Offshore wind and hydrogen

Offshore Wind Electricity to Hydrogen, Synthetic Gas and Liquid Fuels in the Baltic Sea

Interreg Baltic Sea Region
EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION
EUSBSR EU STRATEGY FOR THE BALTIC SEA REGION

State of play report

The State of play report is a product of an international project entitled "Baltic Offshore Wind Electricity to Hydrogen, Synthetic Gas and Liquid Fuels in the Baltic Sea" (acronym: BOWE2X). The project is financed by the Interreg Baltic Sea Region Programme Seed Money Facility and executed by a consortium of four partnering organisations:

1. The University of Greifswald from Germany,
2. The German Offshore Wind Energy Foundation (Stiftung OFFSHORE-WINDENERGIE),
3. The Energy Agency for Southeast Sweden (Energikontor Sydost AB) and
4. Forum Energi (FE) from Poland.

AUTHORS
Mariusz Wójcik
Thilo Krupp
Pierre Ståhl
Anika Nicolaas Ponder
Dàmir Belltheus Avdic
Tobiasz Adamczewski

GRAPHIC DESIGN
Karol Koszniec

PHOTO
©Askjell Nicolas Raudøy

DATE OF PUBLICATION
June 2021

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JUNE 2021

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Foreword

Hydrogen and renewable energy technologies will be fundamental in reaching a carbon neutral economy. Through its strategies on hydrogen and offshore renewable energy, along with new financial incentives, the EU is planning to be the frontrunner in both sectors.

Europe has already successfully proven a leadership role in RES deployment, with offshore wind energy being an excellent example. Nearly 90% of all offshore wind farms are located in Europe and now the technology is quickly being taken up by American and Asian markets. This success story can be repeated with hydrogen, which may be the missing link to making the energy sector, and other related sectors like transport or the chemistry industry, sustainable. If the levelised cost of green hydrogen produced from RES can be reduced to levels comparable to hydrogen produced from fossil fuels it can become a key advantage of the European economy and a means to reaching climate goals.

We hope that this report provides useful insights into the state of play of offshore wind and hydrogen technologies from a global and European perspective. Its purpose is to define key areas of action for further development of these sectors.

1. Key conclusions

1. Hydrogen production, or power-to-X in general, is likely to play a very important role in reaching the EU climate neutrality goal in 2050. It can help reduce emissions in hard-to-decarbonise sectors like heavy transport, aviation, steel industry, chemicals production.
2. The potential for hydrogen to help balance variable energy production from RES can be a game changer, provided that the cost of hydrogen outweighs the low efficiency of the process of power-to-hydrogen-to-power (estimated at around 30%).
3. Out of the currently produced 11.5 million tonnes of hydrogen per year, over 90% is produced from fossil fuels, with only 0.1% from RES (green hydrogen) and 0.7% coupled with CCS (blue hydrogen). It means a long path to increase the share of clean hydrogen, but also an immense potential to substitute its grey counterpart.
4. Within the first three top producers of hydrogen in Europe, two (Germany and Poland) are located in the Baltic Sea Region, together accounting for 32% of the market production.
5. Power-to-X technologies are currently at an early stage of development, which on the one hand means high uncertainty of deployment success, but on the other hand entails vast opportunity for first movers.
6. The European hydrogen strategy assumes green hydrogen production capabilities of 6 GW by 2024 and 40 GW within EU by 2030. However, not all countries, in particular in Eastern Europe, have adopted national hydrogen strategies. Usually, green hydrogen is mentioned in strategic documents as one of the elements in the path to a low-emission energy sector, but no distinct goals are given. In the Baltic Sea Region only Germany has fully adopted a dedicated hydrogen strategy while Poland developed a draft.
7. Offshore wind energy is nowadays gaining momentum worldwide, with very ambitious goals on the EU level, reaching 60 GW in 2030 and 300 GW in 2050. Many countries have also clearly defined strategic national goals for offshore wind.
8. The Baltic Sea is one of the biggest offshore wind markets after the North Sea. However, currently it accounts for only 9% (2.2 GW installed in the Baltic Sea) of European[1] offshore wind deployment – but the potential is estimated at some 93 GW.
9. All Baltic Sea Region countries have included (on different levels) offshore wind energy in their maritime spatial plans. However, there are very big differences in the level of ambition and the status of offshore market development. Germany and Denmark can be considered almost mature offshore wind energy markets. Sweden and Finland are currently focused on other energy investments but already have offshore wind assets. Poland and the Baltic States are still developing their first projects.
10. Offshore wind and green hydrogen technologies can bring great benefits, there are already initiatives investigating their coupling (some of them are described in this document). The initiatives are often promoted by wind farm investors or transmission system operators. Nevertheless, they are still at a conceptual stage and further investigations must be made. High capacity of offshore wind installations, availability of water, potential balancing capabilities of offshore wind energy makes hydrogen and offshore wind energy an attractive couple worth further exploring.

For more see also Chapters: Barriers and opportunities and Recommendations

1 Whenever Europe is mentioned it means EU plus United Kingdom and Norway.

2. Introduction

The state of play report is a product of an international project entitled "**Baltic Offshore Wind Electricity to Hydrogen, Synthetic Gas and Liquid Fuels in the Baltic Sea**" (acronym: **BOWE2X**). The project is financed by the Interreg Baltic Sea Region Programme Seed Money Facility and executed by a consortium of four partnering organisations:

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The general aim of this document is to present the current status, future potential and barriers of **power-to-X** technology development (mainly focusing on green hydrogen powered by offshore wind). Particular attention is given to the Baltic Sea Region. The main goal of this report is to identify barriers that can be addressed by future projects in order to enable the dynamic development of both technologies.

Power-to-X and in particular green hydrogen (produced from renewable energy sources) and blue hydrogen (produced with the use of carbon capture and storage) will play a crucial role in reaching net zero emissions. Clean hydrogen may in fact become the missing link to solve many of today's problems, such as:

1. **Intermittency of renewable energy sources –** excess energy may be used for hydrogen production, which can be further used to produce electricity when wind and sun conditions are not optimal,
2. **Reduction of greenhouse gas emissions in hard–to-decarbonise sectors** like heavy transport, aviation, steel industry, chemicals production etc. – green hydrogen may be used as feedstock in high-emission processes,
3. **Transition to a net-zero-emissions economy** – hydrogen and derived methane can be fed into the existing natural gas grid which allows countries with high dependency on natural gas to slowly substitute fossil fuels with clean hydrogen.

Within this document green hydrogen and offshore wind technologies are described individually in separate chapters, with the focus on current status of development and future potential and policy background. Possible solutions of coupling hydrogen and offshore wind were also analysed. Whenever possible, the information was provided for the EU level and for each of the Baltic Sea Region countries individually. Furthermore, the report provides a general outline of the current pipeline of offshore wind and power-to-X technologies.

3. Offshore wind energy

3.1. Offshore wind potential

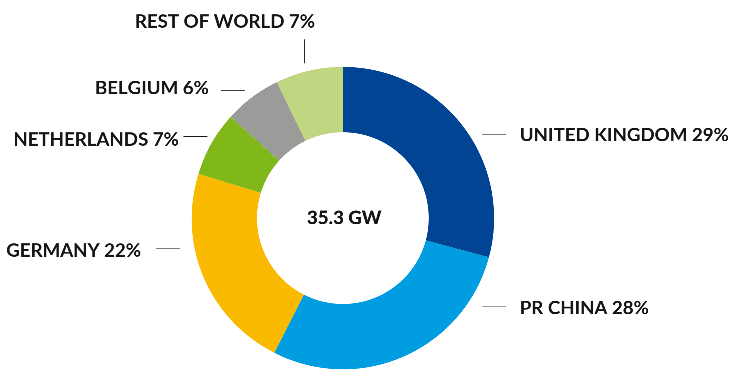
3.1.1. Global offshore wind potential

In 2020, the global offshore wind market reached a total installed capacity of 35.3 GW[2], with an increase of 6.2 GW since 2019[3].

The year 2020 was second best in history in terms of new added capacity, mainly in China (50%), the Netherlands (25%), Belgium (12%) and the UK (8%).

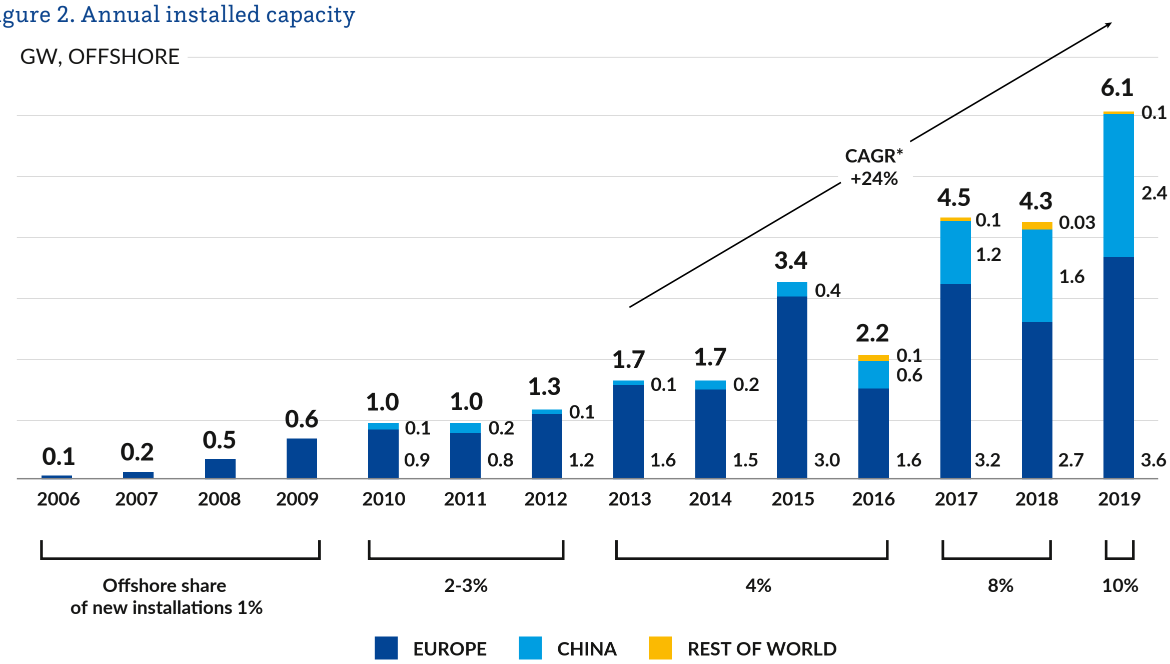
The UK remains the global leader in installed offshore wind capacity (29%), followed – and soon to be surpassed by – China (28%). They are followed by Germany (22%), the Netherlands (7%) and Belgium (6%).

Figure 1. Total offshore wind installed capacity by country at the end of 2020



Source: GWEC, *Global Wind Report 2021*, 2021. https://gwec.net/global-wind-report-2021/

Figure 2. Annual installed capacity



Source: GWEC, *Global Offshore Wind Report 2020*, 2021. https://gwec.net/global-offshore-wind-report-2020/

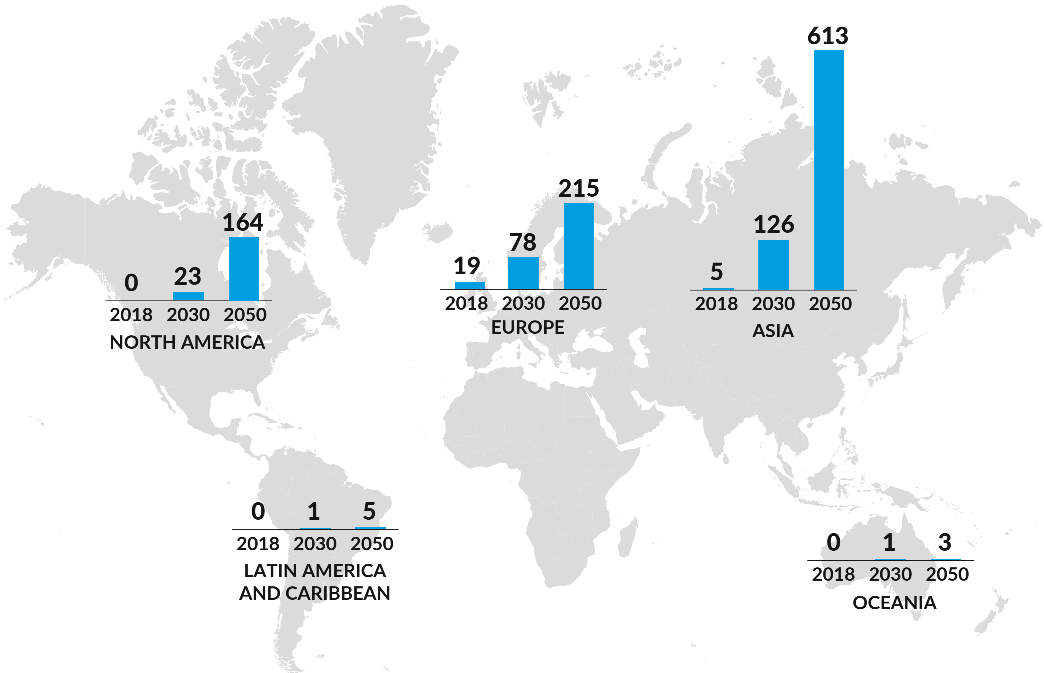
2 GWEC, *Global Wind Report 2021*, 2021. https://gwec.net/global-wind-report-2021/ [Access date 18.05.2021]
3 GWEC, *Global Offshore Wind Report 2020*, 2021. https://gwec.net/global-offshore-wind-report-2020/ [Access date: 24.04.2021]

It is estimated that by 2030 the global offshore wind market can grow up to 228 GW of installed capacity with Europe being a frontrunner and China close behind. It is worth to note that the US set a pace for offshore wind goals at a level of 30 GW by 2030.

By 2050 the potential for offshore wind is estimated to be nearly 1000 GW, with Asia taking the lead with 60% of global installations, followed by Europe (22%) and North America (16%).

