore wind farms in Eemshaven for hydrogen production. The project also seeks to further scale-up the hydrogen production capacity to 10,000 MW with 0.8 million tons of annual hydrogen production by 2040. In the same region with the NortH2 project (Groningen region), German energy companies RWE and Innogy are also conducting a feasibility study on hydrogen production using offshore wind power. The Dutch government plans to construct an energy island in the North Sea with offshore wind power generation and hydrogen production facilities by 2030. The government is also considering auctions of combined offshore wind power and hydrogen production projects.

For the long-term environmental policy, the Netherlands supports the European Commission's 2050 carbon neutral proposal and is preparing a bill to cut domestic GHG emissions by 95% from the 1990 level by 2050. CO_2-free hydrogen is expected to play an important role in the Netherlands' long-term energy strategy. And the period through 2030 is perceived as a critical preparation period towards scaling up of CO_2-free hydrogen deployment and supply in the long-term.

[29] The Oxford Institute for Energy Study, The great Dutch gas transition, 2019, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/07/The-great-Dutch-gas-transition-54.pdf

[30] Seeking to cut costs from 1 million euros/MW at present to 0.35 million euros/MW in 2030 (Climate Agreement page 181).

[31] In line with the Dutch government's target of installing a 3,000-4,000 MW electrolyser system by 2030.

The budget requirement for the government's hydrogen strategy by 2030 is estimated to be around 1.5-2.0 billion euros (Table 2).

Table 2 Estimated budget required on hydrogen programmes until 2030

Item	**Target year**	**Estimated budget (in millions of euros)**
Program development	Continuing	0.2-0.5/year
Realizing large-scale (gigawatt-class) hydrogen production	2030	1,000 or more
Construction of a hydrogen backbone in the Netherlands and hydrogen storage	2030	Undecided (including some private sector investment)
Deployment of controllable and flexible power plants using hydrogen	2030	250 or more
Pilot projects of hydrogen in the built surroundings (3-5 projects)	2025	10-0
Mobility on hydrogen (including hydrogen stations)	2025	10-20
Pilot and demo projects for hydrogen in industry	2025-2030	50-100
Integration of decentralized sustainable electricity production via hydrogen	2025	10-20
Designing and constructing an energy island for demonstration	2030	100 or more
Preconditions (including safety, legislation and regulations, gas quality, standardization)	2020-2021	10-20
Medium- to long-term R&D agenda	2020-2030	5-10/year

Source: Prepared by the author from TKI New Gas documents[32]

Like Germany, the Netherlands is also putting great emphasis on effectively utilizing the existing natural gas infrastructure for hydrogen network development. For the short-term, hydrogen blending into existing natural gas pipelines is what the government is looking to (raising hydrogen

[32] TKI New Gas, Multi-year Programmatic Approach for Hydrogen, https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/Waterstof%20voor%20de%20energietransitie%20-%20innovatieroadmap%20(jan%202020).pdf

blending from 2vol% to 10-20vol%) for scaling up hydrogen deployment. The country's hydrogen strategy[33] published in April 2020 indicates that there might even be a mandatory requirement for green hydrogen blending into the existing gas pipelines.

Gas pipeline operator Gasunie and other companies have launched several demonstration projects on converting existing natural gas pipelines for hydrogen delivery. For example, the Hydrogen Symbiosis project implemented in 2016 in the Netherlands' Zeeland region retrofitted a 12 km gas pipeline for hydrogen delivery purpose[34]. The pipeline has already started operation, with the hydrogen blending ratio around 70%[35] at the initial phase and is able to deliver more than 4,000 tons of hydrogen per year[36]. Gasunie is also implementing several other projects on pipeline hydrogen delivery for industry users in Eemshaven, North Sea Canal, Rotterdam, etc.

2.4. Others

In addition to the United Kingdom, Germany and the Netherlands, Denmark is also working on hydrogen production using electricity from offshore wind. In December 2019, the Danish government provided a more-than-$5-million subsidy to the H2RES project that is undertaken by 7 companies including Ørsted, the largest offshore wind power generator. Under the project, a 2 MW electrolyser system and a hydrogen storage facility will be built at the Avedore power plant in suburban Copenhagen, and electricity from an offshore wind farm operated by Ørsted will be fed into the system for hydrogen production (planned hydrogen production capacity is 600 kg per day). The hydrogen will be supplied to fuel-cell buses and trucks.