In the next three decades the sector is expected to grow with an average 11.5% CAGR (Compound Annual Growth Rate).[4]

Figure 3. Offshore wind installed capacities (current and future potential)



Source: IRENA, *Future of Wind Deployment, investment, technology, grid integration and socio-economic aspects*, 2019. https://irena.org/publications/2019/Oct/Future-of-wind

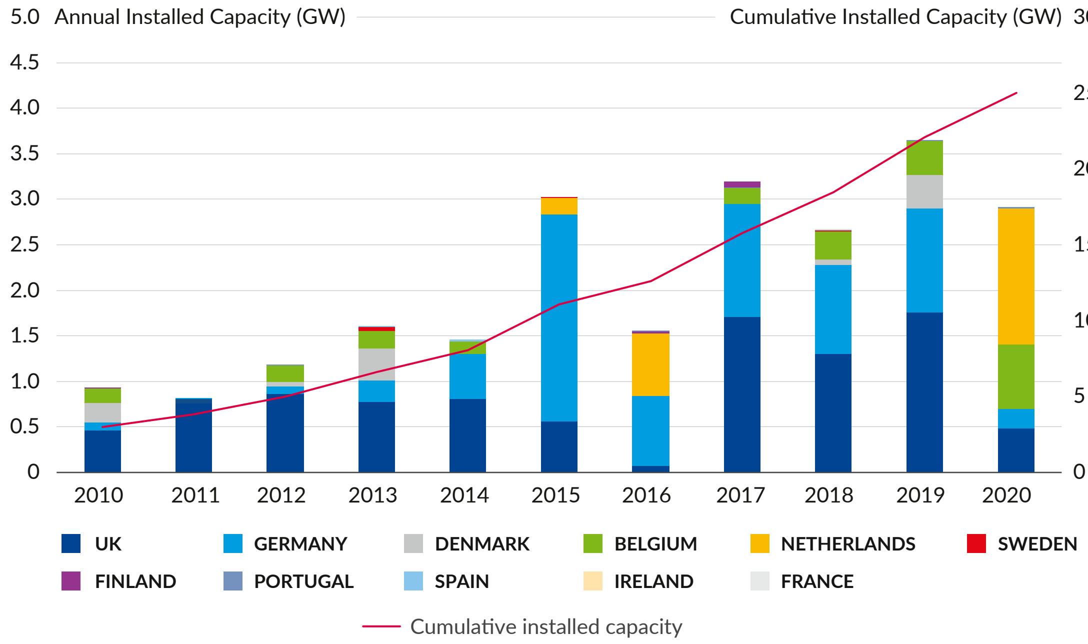
At the end of 2020, Europe had an installed offshore wind capacity of 25 GW. 79 % of this capacity is installed in the North Sea. The United Kingdom has the largest offshore wind capacity in Europe, with 42% of all installations. Thus, in the European Union (considering Brexit) there is an installed offshore capacity of around 14.5 GW.[5] But the EU has ambitious plans and targets to tackle climate change. The European Commission estimates to have an installed capacity of at least 60 GW by 2030 and the objective to reach 300 GW by 2050.[6] This long-term target will not only provide many EU households with clean energy, but will deliver green energy to other sectors (e.g. heating, mobility).

4 IRENA, *Future of Wind Deployment, investment, technology, grid integration and socio-economic aspects*, 2019. https://irena.org/publications/2019/Oct/Future-of-wind [Access date: 24.04.2021]

5 WindEurope, *Offshore Wind in Europe - Key trends and statistics 2020*, 2021. https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/ [Access date: 3.04.2021]

6 European Commission, *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf.

Figure 4. Annual offshore wind installation by country [left axis] and cumulative capacity [right axis] [GW]



Source: WindEurope, *Offshore Wind in Europe - Key trends and statistics 2020*, 2021. https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/

3.1.2. Baltic Sea potential

The Baltic Sea is one of the biggest offshore wind markets after the North Sea. It has many favourable conditions, such as shallow waters, low salinity and stable high wind speed. However, it only accounts for 9% of European offshore wind deployment. By the end of 2020 there was 2.2 GW installed in offshore wind in the Baltic Sea basin[7], mainly in Germany and Denmark. The future potential is however much harder to predict. There are many estimates related to offshore wind potential in the Baltic Sea basin taking into account different factors like technical potential, organisational maturity or national goals and political commitments.

According to WindEurope the Baltic Sea technical potential amounts to 83 GW, which would need to be installed to reach the European goal of 450 GW and be able to reach climate targets.[8] This value is close to the 93 GW technical potential identified within a BEMIP (Baltic Energy Market Interconnection Plan) study.[9] The same BEMIP study estimated also the economic potential basing on political commitments and economic capabilities – the ambitious scenario assumed 32 GW by 2050 and the low scenario approximately 16 GW by 2050. A study performed under the Baltic InteGrid project presented similar results where the Baltic Sea is expected to host up to 9.5 GW in offshore wind by 2030 and up to 35 GW by 2050.[10] These values were put together against the targets from the National Energy and Climate Plans in the table below.

7 WindEurope, *Offshore Wind in Europe - Key trends and statistics 2020*, 2021. https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/ [Access date: 3.04.2021]

8 WindEurope, *Our energy, our future*, 2019. https://windeurope.org/about-wind/reports/our-energy-our-future/ [Access date: 3.04.2021]

9 European Commission. *Study on Baltic offshore wind energy cooperation under BEMIP*, Brussels 2019, ENER/C1/2018-456. https://op.europa.eu/en/publication-detail/-/publication/9590cdee-cd30-11e9-992f-01aa75ed71a1/language-en [Access date: 3.04.2021]

10 Baltic InteGrid, *Baltic InteGrid: towards a meshed offshore grid in the Baltic Sea – Final report*, 2019. http://www.baltic-integrid.eu/index.php/download.html [Access date: 3.04.2021]

Table 1. Summary of identified potential offshore wind capacity in the BEMIP member countries

Country	Technical potential [GW]	Potential net energy production [TWh]	Offshore wind capacity under different policy scenarios by 2050		Offshore wind capacity by 2030 according to national energy & climate plans (NECP) [GW]
			Ambitious offshore development [GW]	Low offshore development [GW]	
Denmark*	19.5	70.7	2.8	2.1	10 GW offshore and onshore together (both North Sea and Baltic Sea) Offshore wind approx. 12% of final energy consumption**
Estonia	7	24	1	0.5	1.2 GW offshore and onshore together
Finland	8	26	4.5	2	5.5 GW offshore and onshore together
Germany*	8	29.1	6.4	4.3	20 GW offshore wind (both North Sea and Baltic Sea)
Latvia	14.5	49.2	1	0.5	1.1 GW offshore and onshore together
Lithuania	4.5	15.5	1	0.5	0.35 GW offshore (0.7 GW until 2035)
Poland	12	43.2	8.4	4	3.8 GW offshore (8 GW until 2040)
Sweden	20	68.2	7	3	Approx. 12 GW offshore and onshore together**
Total	**93.5**	**325.9**	32.1	16.9	Not applicable

*only Baltic Sea is considered, ** own calculations based on NECPs
Source: (1) European Commission. *Study on Baltic offshore wind energy cooperation under BEMIP*, Brussels 2019, ENER/C1/2018-456. https://op.europa.eu/en/publication-detail/-/publication/9590cdee-cd30-11e9-992f-01aa75ed71a1/language-en [Access date: 3.04.2021]; (2) National Energy and Climate Plans as published by European Commission. https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en

It has to be noted, that technical potential does not necessarily translate to realistic potential, due to political and economic reasons. From a technical perspective Sweden and Denmark are at the forefront in the Baltic Sea region. However, the situation is very different when looking at the potential under political scenarios, where Poland and Germany have the most backing.

It is also important to point out that the values presented above are only estimates and given very dynamic policy developments, in particular with the introduction and implementation of the EU Green Deal, and the situation may change, they can significantly change. Poland can be given as example, current Polish Energy Policy assumes up to 11 GW in offshore wind until 2040 whereas the BEMIP study assumes only 8.4 GW until 2050.

Presented below is a short summary of the Baltic Sea countries' current status on offshore wind energy development.

Germany

Since the end of 2020, 1.501 offshore wind turbines with a capacity of 7.770 MW are in operation in Germany. That is 31% of the offshore wind capacity currently installed in Europe. However, most of the German capacity is located in the North Sea. The Baltic Sea only accounts for 1.072 MW. No new offshore wind power projects are under construction, so no capacity additions are expected for 2021. Starting in 2022, offshore wind parks that have been awarded in the 2017/2018 bidding rounds are expected to be commissioned. These projects will gradually increase the total capacity to 10.8 GW by 2025. This also includes two offshore wind farms in the German Baltic Sea: The OWF Arcadis Ost (247 MW) will be commissioned in 2023 and the OWF Baltic Eagle (476 MW) in 2024.[11] There are no final investment decisions for offshore wind projects in the German Baltic Sea beyond 2025 yet, but there is still some untapped potential.

Denmark

By the end of 2020, Denmark had 559 offshore wind turbines connected, reaching a total capacity of 1.703 MW. This means that 7% of the offshore wind capacity in Europe is currently installed in Danish waters. 872 MW of this capacity is allocated in the Baltic Sea. However, these numbers exclude Denmark's largest offshore wind project, Kriegers Flak (605 MW), that is not yet connected to the grid. But this project does not stand out by size alone: Kriegers Flak is also an offshore hybrid project combining an interconnector with an offshore wind farm. Thus, this project allows the direct export of electricity to Denmark and Germany.

Poland

Currently there are no offshore wind farms in the Polish maritime areas but several projects are sufficiently advanced to give high probability of commissioning.

By February 2021 the Polish Transmission System Operator (TSO) has issued grid connection conditions or signed connection agreements for offshore wind farms with a total capacity of 8.4 GW.[12] These projects are still at an initial stage of development and don't have building permits yet obtained. However, in 2021 several contracts for difference for most advanced projects will most likely be signed and will speed-up the development. At the time of writing of the report 5 projects totalling 4.3 GW were given a positive decision of the energy regulatory office, enabling signing of the contract for difference. It is expected that the value will eventually reach 5.9 GW in projects.

Sweden

The history of offshore wind in Sweden goes back to 1990 when one of the world's first offshore turbines was installed. After this some small projects were built and then in 2007 a large wind farm, Lillgrund, was inaugurated. It contains 48 turbines with a total installed power of 110 MW.[13] In total there are 79 turbines in operation today with a capacity of 190 MW.

Offshore wind development in Sweden has slowed down. Even though some projects have permits and more are under development, none are under construction at the moment.

Technology development and political incentives in the last decade created a boom for onshore wind in Sweden. Due to cost competitiveness, the focus on offshore wind has been smaller. Uncertainty about the cost of grid connections for offshore wind power has also been a factor in preventing development of new projects. A potential national subsidy will be established during the first half of 2021 and project cost calculations can be made at a higher accuracy. After that it is expected that some projects will be implemented.

The potential for offshore wind energy in the Swedish part of the Baltic Sea is very high. SvK, the main Swedish TSO has received 50 GW of preliminary applications for grid connection at sea. Counting emerging technologies for floating turbines it is even higher. At the date of this report there are a number of projects under development in Swedish

11 WindGuard, *Status des Offshore-Windenergieausbausin Deutschland*, 2020. https://www.windguard.de/jahr-2020.html?file=files/cto_layout/img/unternehmen/windenergiestatistik/2020/Status%20des%20Offshore-Windenergieausbaus%20-%20Jahr%202020.pdf

12 *PSE podpisały kolejne umowy o przyłączenie do sieci morskich farm wiatrowych*. Polskie Stowarzyszenie Energetyki Wiatrowe – website, 3 February 2021. http://psew.pl/pse-podpisaly-kolejne-umowy-o-przylaczenie-do-sieci-morskich-farm-wiatrowych/ [Access date: 3.04.2021]

13 *Lillgrund – the largest offshore wind farm in Sweden.* Vattenfall website. https://powerplants.vattenfall.com/lillgrund/ [Access dat: 30.05.2021]

waters from the north part of the Baltic Sea to the west coast between Sweden and Denmark. An example is the Swedish part of the Kriegers Flak cluster developed by Vattenfall.

Finland

Currently there is one offshore wind farm project in operation in Finnish waters with a capacity of 42 MW (not counting wind farms located at the coast). Numerous projects are at the development stage; one, with the estimated capacity of 140 – 240 MW, was recently permitted by local authorities.[14]

Baltic states (Lithuania, Latvia, Estonia)

Lithuania, Latvia and Estonia do not have any offshore wind farms installed, however some development is taking place.

Lithuanian offshore wind sector is still at a very early stage. There are around 10 projects being developed but they are still at conceptual stage and require development of national regulations.[15] In December 2020 the Lithuanian government decided to prepare the first tender for 700 MW offshore wind farm which is to be launched in 2023. The plan is to build the first wind farm by 2030.[16] This will most likely initiate broader offshore wind development in Lithuania.

Latvia and Estonia also have not yet built any offshore wind farms and are developing several projects, which are still at a conceptual stage. In 2020 Latvia and Estonia signed a memorandum of understanding to develop a joint offshore wind farm in the Gulf of Riga. It will be a hybrid project with a capacity of 1000 MW consisting of a dual use transmission network and an offshore wind farm. A joint auction will be run in 2026.[17,18]

In addition, as of 2019 a total capacity of 2.5 GW in offshore wind farm applications have been filed in Estonia. According to maritime spatial planning, a further total capacity of 5GW is being planned.[19]

3.2. Clustering of Offshore wind farms and Hybrid projects

Traditionally each OWF has one electrical connection to one country (radial connection) – the country in whose territorial waters the wind farm is located. There are often several wind farms located close to each other and all with separate cables to shore. OWFs that are close to each other can logically be connected to each other. This can reduce the cost for grid connection. It also reduces environmental impact, with fewer cables and landfall stations. In many seas there are a large number of OWFs planned and cooperation is natural. For example, a large cluster is located in the North Sea outside Belgium and the Netherlands.

14 *Finland: Plans Approved for New Offshore Wind Farm*, offshoreWIND.biz news, 8 December 2020. https://www.offshorewind.biz/2020/12/08/finland-plans-approved-for-new-offshore-wind-farm/ [Access date: 6.04.2021]

15 *Offshore Wind farms in Lithuania*, 4COffshore website. https://www.4coffshore.com/windfarms/lithuania/ [Access date: 3.04.2021]

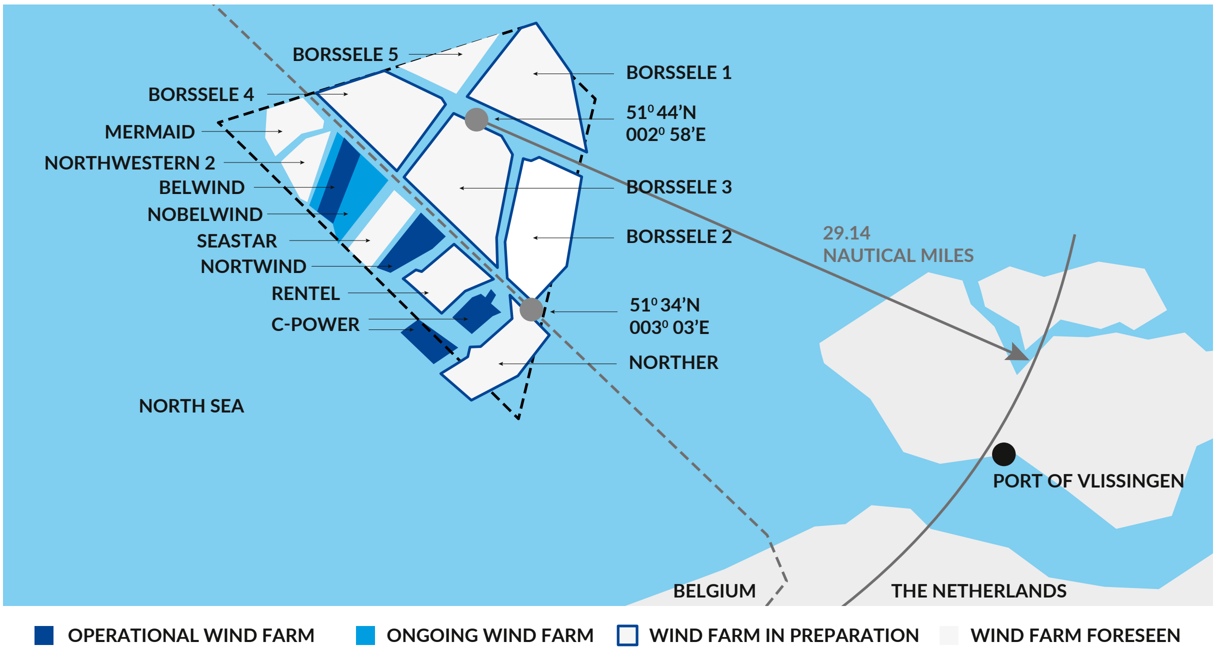
16 *Lithuania Pours EUR 7.5 Million into Preparation for First Offshore Wind Tender*, offshoreWIND.biz news, 3 December 2020. https://www.offshorewind.biz/2020/12/03/lithuania-pours-eur-7-5-million-into-preparation-for-first-offshore-wind-tender/ [Access date: 3.04.2021

17 *Estonia and Latvia in talks to build 1GW Baltic offshore wind complex*, RECHARGE NEWS, 9 December 2019. https://www.rechargenews.com/wind/estonia-and-latvia-in-talks-to-build-1gw-baltic-offshore-wind-complex/2-1-720837 [Access date: 6.04.2021]

18 *Significant developments on offshore wind in the Baltic Sea*, WindEurope Newsroom, 7 January 2021. https://windeurope.org/newsroom/significant-developments-on-offshore-wind-in-the-baltic-sea/ [Access date: 6.04.2021]

19 Estonia's Communication to the European Commission, *Estonia's 2030 National Energy and Climate Plan (NECP 2030), 2019*. https://ec.europa.eu/energy/sites/ener/files/documents/ee_final_necp_main_en.pdf [Access date: 11.04.2021]

Figure 5. Wind farm cluster in the North Sea

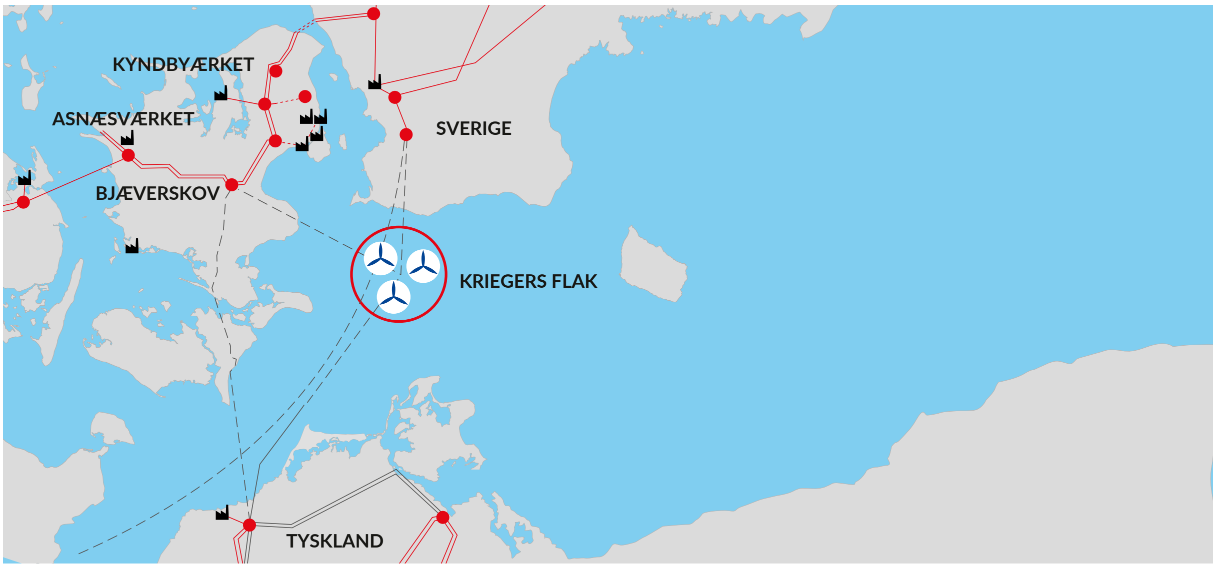


Source: Allaerts D. et al, *Annual impact of wind-farm gravity waves on the Belgian–Dutch offshore wind-farm cluster*, 2018. https://www.researchgate.net/publication/325831861_Annual_impact_of_wind-farm_gravity_waves_on_the_Belgian-Dutch_offshore_wind-farm_cluster

A limiting factor is the size and capacity of a single cable. If the offshore wind farm's size exceeds 1 GW in capacity, a separate cable can be needed and the benefit of clustering is less obvious.

Another concept are hybrid projects. This refers to projects where the connections of the OWFs are also used as interconnectors between two or more countries. The most well-known example is Kriegers Flak. The location is highly suitable for offshore wind power. The investment is divided into three segments, between the territories of Germany, Denmark and Sweden respectively. The completed Danish and German installations have a combined grid solution with the possibility to transfer electricity to both countries. A third segment, located in Swedish waters, is in its final permitting process and will hopefully be built within coming years.

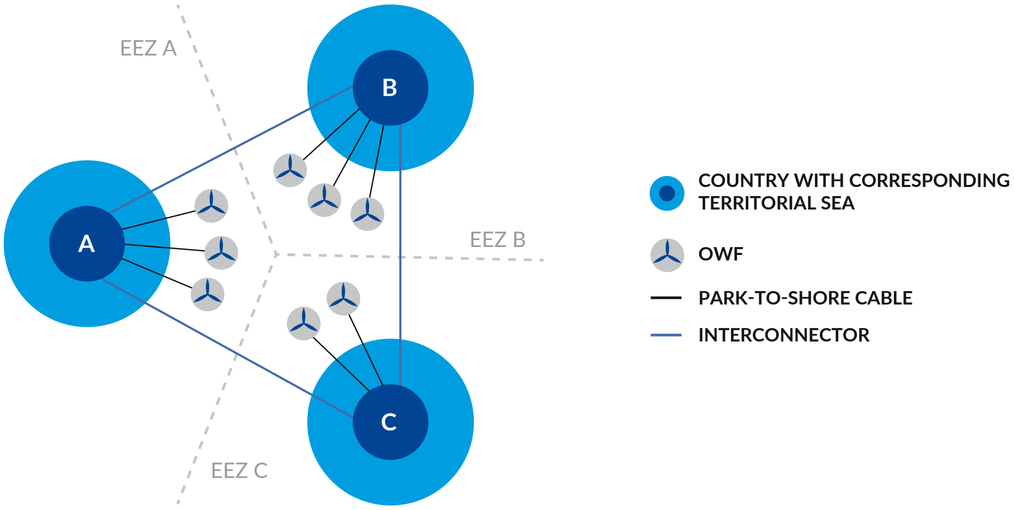
Figure 6. Kriegers Flak hybrid project



Source: Energinet.dk

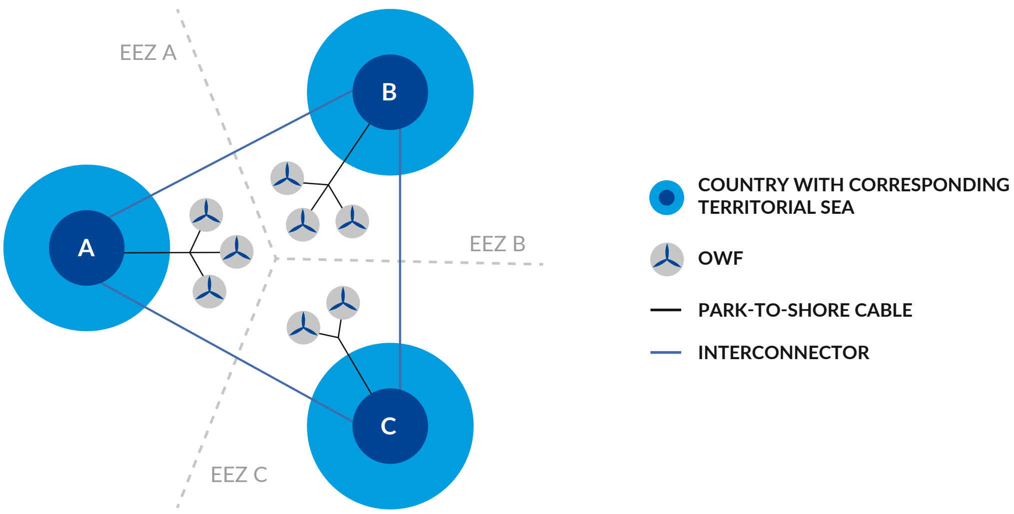
Pictures below give a schematic of different types of OWF connections.[20]

Figure 7. Radial connection and separate interconnectors



Source: Baltic InteGrid, *Baltic InteGrid: Establishing an offshore meshed grid, Policy and regulatory aspects and barriers in the Baltic Sea Region*, 2018. http://www.baltic-integrid.eu/index.php/download.html

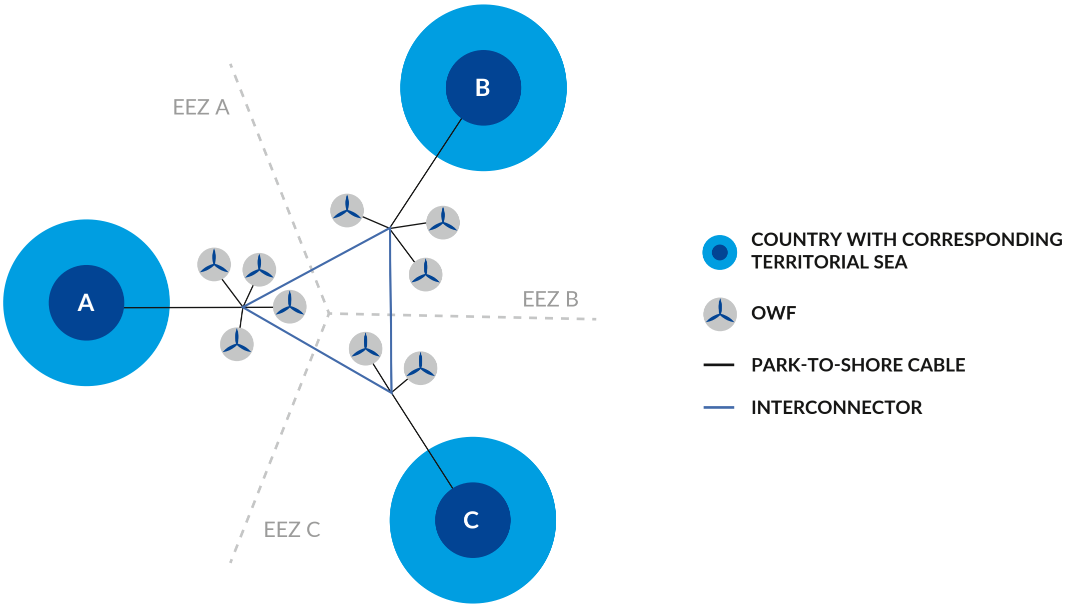
Figure 8. Clustering of OWFs and separate interconnectors



Source: Baltic InteGrid, *Baltic InteGrid: Establishing an offshore meshed grid, Policy and regulatory aspects and barriers in the Baltic Sea Region*, 2018. http://www.baltic-integrid.eu/index.php/download.html

20 Baltic InteGrid, *Baltic InteGrid: Establishing an offshore meshed grid, Policy and regulatory aspects and barriers in the Baltic Sea Region*, 2018. http://www.baltic-integrid.eu/index.php/download.html

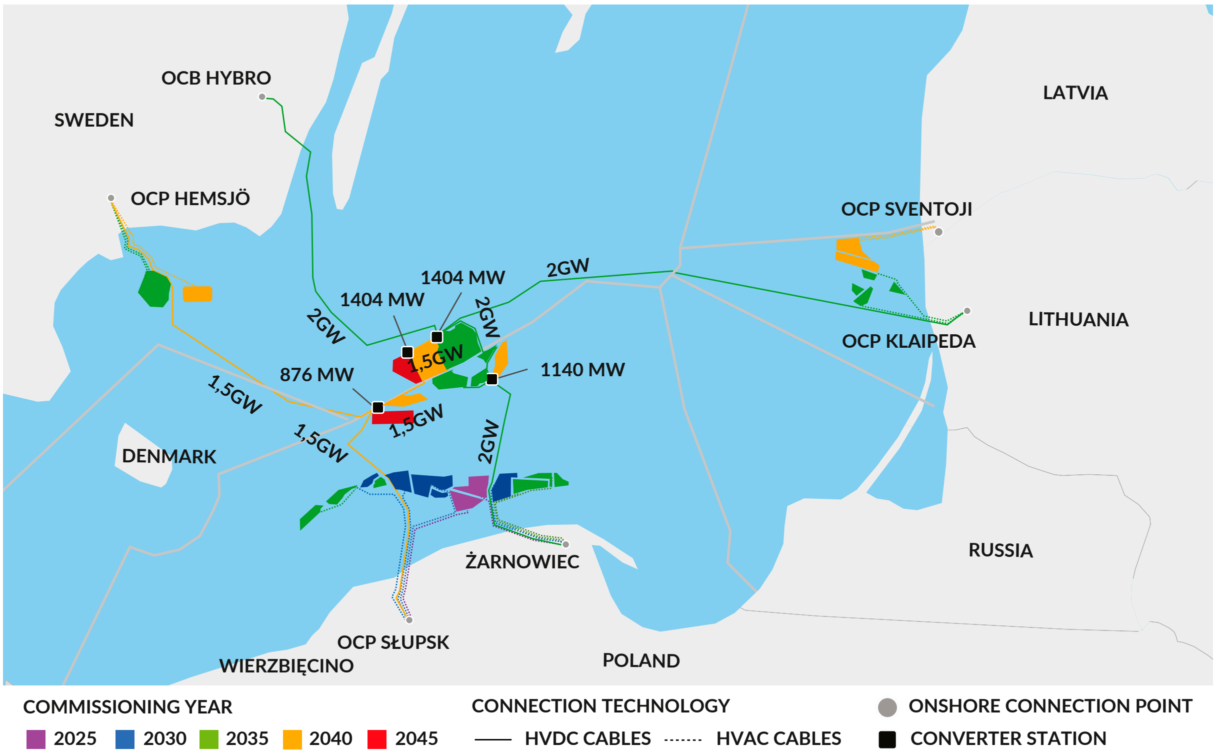
Figure 9. Hybrid projects with a meshed grid including interconnectors



Source: Baltic InteGrid, *Baltic InteGrid: Establishing an offshore meshed grid, Policy and regulatory aspects and barriers in the Baltic Sea Region*, 2018. http://www.baltic-integrid.eu/index.php/download.html

The planned large expansion of OWE in the Baltic Sea gives many opportunities for clustering and hybrid projects. Examples of how this can be done was explored in the Baltic InteGrid[21] project, as illustrated below.

Figure 10. Meshed grid concept in the south Baltic Sea, Baltic InteGrid



Source: Baltic InteGrid, *Baltic InteGrid: PreFeasibility Studies report September*, 2018. http://www.baltic-integrid.eu/index.php/download.html

21 Baltic InteGrid, *Baltic InteGrid: PreFeasibility Studies report September*, 2018. http://www.baltic-integrid.eu/index.php/download.html

3.3. Offshore Wind in Strategic Documents – European/regional level

European Union

The European Commission published an Offshore Renewable Energy Strategy on 19 November 2020.[22] The Strategy proposes to boost overall offshore wind capacity from 12 GW now to at least 60 GW in 2030 and 300 GW in 2050. This is to be complemented with around 40 GW of ocean energy and other emerging technologies by 2050.[23]

Offshore wind was often supported by technology specific auctions allowed in the past by the Renewable Energy Directive. Over the coming years, the Renewable Energy Directive will support cross-border projects in the form of joint and hybrid projects. The mechanisms such as statistical transfers or joint projects could also help countries with not access to sea to support the offshore wind energy development.[24]

On 30 September 2020, the European Commission and the eight EU Member States of the Baltic Sea Region signed a joint declaration.[25] This document stipulates an increase in offshore wind power production from 12 GW today to up to 450 GW in 2050, with the Baltic Sea accounting for up to 93 GW – making it a crucial pillar of the EU's energy mix. The Joint Declaration calls for a cooperative regional approach to reach this potential in the most efficient way possible. Specifically, the parties plan to intensify their cooperation within the Baltic Energy Market Interconnection Plan (BEMIP) High-Level Group and work on "*joint and hybrid offshore wind projects, as well as smart grids, offshore wind parks, energy system integration, low-emission offshore technologies and digitalisation*". Concrete joint and hybrid projects are highlighted, as well as enhancement of transmission infrastructure across the Baltic Sea. This meeting echoed one that took place among North Sea countries in July 2020.[26] The countries tasked the BEMIP High-Level Group to adopt a work programme for offshore wind development by the spring of 2021.