Ørsted has also proposed to the Danish government a plan for building an energy hub of offshore wind power and green hydrogen near Bornholm Island. The proposal includes an auction of around 1,000 MW offshore wind near Bornholm Island and construction of power transmission lines connecting Denmark and Poland via Bornholm Island, which is located between the two countries. Offshore wind power generation capacity could be further expanded to 3,000-5,000 MW to provide electricity also to other neighboring countries including Sweden and Germany. Using the electricity from the offshore wind farms for green hydrogen production is also within the scope of the project.

To effectively use the offshore wind resources in the North Sea region, multilateral cooperation is required. The North Sea Wind Power Hub (NSWPH) programme, which has been proposed by several power/gas network operators (Energinet for Denmark, Gasunie for the Netherlands and TenneT for Germany and the Netherlands) and the largest European port, the port of Rotterdam, is one of such multilateral efforts. According to the NSWPH programme, several existing

[33] Government Strategy on Hydrogen. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen
[34] Deliver by-product hydrogen generated at a Dow Benelux plant to fertilizer plants of Yara and ICLIP.
[35] http://www.vndelta.eu/files/4014/7573/9067/Europees_werkbezoek_LSNED_SDR_08092016.pdf
[36] https://www.weltenergierat.de/wp-content/uploads/2018/03/Bringing-North-Sea-Energy-Ashore-Efficiently.pdf

long-term scenarios suggest that offshore wind deployment in the North Sea could be as much as 150,000 MW by 2040.[37] For future offshore wind development in the North Sea, the programme proposes a Hub-and-Spoke concept (Figure 3): constructing several artificial islands in the North Sea with offshore wind power generation and water electrolysis facilities and the artificial islands will be used as energy hubs providing renewable electricity and green hydrogen to the surrounding North Sea countries.

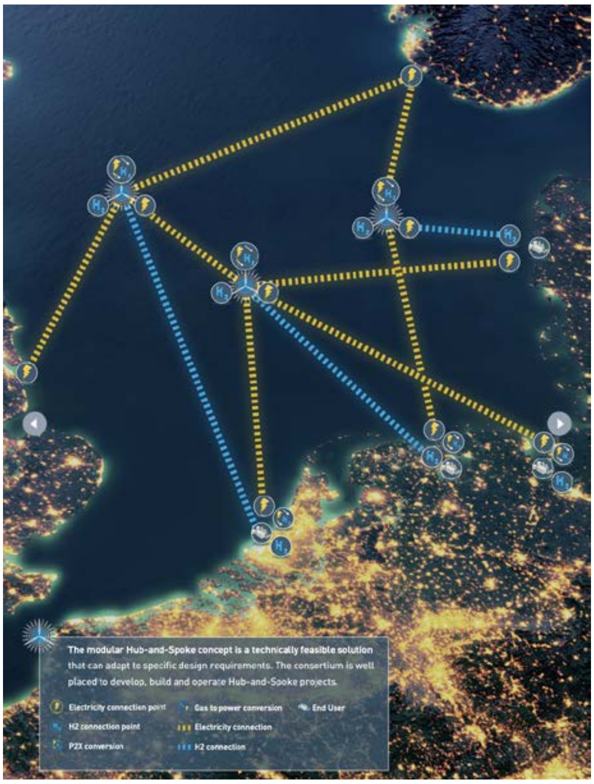

Figure 3 Hub-and-Spoke

Source: North Sea Wind Power Hub[38]

3. Conclusion and implications for Japan

Further scaling up of Europe's offshore wind deployment is not without challenges. For example, in order to make sure that electricity from offshore wind is delivered to users in inland areas, additional investment for reinforcing the onshore power transmission and distribution networks will be required. If a large amount of low-marginal-cost offshore wind electricity flows into electricity

[37] NSWPH report, The Challenge, https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_1-TheChallenge.pdf

[38] https://northseawindpowerhub.eu/wp-content/uploads/2019/11/NSWPH-Drieluik-Herdruk_v01.pdf

exchange markets, market prices will substantially be pulled down, which in turn will erode the revenue of offshore wind projects (the so-called cannibalism phenomenon). However, the challenges could partly be addressed by converting some of the offshore wind electricity into hydrogen.