Germany

With the Amendment to the Wind Energy at Sea Act (WindSeeG) new expansion targets for offshore wind energy in Germany have been set. The previous expansion target was increased from 15 GW to 20 GW by the year 2030 and supplemented by a target of 40 GW of installed capacity by 2040.

Denmark

The current Danish political framework for 2020 to 2030 includes three new offshore wind parks with a total capacity of 2,400 MW. Furthermore, Denmark has identified roughly 12 GW of offshore capacity to be auctioned in the coming decade. The Danish government is evaluating plans to build an artificial energy island in the North Sea to serve as an energy hub for offshore wind power. The plan is for the island to be connected to the power grids of several countries. When fully connected, it will help transmit up to 10 GW of offshore wind across Europe. By supporting innovative projects like Kriegers Flak or developing energy islands, the Danish government is pushing offshore wind technologies to the next level.

Estonia

According to the National Energy and Climate Plan (NCEP), Estonia foresees potential development of offshore wind with capacity of 1 GW by 2030. Considerable attention is given to the joint projects with Latvia in the Gulf of Riga and west of Saaremaa. These projects could increase the connectivity in the Baltic States as the offshore wind farms can be connected with an interconnector between Latvia and Estonia.

One of the actions included in the NCEP includes the "pre-development of offshore wind farms (subscriptions, planning), joint project".

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22 European Commission, *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf.

23 *Boosting Offshore Renewable Energy for a Climate Neutral Europe*. European Commission website, 19 November 2020. https://ec.europa.eu/commission/presscorner/detail/en/IP_20_2096

24 Directive (EU) 2018/2001, OJ L 328, 21.12.2018

25 *Baltic Sea offshore wind joint declaration of intent*, 2020. https://ec.europa.eu/energy/sites/ener/files/signature_version_baltic_sea_offshore_wind.pdf

26 *Countries kick off cooperation on offshore wind potential in the Baltic Sea*. Climate Action Network Europe. 30 September 2020. https://caneurope.org/countries-kick-off-cooperation-on-offshore-wind-potential-in-the-baltic-sea/

Finland

Finland has set a goal of 51% of RES in final energy consumption in its Integrated Energy and Climate Plan. However, the Plan does not give any details on the planned capacity for offshore wind.[27] It has to be noted, however, that Finland focuses mainly on onshore wind development. The planned capacity of wind turbines is estimated at around 5.5 GW by 2030.

Lithuania

Lithuania approved a National Energy Independence Strategy for 2030. In the strategy Lithuania committed to increase the share of RES in its total final energy consumption to 45% in 2030 and 80% in 2050. The strategy does not provide a distinction between onshore and offshore wind capacities, but the estimates are that by 2030 wind will account for 53% electricity production.[28]

According to National Energy and Climate Plan of Lithuania the rollout of offshore wind assumes two stages: 350 MW in 2028 and an additional 350 MW in 2031.[29]

Latvia

In January 2020 Latvia adopted a National Energy and Climate Plan 2021-2030 and Strategy towards Climate-Neutrality 2050 (also known as the long-term strategy). There are no direct indications of planned capacity for offshore wind, however it is indicated that Estonia and Latvia have included in their policies and measures the development of an 800 MW wind farm.[30] This is in line with the announcement to develop a joint offshore wind farm in the Gulf of Riga with the capacity of 1000 MW (see section 4.1.2).

Poland

We can observe a dynamic change in the legal environment dedicated to offshore wind in Poland. In February 2021 the Polish Energy Policy until 2040 was adopted. The strategic document sets new goals for offshore wind energy with 5,9 GW capacity until 2030 and up to 11 GW until 2040.

Also, in February 2021 a dedicated act on the promotion of electricity generation from offshore wind farms came into force.[31] The act covers mainly issues related to a dedicated support system for offshore wind in Poland but also eliminates some regulatory barriers related e.g. to duration of chosen administrative procedures or possibility to change certain decisions. In March 2021, the Polish government has set the maximum value for the contract for difference at the level of 319.6 PLN/MWh (around 70 EUR/MWh with the exchange rate of 4.59 PLN/EUR).

Those and other regulatory actions show the commitment of the Polish government to develop offshore wind energy in the Polish maritime areas.

Sweden

The key strategic goal for Sweden is to have 100% electricity production from renewables by 2045. This was agreed in 2016 by five out of eight parties in the parliament. Recently, a debate has arisen since this goal excludes nuclear production. Some parties argue nuclear power is needed to have enough capacity to cover cold winter days with low wind. Others argue this can be achieved with storage and transmission solutions.

There is no specific goal for wind power and consequently none for offshore wind. Recently a strategy for sustainable wind power[32] was released. The report talks about a need for 80 TWh production from onshore

27 Ministry of Economic Afairs and Employment of Finalnd, *Finland's Integrated Energy and Climate Plan* , Helsinki 2019. https://ec.europa.eu/energy/sites/default/files/documents/fi_final_necp_main_en.pdf [Access date: 9.04.2021]

28 Ministry of Energy of Lithuania, National energy independence strategy executive summary – energy for competitive Lithuania [/Unofficial translation from Lithuanian to English], 2020 https://enmin.lrv.lt/uploads/enmin/documents/files/National_energy_independence_strategy_2018.pdf [Access date: 11.04.2021]

29 *National Energy and Climate Action Plan of the Republic of Lithuania for 2021-2030*. https://ec.europa.eu/energy/sites/ener/files/documents/lt_final_necp_main_en.pdf [Access date: 11.04.2021].

30 Cabinet of Ministers of Latvia, *Latvia's National Energy and Climate Plan 2021–2030*, Riga 2020. https://ec.europa.eu/energy/sites/default/files/documents/lv_final_necp_main_en.pdf [Access date: 11.04.2021]

31 *Act of 17 December 2020 on the promotion of electricity in offshore wind farms*. Poland. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20210000234 [Access date: 15.05.2021]

32 The Swedish Energy Agency, *National strategy for sustainable wind power*, 2021. ER 2021:02 https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=183601

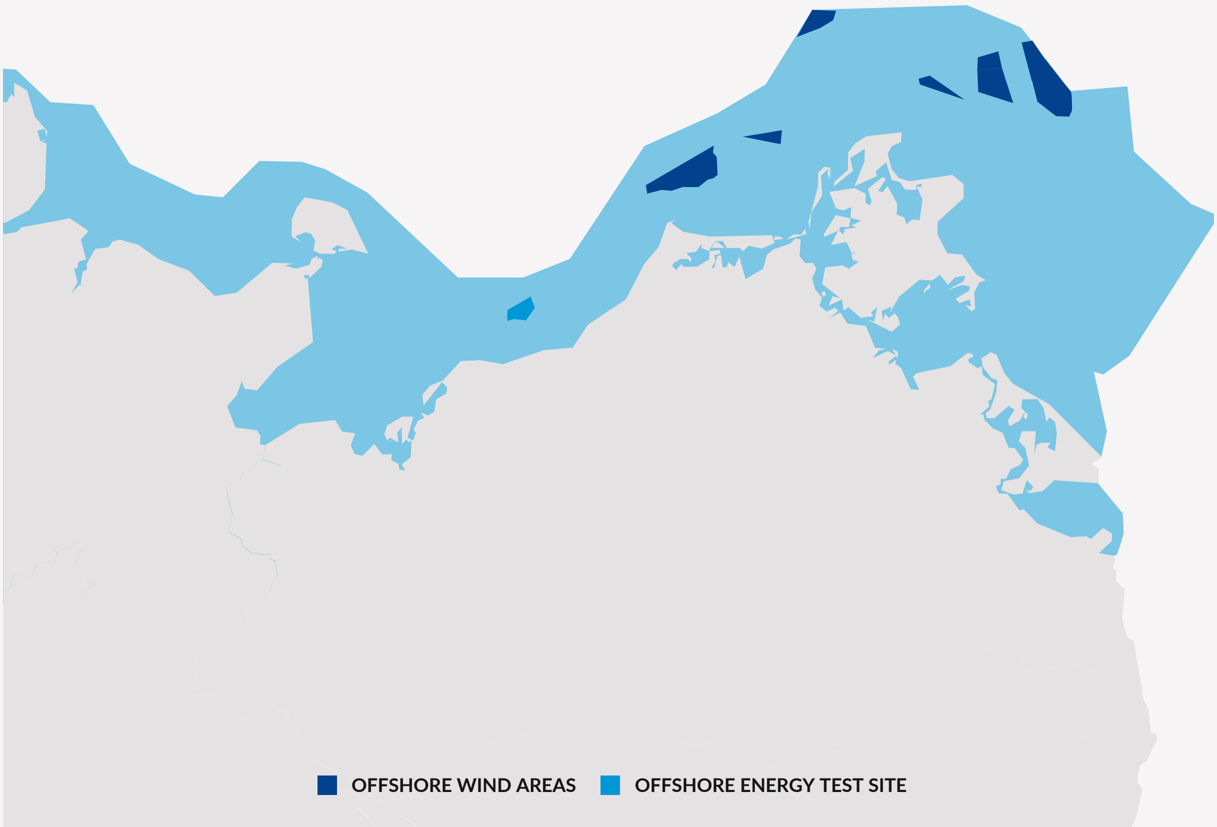
and 20 TWh from offshore in 2040. However, these figures are not seen as binding goals. They are meant to help in further planning. As a reference Sweden's electricity consumption is about 140 TWh a year. There is a common understanding that the use of electricity will increase rapidly over the next decades. Offshore wind power is expected to cover a large portion of this need for capacity after 2030.

3.4. Spatial plans

The Federal Maritime and Hydrographic Agency (BSH) carries out the task of maritime spatial planning. They do so in the German Exclusive Economic Zone (EEZ) of the North Sea and Baltic Sea on behalf of the responsible Federal Ministry. With regard to offshore wind energy, the central tool is the spatial development plan (FEP). The FEP specifies wind turbines at sea and offshore grid connections. The scope of the FEP primarily relates to the German EEZ of the North Sea and Baltic Sea. On the basis of an administrative agreement between the BSH and the federal state of Mecklenburg-Vorpommern, it also makes technical planning specifications for the territorial waters. That said, the responsibility for maritime spatial planning in the 12 nautical miles zone of territorial waters lies with the respective ministry on state level. The Ministry of Energy, Infrastructure and Digitalization of Mecklenburg-Vorpommern publishes - roughly every ten years - the Mecklenburg-Vorpommern Spatial Development Programme (LEP M-V 2016). The LEP M-V includes the 12 nm zone of territorial waters and thereby constitutes the maritime spatial planning (MSP) of Mecklenburg-Vorpommern. Provisions are made for offshore wind farms and cables, but also for pipelines, maritime traffic, fishing, aquaculture facilities, tourism, coastal protection, securing of raw materials, and nature conservation.

The map below portrays the areas dedicated for renewable energy for the EEZ and the German Baltic Sea.

Figure 11. Offshore wind in the Maritime Spatial Plan of Germany (Baltic Sea)



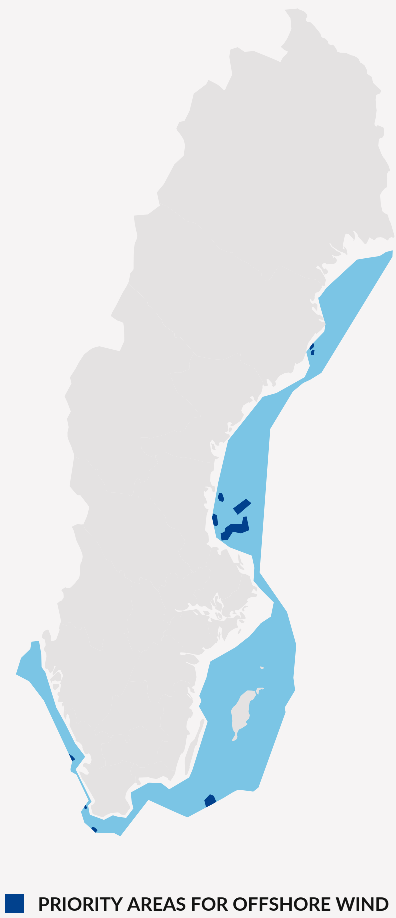
Source: based on BSH. Spatial plans available at: www.bsh.de

Sweden
In first half of 2021 the Swedish sea plans are expected to be approved by the government. The plans are divided into three sections covering: The Baltic Sea, the Bothnian Bay and the Western Sea.

The plans describe 13 different uses. Energy is included in three of them: transfer of electricity (cables), energy recovery (suitable for wind energy) and "study area for energy" (can be suitable, but must be investigated in more detail). Other uses are, for example, meant for the Armed Forces, nature, and recreation. Production of hydrogen is not mentioned in the plans. Pipes for transfer of gas is said to "have priority when possible". Large areas of the seas are labelled "General". In these areas all uses are posiible and permits can be applied for.

At the start of the national sea planning process in 2016, a target was set to find suitable areas where offshore wind would have priority of at least 50 TWh. Now, when the plan is almost completed, only areas corresponding to 23-31 TWh have priority. In addition to this some areas have a general/neutral status where OWE investment is possible.

Figure 12. Offshore wind in the Maritime Spatial Plan of Sweden



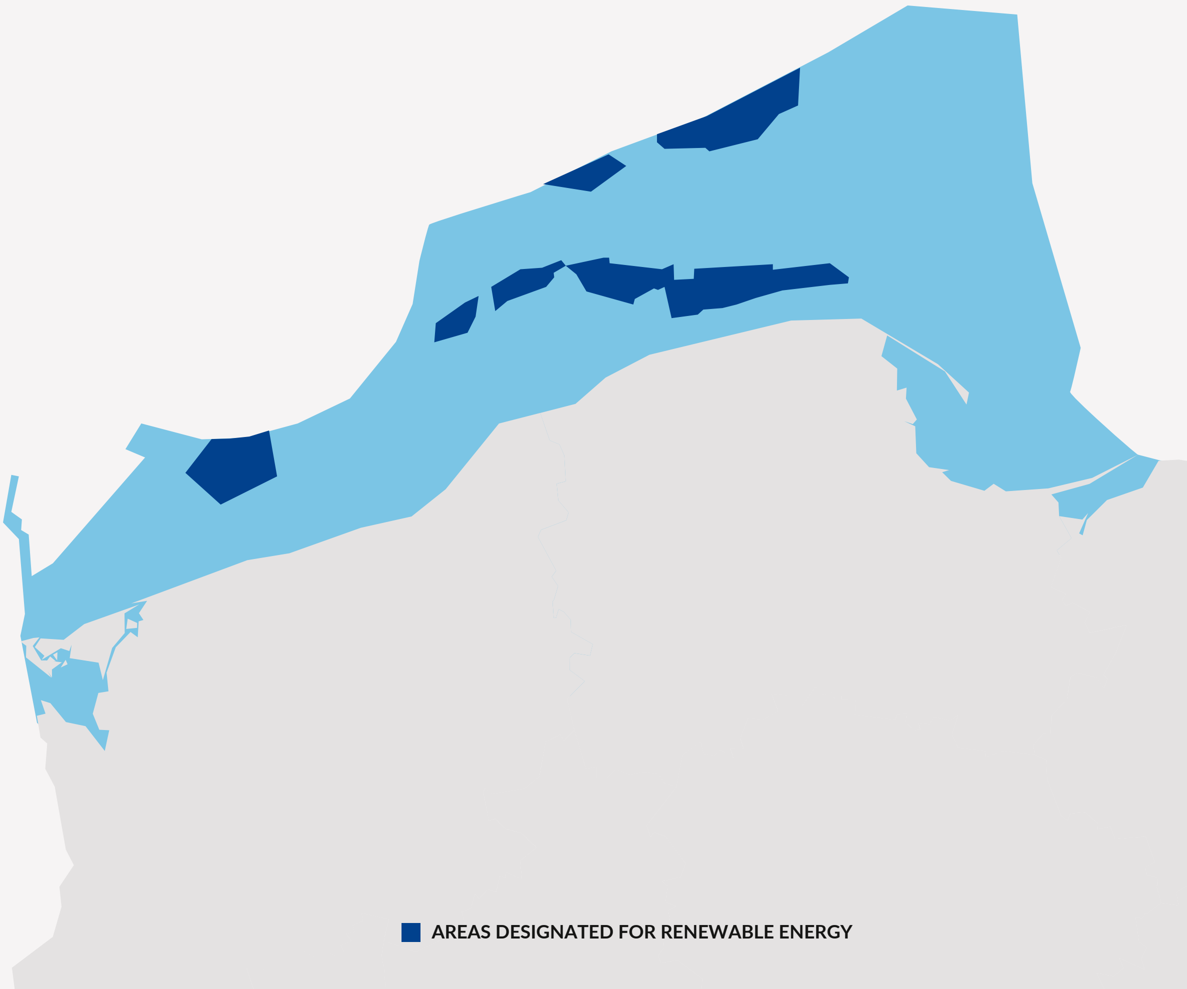
Source: based on Swedish Agency for Marine and Water Management. Original map avilable: https://www.havochvatten.se/planering-forvaltning-och-samverkan/havsplanering/havsplaner/forslag-till-havsplaner/karta-att-utforska.html#

The plans are said to be indicative and non-binding. A permit for OWE can, for example, be applied for in all areas regardless of priority. Having an area marked priority for wind energy will of course be a large advantage for choosing this area for a project location. How flexible and strong the priorities are will be known after some applications has been tested by authorities and precedent has been set.

Poland

In April of 2021 the Ministry of Infrastructure adopted the Maritime Spatial Plan for Poland. It was broadly consulted among different industries and authorities in the past few years. The plan is binding and offshore wind energy can be developed only within the 7 areas with primary function – energy production with the total area of approx. 2300 km^2. A major part of the maritime areas is still reserved for "future use". This means that further development of offshore wind energy is possible, however it will require a revision of the spatial plan which is a lengthy process.

Figure 13. Offshore wind in the Maritime Spatial Plan of Polish Waters



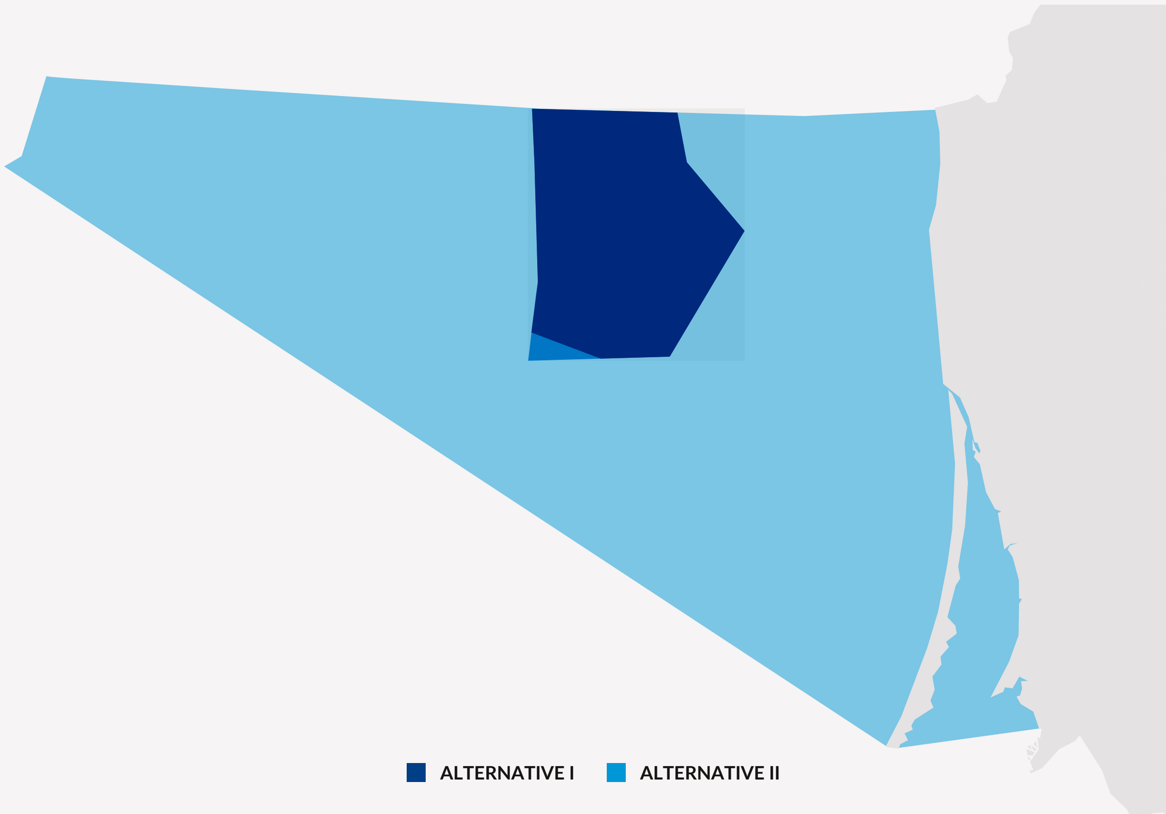
Source: based on Maritime office in Gdynia. Original map available at: https://www.umgdy.gov.pl/?cat=274

Lithuania

A fully binding Comprehensive Plan of the Territory of the Republic of Lithuania was adopted in 2015. Nevertheless, the validity of the plan ended in 2020 and currently a new Comprehensive Plan (including maritime spatial planning - MSP) is under consultation. The Plan is in the finalisation phase, in preparation for its approval to the Lithuanian Government.[33]

The new plan identifies areas dedicated for renewable energy as indicated in the map below.

Figure 14. Offshore wind in the Maritime Spatial Plan of Lithuania



Source: based on comprehensive plan of the territory of the republic of Lithuania. Original plan available at: http://www.bendrasisplanas.lt/2019/12/13/en/

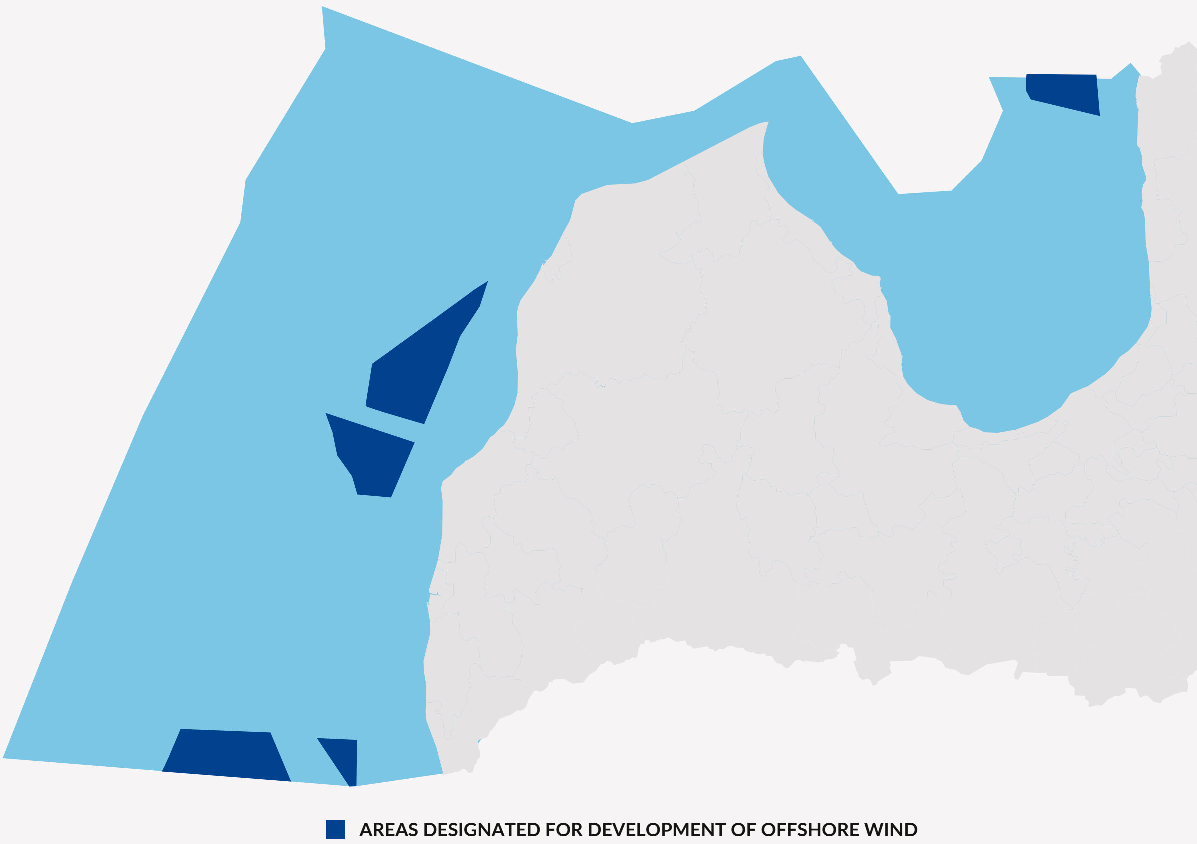
33 EU MSP Platform, *Maritime Spatial Planning Country Information Lithuania*. 2020. Msp-platform.eu [Access date: 6.04.2021]

Latvia

The Maritime Spatial Plan for Internal Waters, Territorial Waters and Exclusive Economic Zone of the Republic of Latvia (MSP 2030) was adopted by the Latvian Government in May 2019.[34]

The plan foresees 4 areas for offshore wind energy development. What is interesting - they overlap to a certain extent with areas designated for investigation of nature values.

Figure 15. Priority of use the sea areas of Latvia - MSP



Source: Based on EU MSP Platform, Maritime Spatial Planning Country Information Latvia, 2020. Msp-platform.eu

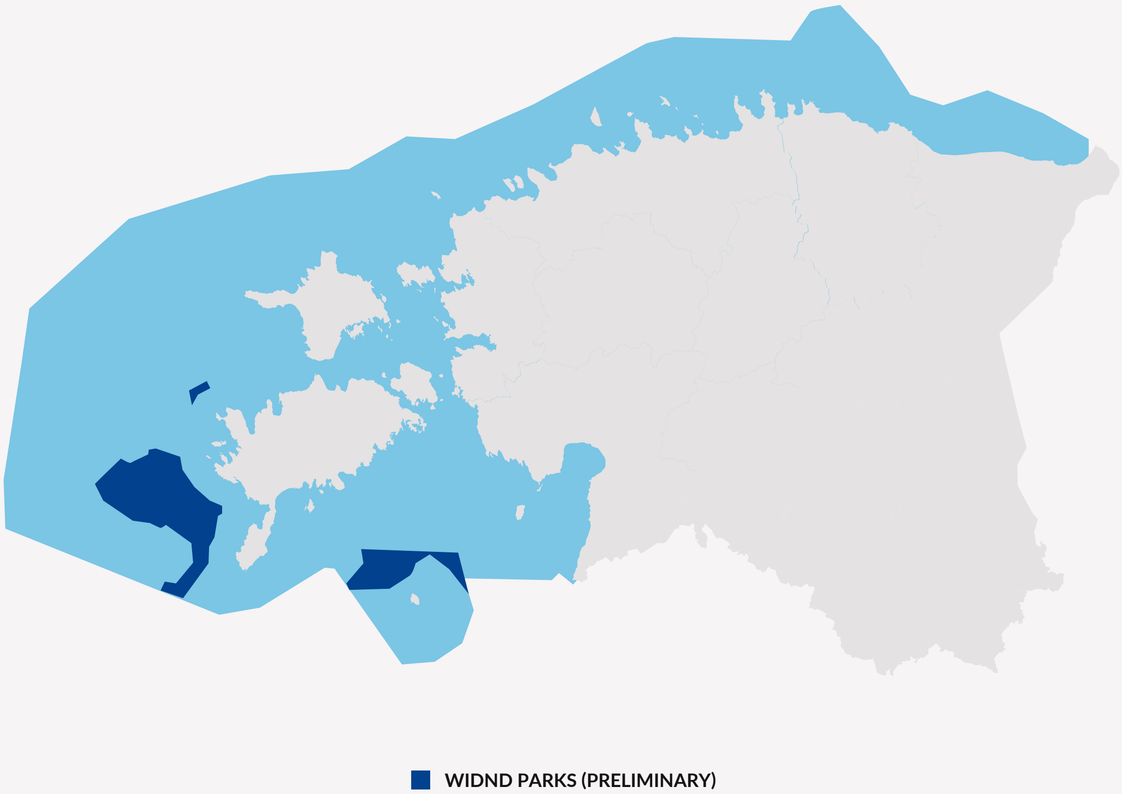
34 EU MSP Platform, *Maritime Spatial Planning Country Information Latvia*, 2020. Msp-platform.eu [Access date: 6.04.2021]

Estonia

Estonia is also at the final stage of adoption of an MSP. Currently there are two pilot MSPs for the area close to the Hiiu Island and Pärnu Bay. A broadly consulted draft of the full MSP is available since 2019.

According to this draft MSP, certain areas were designated for offshore wind development, mainly in the southern part of the maritime areas of Estonia.