Offshore wind exhibits a higher capacity factor (40-50% for new projects in Europe) and lower output intermittency compared with other variable renewable technologies such as onshore wind or solar PV, which makes it preferable for hydrogen production. Offshore wind has also been getting more and more economically competitive in Europe in recent years, with electricity prices even falling below $0.05/kWh for some auctions. The Hydrogen Council expects that hydrogen production cost with offshore wind power in Europe could become as low as $2.6/kg if proactive policies are in place.[39]

The North Sea is at the center of Europe's offshore wind development and demonstrations of feasibility studies on hydrogen production with offshore wind have already been launched in several North Sea countries. Some countries are even considering auctions of offshore wind combined with hydrogen production. Hydrogen production also plays a key role in multilateral initiatives for scaling up offshore wind deployment such as the North Sea Wind Power Hub programme.

In Japan, offshore wind power generation projects were promoted after the enactment of the "Act of Promoting Utilization of Sea Areas in Development of Power Generation Facilities Using Maritime Renewable Energy Resources." However, constraints in grid connection capacity and the high cost of grid connection for offshore wind power are identified as two of the key problems for further development of offshore wind power. In this regard, European experiences suggest that hydrogen production with offshore wind power might be an option to avoid the grid interconnection constraints.

Japan's technical potential for offshore wind is estimated to be around 1.5-1.6 billion kW.[40] In the case of a 35% capacity factor, offshore wind could supply about 5,000 TWh electricity per year, which is 4.7 times of Japan's current total annual power generation (1,051 TWh[41] in FY2018) and is equivalent to more than 80% of Japan's total primary energy supply (19,728 PJ[42] in FY2018). If offshore wind resources in Japan are utilized to the maximum extent, it could provide not only green electricity but also green hydrogen to the country's energy users.

However, given that Japan's offshore wind power generation costs are still high and that the domestic supply chain for offshore wind is still underdeveloped, large-scale hydrogen production with offshore wind power in Japan is not considered practical in the short term. Even if technical and

[39] Hydrogen Council, "Path to hydrogen competitiveness: A cost perspective," 2020, https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/

[40] Offshore wind resources in areas that are not allowed to be developed are excluded in the technical potential estimation. However, in the technical potential estimation, economic efficiency is not taken into account. Source: NEDO, "Renewable Energy White Paper," https://www.nedo.go.jp/content/100544818.pdf

[41] METI, Comprehensive Energy Statistics, https://www.enecho.meti.go.jp/statistics/total_energy/pdf/stte_030.pdf

[42] Op. cit.

engineering barriers could be cleared, hydrogen production with offshore wind power would still face challenges such as the economic competitiveness against other CO_2-free hydrogen supply options, ensuring enough domestic offtakers (that is, scaling up of domestic hydrogen deployment) and so on. Given the cases in the European countries studied in this paper, however, hydrogen production with offshore wind power could become one of the options for long-term energy supply.

In most European countries' hydrogen strategies, how to develop hydrogen infrastructure is one of the central issues. The countries studied in this paper (the United Kingdom, Germany and the Netherlands) all intend to develop their future hydrogen infrastructure with maximum utilization of existing natural gas networks. Shifting from natural gas to hydrogen is a long-term process which will require technical and regulatory changes to the existing natural gas networks and some of the natural gas appliances. The European countries are looking to raise hydrogen blending ratios into natural gas pipelines as a short-term measure to scale up the use of CO_2-free hydrogen and at the same time to gradually convert existing gas pipelines into dedicated hydrogen networks for the long term. In Europe, gas pipeline operators are actively engaging in developing hydrogen infrastructure.

Japan has set a target of cutting GHG emissions by 80% by 2050. Low-carbonization or decarbonization of the gas sector would be indispensable for achieving the target. While the natural gas network in Japan is not as developed as those in European countries, natural gas infrastructure in Japan will also need to be ready to accommodate low-carbon gases such as biomethane, carbon-neutral methane, as well as hydrogen. Given that a long-term viewpoint is required for infrastructure development, it is necessary for Japan to accelerate policy discussions on how to transform the existing gas infrastructure to accommodate those low-carbon gases.

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