Figure 16. Offshore wind in the Maritime Spatial Plan of Estonia



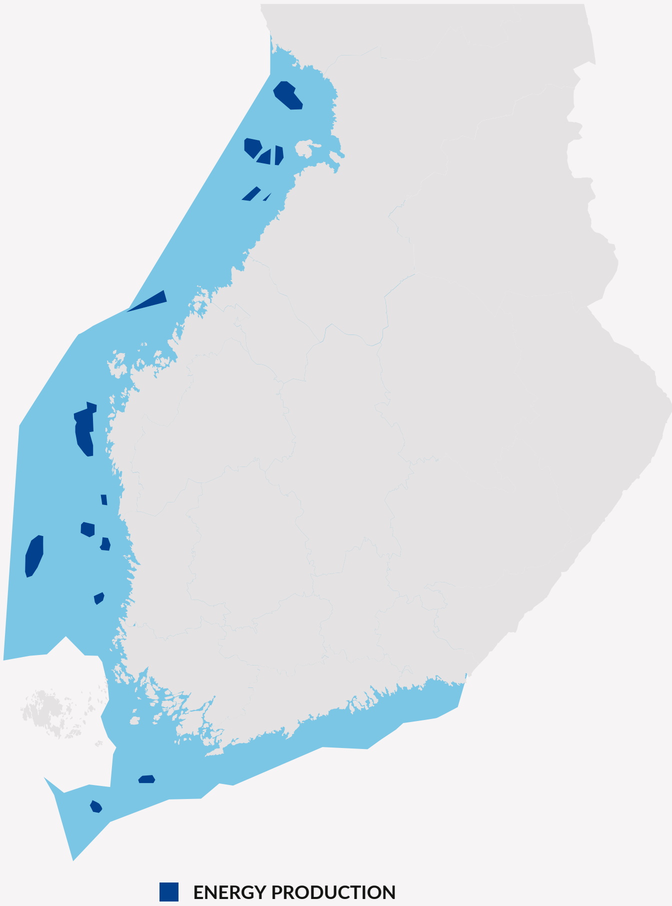
Source: based on Rahandusministeerium. Estonian maritime spatial plan – Draft Plan, 2019. http://mereala.hendrikson.ee/draft.html

Finland

Maritime spatial plans in Finland are prepared by Regional Councils and are non-binding. Finland's complete MSP is divided into 3 main parts, which were approved in December 2020. An additional part which included Åland Islands, was approved in march 2021.

The plan foresees numerous potential areas for offshore wind development (dark blue), it has to be kept in mind however that the plans are non-binding and the areas are indicated based on favourable conditions.[35]

Figure 17. Offshore wind in the Maritime Spatial Plan of Finland



Source: based on Maritime Spatial Plan for FIndland 2030 website. https://meriskenaariot.info/merialuesuunnitelma/en/suunnitelma-johdanto-eng/ [Access date: 06.04.2021]

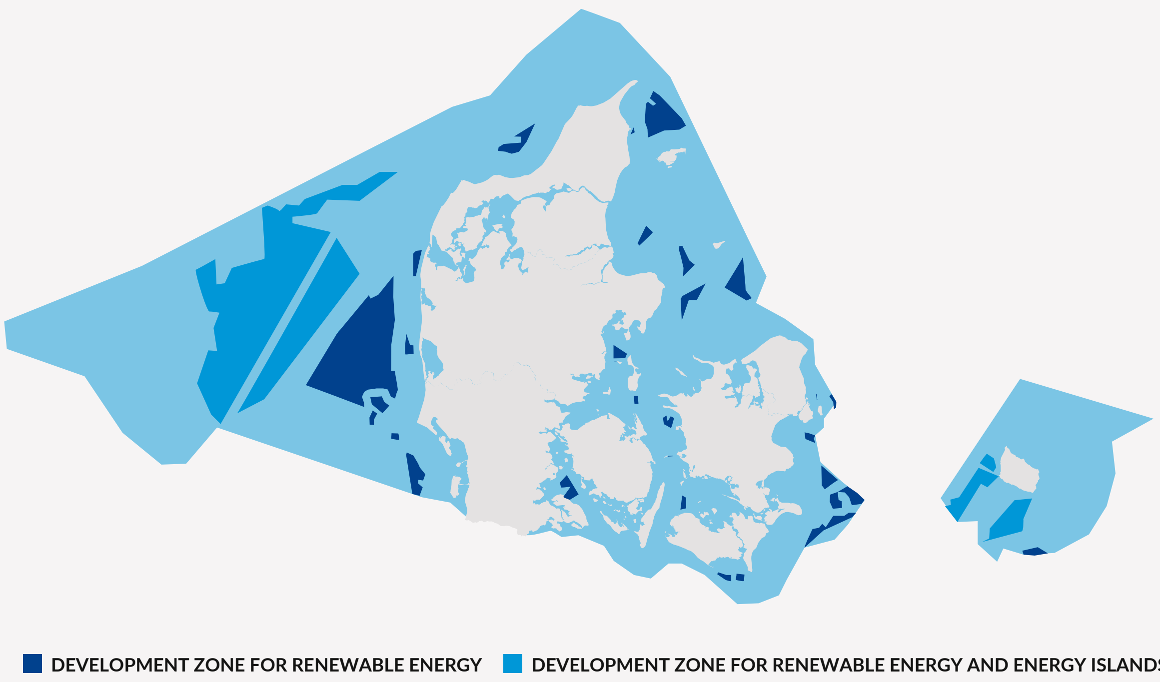
35 An interactive plan is available at: www.meriskenaariot.info.

Denmark

According to VASAB[36] Denmark has not adopted the maritime spatial plan.[37] The consultation process began in 2017 and in April 2021 the full plan has been put to general consultation.[38]

There are numerous areas either already occupied or reserved for renewable energy development and energy islands. The latter can be seen in particular south-west of Bornholm.

Figure 18. Offshore wind in the Maritime Spatial Plan of Denmark



Source: based on MSP in Denmark https://havplan.dk/en/page/info

36 VASAB - Vision And Strategies Around The Baltic Sea is an intergovernmental multilateral co-operation of the Baltic Sea Region in spatial planning and development, guided by the Conference of Ministers responsible for spatial planning and development, steered by the Committee on Spatial Planning and Development of the Baltic Sea Region (CSPD/BSR) composed of representatives of respective ministries and regional authorities (Germany, Russia).

37 VASAB MSP country fiches. https://vasab.org/theme-posts/maritimespatial-planning/msp-country-fiches/ [Access date: 6.04.2021]

38 The consulted plan is available at: www.havplan.dk.

4. Power-to-X (Hydrogen)

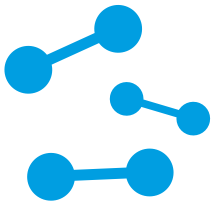
4.1. Potential

Power-to-X is a broad topic, but this report focuses on hydrogen production. Further derivatives like methane or ammonia are produced by post-processing of hydrogen.

The main goal of this chapter is to present the outline of hydrogen production technologies, with main attention given to electrolysis through renewable energy. Furthermore, this chapter will present the current state of hydrogen production and its future potential.

4.1.1. Key technologies

There are numerous ways to produce hydrogen. Depending on the source of hydrogen they are often called:



Brown hydrogen – produced through process of coal gasification ,

Grey hydrogen – produced from natural gas,

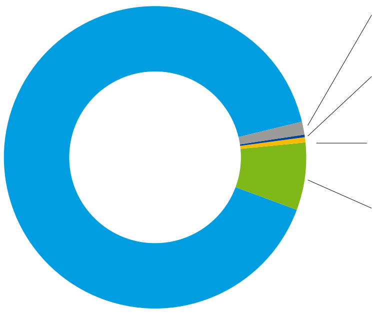
Blue hydrogen – grey hydrogen but accompanied by carbon capture and storage (CCS) systems (also called low-carbon hydrogen),

Green hydrogen – produced from renewable energy sources.

Currently hydrogen is produced mainly from fossil fuels, most often by steam reforming of natural gas (methane) or less commonly by partial oxidation or autothermal reforming. Figure 19 shows the distribution of hydrogen production per technology in Europe. It can be observed that renewable hydrogen constitutes only 0.1% of the total. This, however, needs to be analysed in the view of very ambitious plans for clean hydrogen production in Europe as set out in the EU Hydrogen strategy (6 GW of renewable hydrogen electrolyser capacity by 2024 and 40 GW by 2030).[39]

Future production potential of hydrogen is further described in chapter 5.1.2.

Figure 19. Hydrogen generation capacity by technology



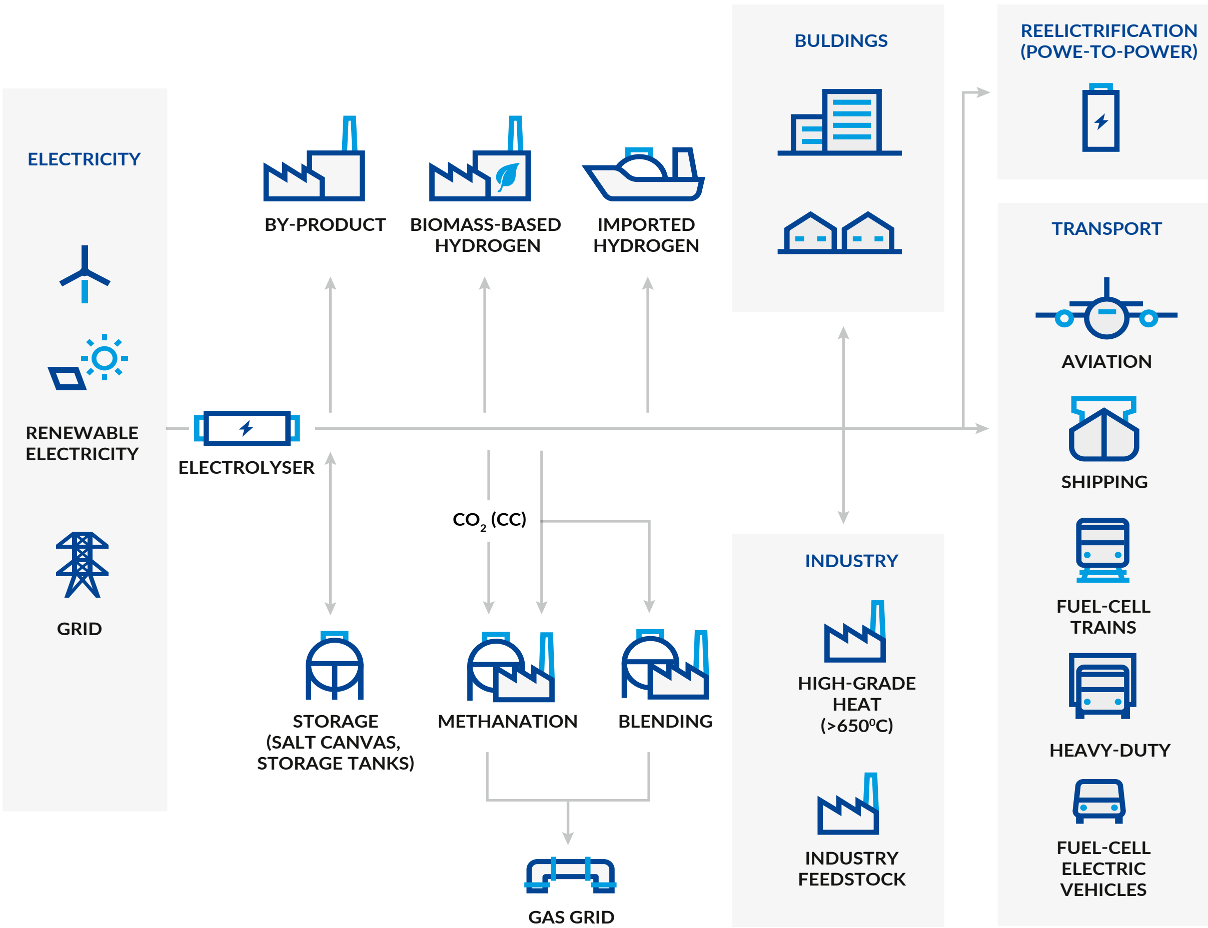
Source: Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

39 European Commission, *A hydrogen strategy for a climate-neutral Europe*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

Hydrogen from electricity is produced through electrolysis. This is a process of splitting water into hydrogen and oxygen by means of an electric current. The hydrogen produced can be:

- stored,
- further processed to produce other derivatives, such as methane or ammonia,
- fed directly into a grid (as hydrogen or as methane),
- used as fuel in the transport, heating or power sector,
- used as feedstock in industrial processes.

Figure 20. Hydrogen production and use pathways



Source: IRENA, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*. Abu Dhabi 2019 (ISBN 978-92-9260-111-9). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf

ELECTROLYSER TECHNOLOGIES

As can be observed in Figure 20 above, electrolysis is at the heart of hydrogen production.

Currently, commercially available technologies can be distinguished into Proton Exchange Membrane (PEM) electrolysis and Alkalyne Electrolysis (AEL). There are also other technologies like solid oxide electrolyser cell (SOEC) which are at an early development stage.

ALKALINE ELECTROLYSIS

In this case, the cathode and anode are submerged in a liquid alkaline electrolyte solution. They are separated by a diaphragm. The hydroxide is transferred from one electrode to another.

AEL is a fairly proven technology that has been used in the industry for a number of years. It is also more advanced than PEM and therefore cheaper and more durable. It has some disadvantages, like corrosive liquid electrolyte, complicated maintenance, relatively slow-start up, low current densities, and low operational pressure.[40]

The AEL technology works best with steady electricity supply conditions (disruptions can reduce the efficiency by over 20% and reduce lifetime). For this reason, alkaline electrolysers may be less suitable for applications with offshore wind. [41]

PROTON EXCHANGE MEMBRANE ELECTROLYSIS

The PEM technology uses a polymer membrane that is responsible for conducting protons (H+). The cathode and anode are submerged in an aqueous solution.

The PEM technology is less developed than AEL, however the advantages are: simple system design with fewer components, no corrosion, and being able to operate safely at higher current densities. In addition, it is able to perform well in fluctuation conditions (with offshore wind) and in partial or overloaded conditions. The disadvantages of the system are higher costs and use of noble metals.[42]

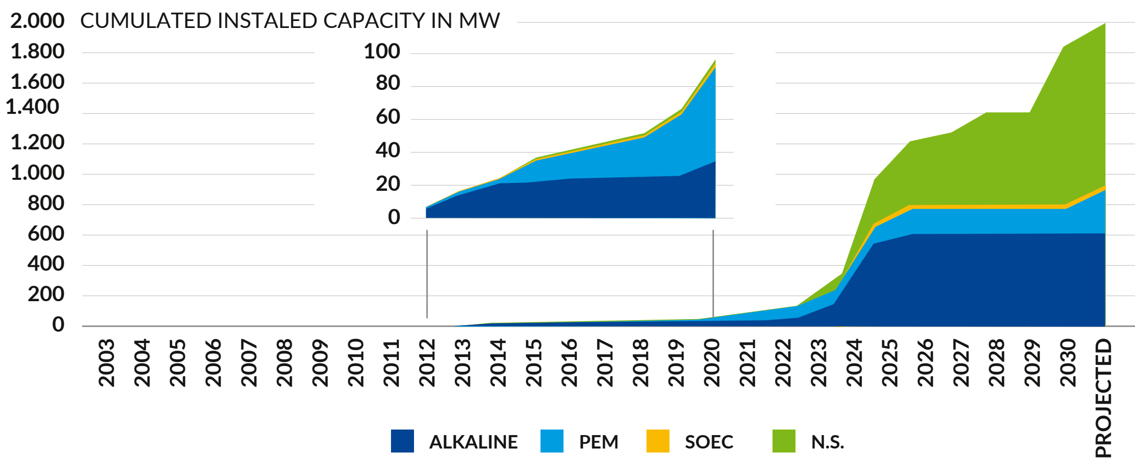
SOLID OXIDE ELECTROLYSER CELL

SOEC is basically a solid oxide fuel cell run in reverse, which means that it electrolyses water into oxygen and hydrogen. It operates at high temperatures (700-1000 °C) which provides for high process efficiency.

The SOEC technology is still at an early stage of development and its market share is very low (only 4% of known electrolyser projects use SOEC[43]). For that reason it is included in this analysis in a limited way. 27

Figure 21 shows the capacity share of electrolyser types in demonstrative power-to-X projects identified across Europe.[44] The PEM technology is gaining importance and becoming a viable alternative for AEL. However, a considerable development of the latter is expected in the coming years. A significant number of projects that are currently in planning have not decided on the technology to be used ('n. s' – not specified). SOEC, as described above has only limited visibility in the general outlook.

Figure 21. Installed capacity according to electrolyser type



Source: Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

40 Langels H., Syrjä O., *Hydrogen Production and Storage Optimization based on Technical and Financial Conditions*. University of Upsala 2021.
41 Spyroudi A. et al., *Offshore wind and hydrogen solving the integration challenge 2020*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf
42 Langels H., Syrjä O., *Hydrogen Production and Storage Optimization based on Technical and Financial Conditions*. University of Upsala 2021.
43 Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf
44 Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

Table 2 shows a general comparison of the two main technologies as of 2020 and envisaged in 2050. The costs of the technology are envisaged to drop significantly in the coming years.

Table 2. Comparison of the commercially available electrolyser technologies

	PEM		AEL	
	2020	Target 2050	2020	Target 2050
Cell pressure	<30 bar	>70 bar	<30 bar	>70 bar
Load range	5%-120%	5%-300%	15%-100%	5%-300%
Voltage efficiency (LHV)	50%-68%	>80%	50%-68%	> 70%
Electrical efficiency (stack)	47-66 kWh/Kg H2	< 42 kWh/Kg H2	47-66 kWh/Kg H2	< 42 kWh/Kg H2
Electrical efficiency (system)	50-83 kWh/Kg H2	< 45 kWh/Kg H2	50-78 kWh/Kg H2	< 45 kWh/Kg H2
Lifetime (stack)	50,000-80,000 hours	100,000-120,000 hours	60,000 hours	100,000 hours
Stack unit size	1 MW	10 MW	1 MW	10 MW
Cold start (to nominal load)	< 20 minutes	< 5 minutes	< 50 minutes	< 30 minutes
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	USD 270/kW	< USD 100/kW
Capital Costs (system) minimum 10 MW	700-1,400 USD/kW	< 200 USD/kW	USD 500-1,000/kW	< USD 200/kW

Source: IRENA, *Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5°C climate gaol*. 2020 p.65. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf [Access date: 18.05.2021]

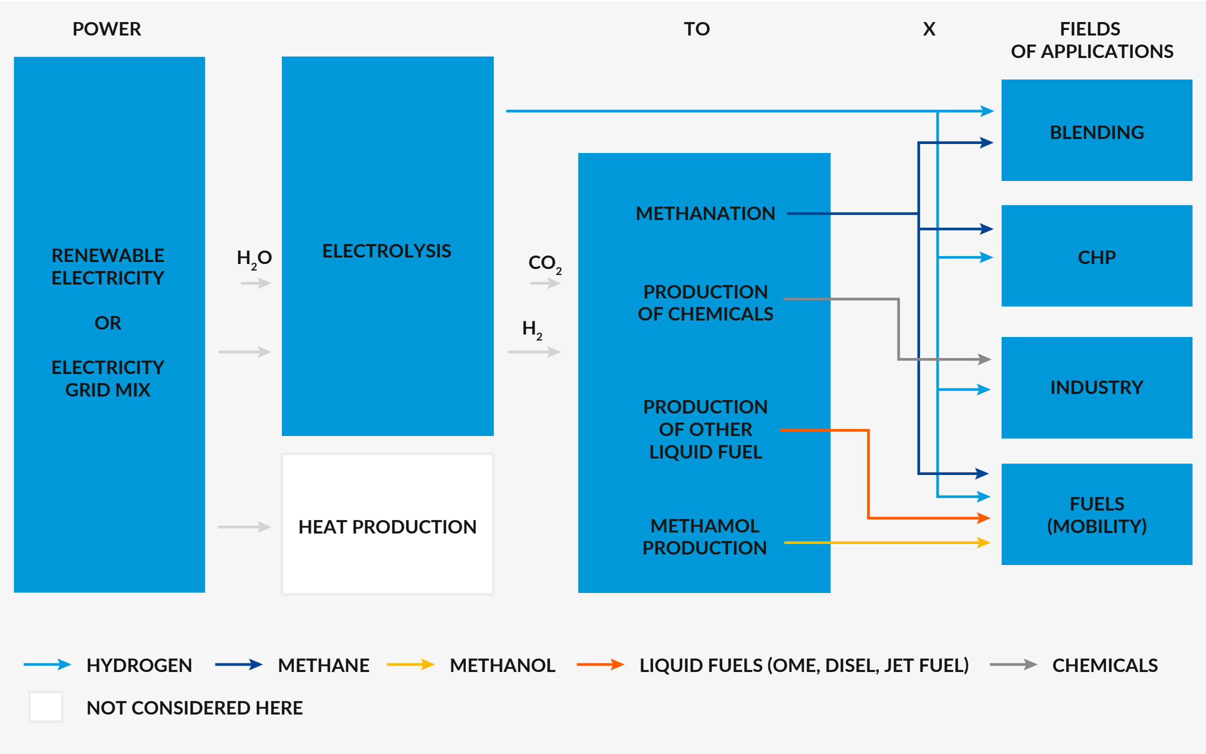
HYDROGEN PROCESSING – METHANE, AMMONIA, SYNGAS

Hydrogen is used for production of other compounds, which are described briefly below:

- Methane – is produced via chemical reaction of hydrogen with carbon dioxide through the process of methanation. Methanation can be processed in a catalytic or biological way. The former provides higher efficiencies; however it is more complex. The latter can be successfully implemented e.g. if biogas or sewage gas needs to be upgraded to biomethane by injecting hydrogen into the biogas.[45]
- Methanol – is produced via hydrogenation of carbon dioxide. This method has been applied in Iceland with CO_2 captured from air.[46]
- Ammonia – is produced via a catalytic reaction of hydrogen with nitrogen. This technology is widely used around the world, in particular in the fertiliser production industry. There is an increasing pressure for sustainable ammonia which can be produced with green hydrogen instead of grey.

45 Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.
46 Kothandarama J. et al, *Conversion of CO2 from Air into Methanol Using a Polyamine and a Homogeneous Ruthenium Catalyst*. Am. Chem. Soc. 2016, 138, 3, 778–781. https://pubs.acs.org/doi/10.1021/jacs.5b12354 [Access date: 13.03.2021]

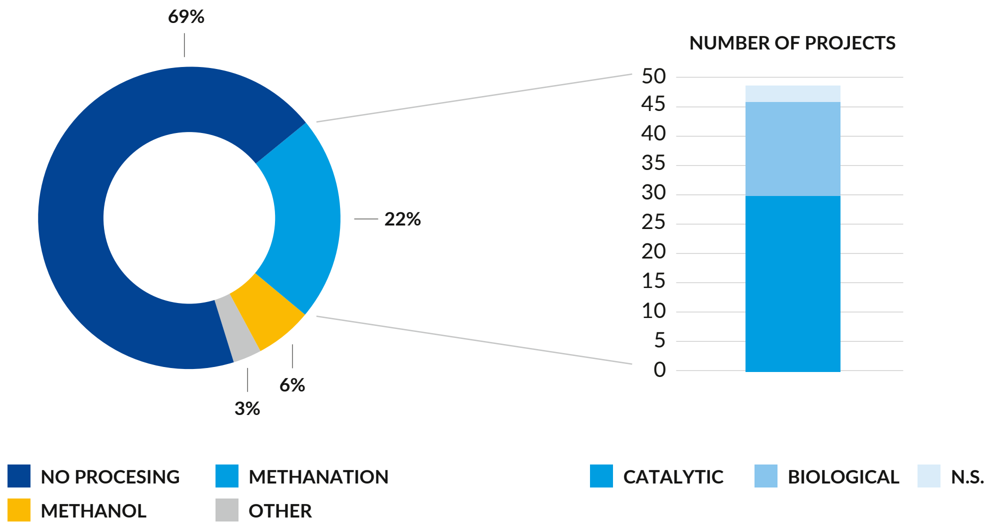
Figure 22. Overview of power-to-X process chains based on hydrogen



Source: Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

Figure 23. presents planned hydrogen production projects; indicated share of projects where H_2 is processed.

Figure 23. Planned power-to-X projects in Europe



Source: Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

OFFSHORE WIND ENERGY HYDROGEN APPLICATIONS

Integration of hydrogen production with offshore wind happens at the wind farm site or at an onshore facility. In the latter case, electricity used for production of electricity is taken either from the grid or from the export transmission infrastructure and the technology is no different to any other onshore application.

Regardless whether the technology is based offshore or onshore, it requires:

- an AC/DC converter, which converts alternating current to direct current,
- an electrolyser which splits water into oxygen and hydrogen,
- an H_2 compressor, to increase the pressure of the hydrogen.

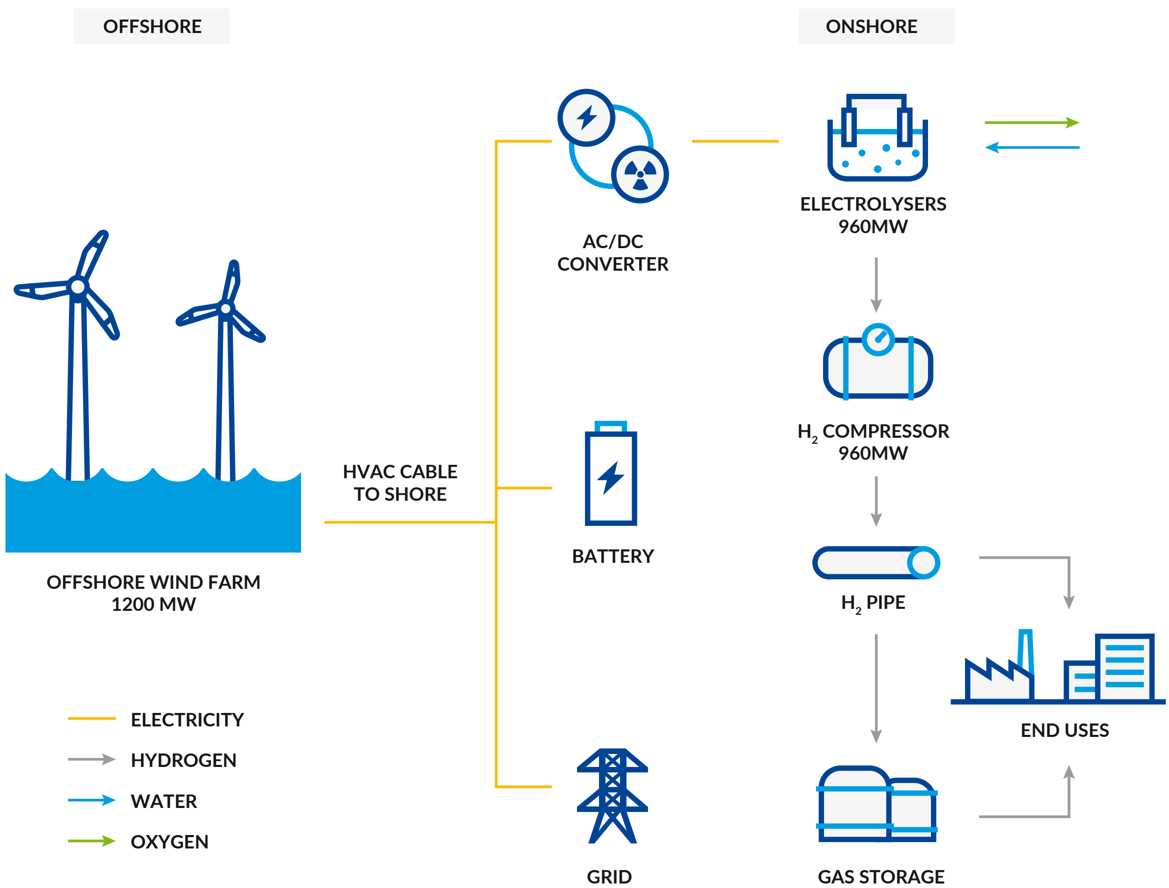
In the offshore application there is also a need for a desalination unit to be installed at the platform, which will convert the saline water into fresh water to be used in the electrolyser. In onshore applications a water treatment installation would also normally be present.

The main difference between the onshore and offshore technology is the placement of the particular components and how the end product of the offshore wind farm (electricity or hydrogen) is transported onshore. The examples are shown in Figure 24 and Figure 25.

With hydrogen production offshore there are several options that can be used:

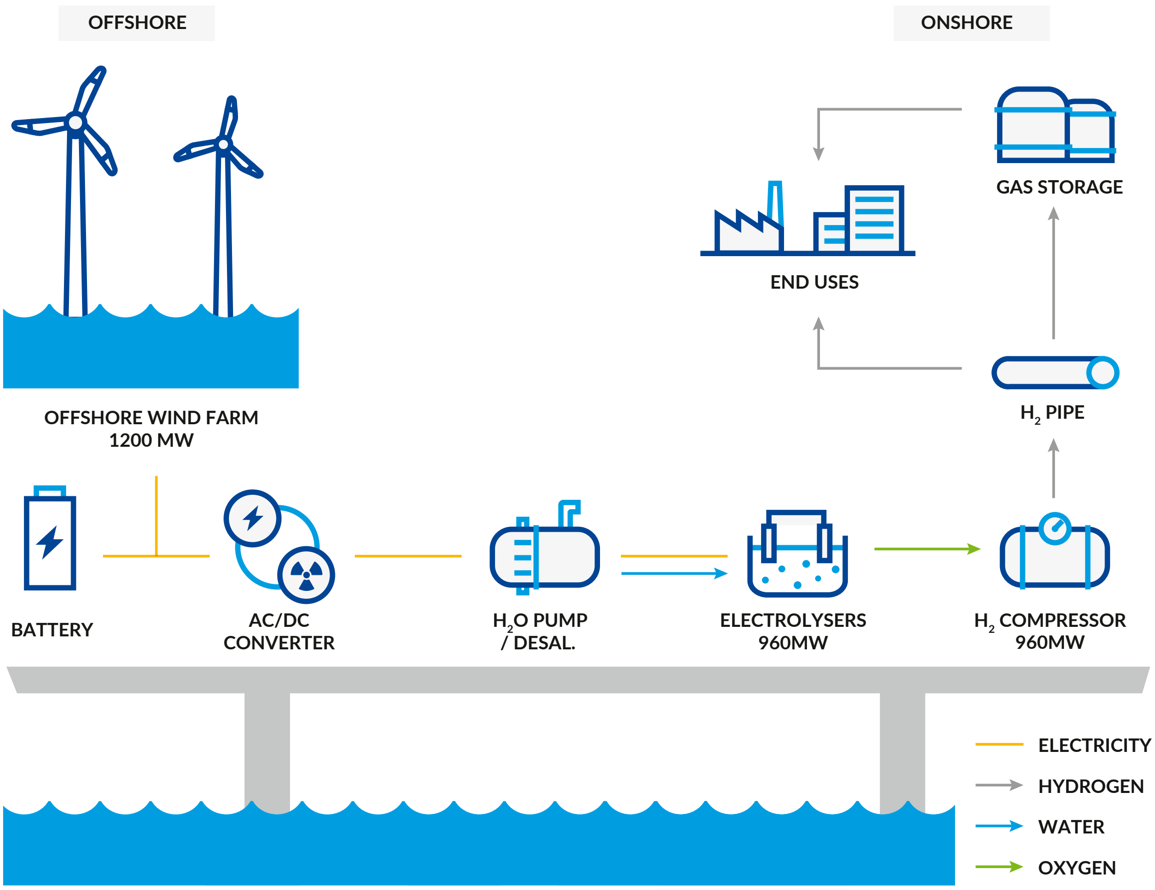
- transmission of hydrogen via pipelines to shore,
- storage and transport of high pressure hydrogen via ships,
- liquification and transport of liquid hydrogen via ships.

Figure 24. Outline of hydrogen production onshore, coupled with offshore wind energy



Source: Spyroudi A. et al., *Offshore wind and hydrogen solving the integration challenge 2020*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf

Figure 25. Outline of hydrogen production offshore, coupled with offshore wind energy



Source: Spyroudi A. et al., *Offshore wind and hydrogen solving the integration challenge 2020*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf

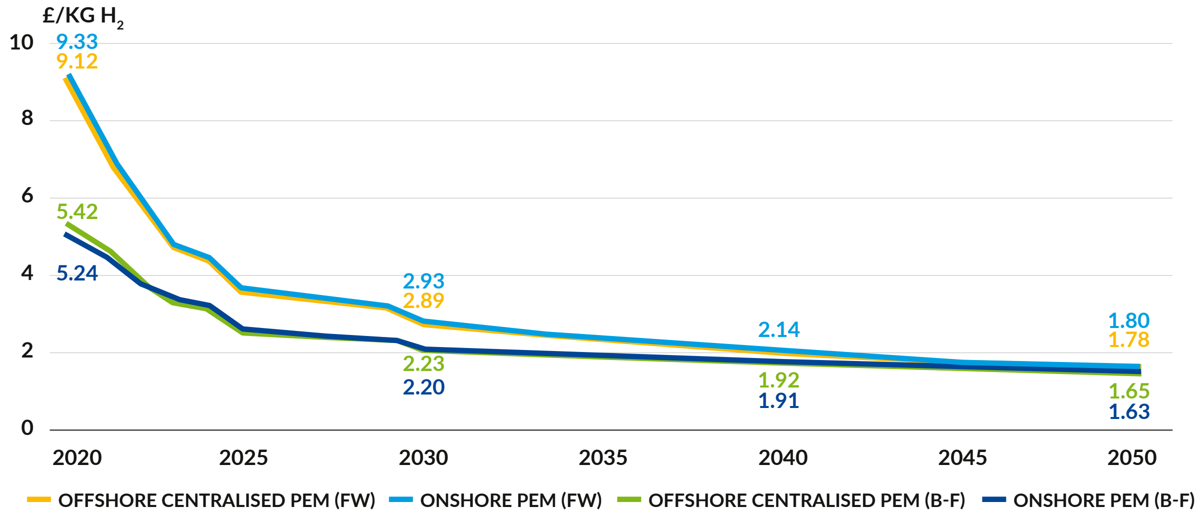
Figure 26 presents interesting results of analyses performed by ORE Catapult[47] which show levelized cost of hydrogen (LCOH) in the offshore centralised scenario (hydrogen produced offshore) and onshore scenario (hydrogen produced onshore). The results further compare the floating wind foundations and bottom-fixed ones. A dynamic reduction in LCOH until 2030 is expected, which, according to authors, will be driven mainly by electricity cost reduction in offshore wind. In fact, offshore wind has delivered incredible levelized cost of energy (LCOE) reductions of more than 67% over the last 8 years, according to BNEF. These costs are foreseen to drop again by one third by 2030.[48] Around 2040 the cost of hydrogen in bottom-fixed installations should drop below 2 EUR/kg of H_2, which is comparable to today's costs of H_2 from SMR with CCS.[49]

47 Spyroudi A. et al., *Offshore wind and hydrogen solving the integration challenge 2020*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf

48 GWEC, *Global Wind Report 2021*, 2021. https://gwec.net/global-wind-report-2021/ [Access date 18.05.2021]

49 European Commission, *A hydrogen strategy for a climate-neutral Europe*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

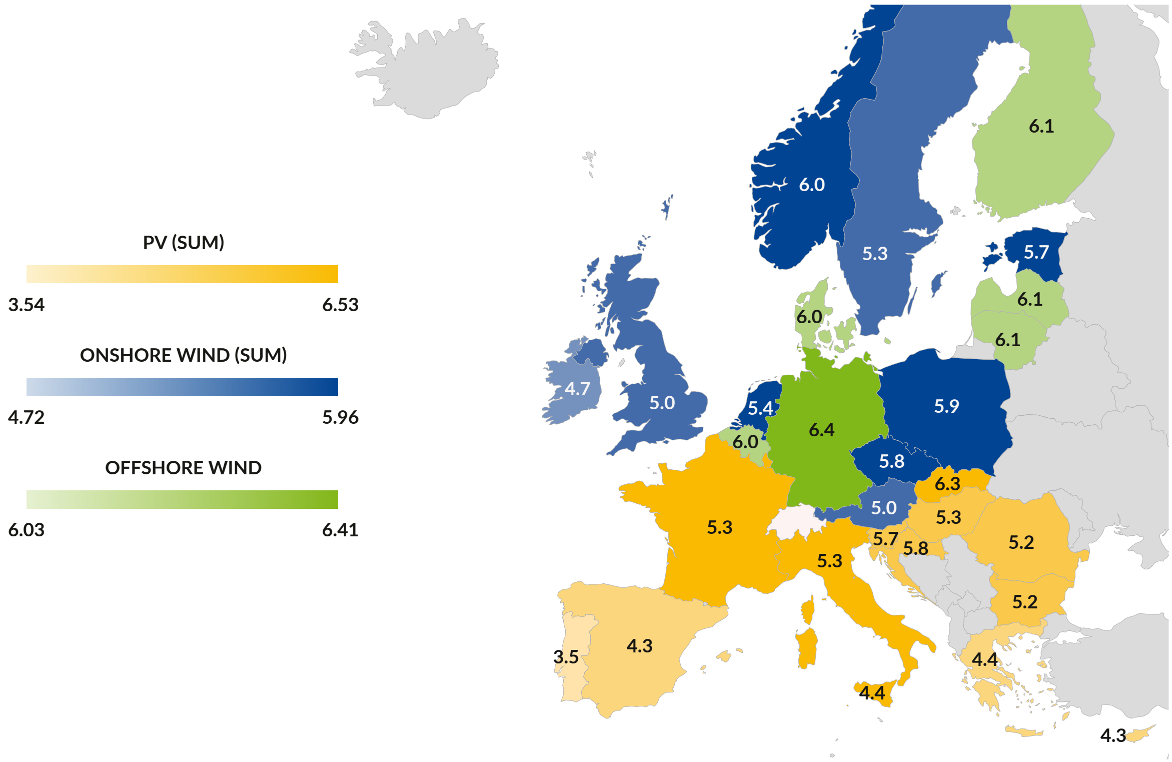
Figure 26. LCOH projection for onshore and offshore concepts with PEM electrolyser by offshore wind substructure [FW – floating foundation], [B-F – bottom fixed]



Source: Spyroudi A. et al., *Offshore wind and hydrogen solving the integration challenge 2020*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf

The costs presented in Figure 26 may be underestimated in comparison to the results of the Hydrogen Europe (Figure 27.) ORE Catapult presents the LCOH based on offshore wind (bottom-fixed foundation) of 5,24/5,42 GBP/kg (5,89/6,09 EUR/kg)[50] and Hydrogen Europe 6.3 – 6.41 EUR/kg in 2019.

Figure 27. Lowest available green hydrogen production costs given average wind and solar conditions in the EU in 2019 (in € per kg)



Source: Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

50 2020 yearly average exchange rage GBP/EUR used: 1 GBP= 1,124569 EUR

4.1.2. Production potential

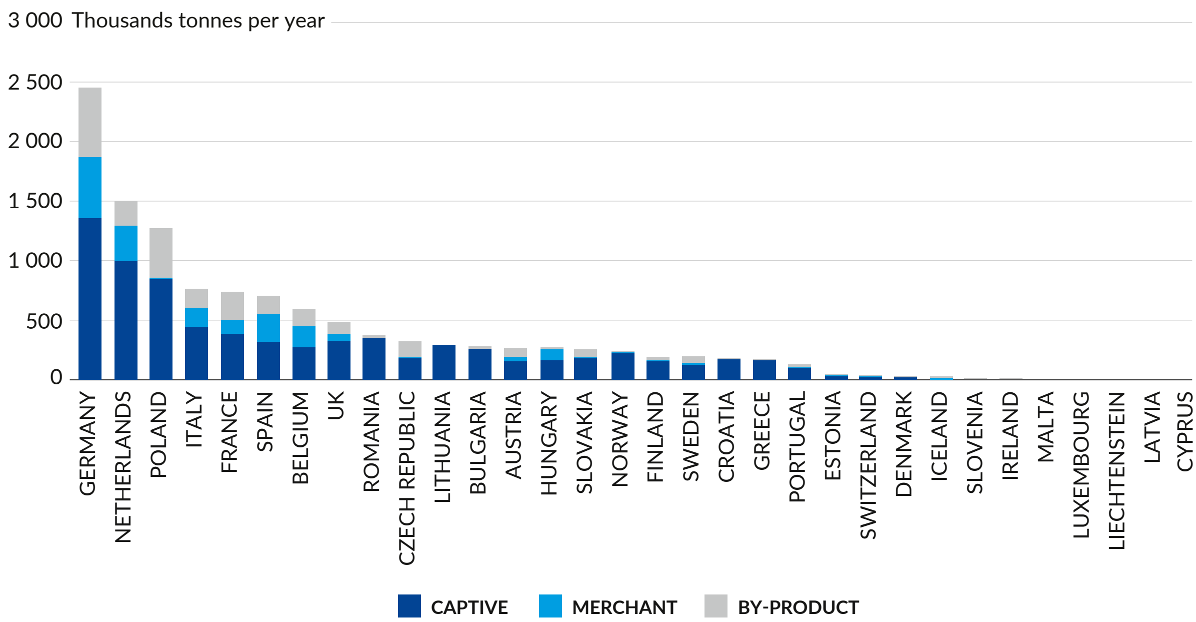
We can observe increased interest in hydrogen production and use across different sectors in the last few years. Currently, hydrogen is mainly produced from fossil fuels, but has high potential to be produced with the use of low-emission or renewable energy.

Total hydrogen production in Europe at the end of 2018 reached 11.5 million tonnes (Mt) per year with 460 identified production facilities. These include captive production facilities (onsite production for own use), merchant production facilities (production for sale) and facilities where hydrogen is produced as by-product. [51]

Majority of hydrogen production relies on fossil fuels, where the most common technology is steam reforming of natural gas (SMR) (see Figure 19).[52]

The largest production of hydrogen in Europe can be observed in Germany, with 21% of the European market. This is followed by the Netherlands (approx. 12%), Poland (11%) and Italy (7%). These 4 countries account for over half of Europe's hydrogen production.

Figure 28. Total hydrogen production capacity by country



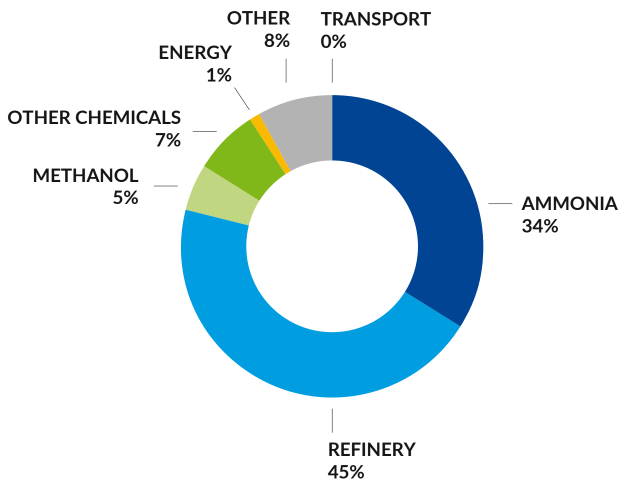
Source: Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

The total demand for hydrogen in 2018 was estimated at 8.3 Mt. The highest shares of hydrogen use are in refineries (44%) and in ammonia production (34%). Other applications account only for 21%, of which energy production is only 1% and transport is below 1%.

51 Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

52 ibidem

Figure 29. Total demand for hydrogen in 2018 by application



Source: Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

RENEWABLE HYDROGEN POTENTIAL

Currently renewable hydrogen production is marginal and is mainly at demonstrative scale. Nevertheless, with dynamically dropping costs of electricity from renewables and increased costs of carbon emission allowances, there is a high potential for increased green hydrogen demand and production.

The EU strategy assumes the development of 6 GW of renewable-energy-based-electrolysers by 2024 and 40 GW by 2030.[53] Currently, JRC estimates that there is a capacity of 1 GW in electrolysers.[54,55] According to Hydrogen Europe, the capacity reaches however only 60 MW.[56] In order to reach the goal of 6 GW by 2024 and 40GW by 2030 in electrolysers, the compound annual growth rate (CAGR) would have to reach approx. 90 %.

The capacity of planned of planned power-to-x (or alternatively power-to-hydrogen; PtH) projects is hard to estimate because not all projects are publicly announced. Furthermore, the situation is changing dynamically and new projects are being announced every day. According to EU's hydrogen strategy between November 2019 and March 2020, planned global investments in electrolysers moved from 3.2 GW to 8.2 GW of electrolysers by 2030 (of which 57% in Europe).[57]

According to Hydrogen Europe, as of 2020[58], the currently planned PtH projects will amount to (Figure 30):

- around 20 GW by 2040,
- around 9 GW by 2030,
- around 2 GW by 2024.

These assume an average annual growth of 63% which is not sufficient to meet the EU hydrogen strategy goals.

53 European Commission, *A hydrogen strategy for a climate-neutral Europe*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

54 Kanellopoulos, K., Blanco Reano, H., *The potential role of H2 production in a sustainable future power system*'. JRC. Publications Office of the European Union p.8, 2019.

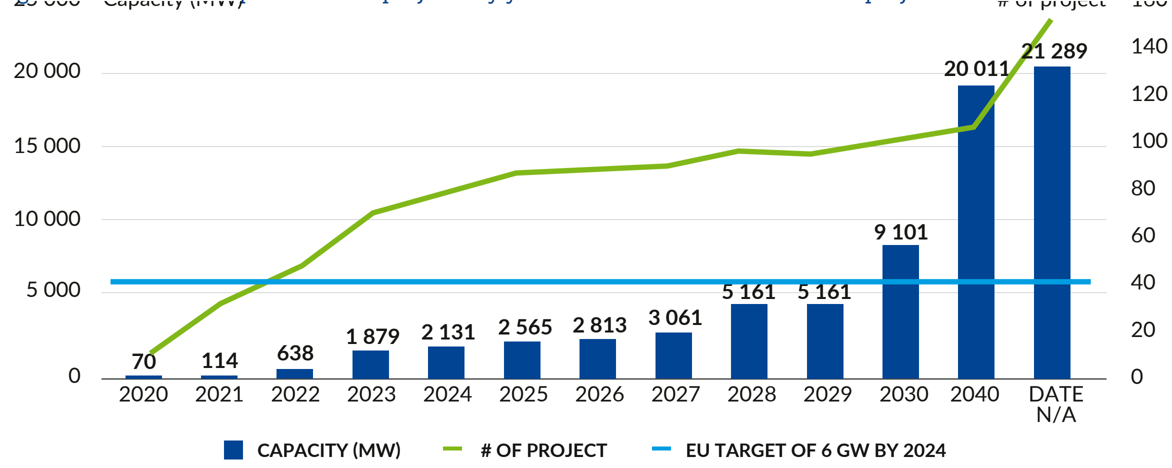
55 It includes electricity grid connected electrolysers.

56 Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

57 European Commission, *A hydrogen strategy for a climate-neutral Europe*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

58 Month not specified.

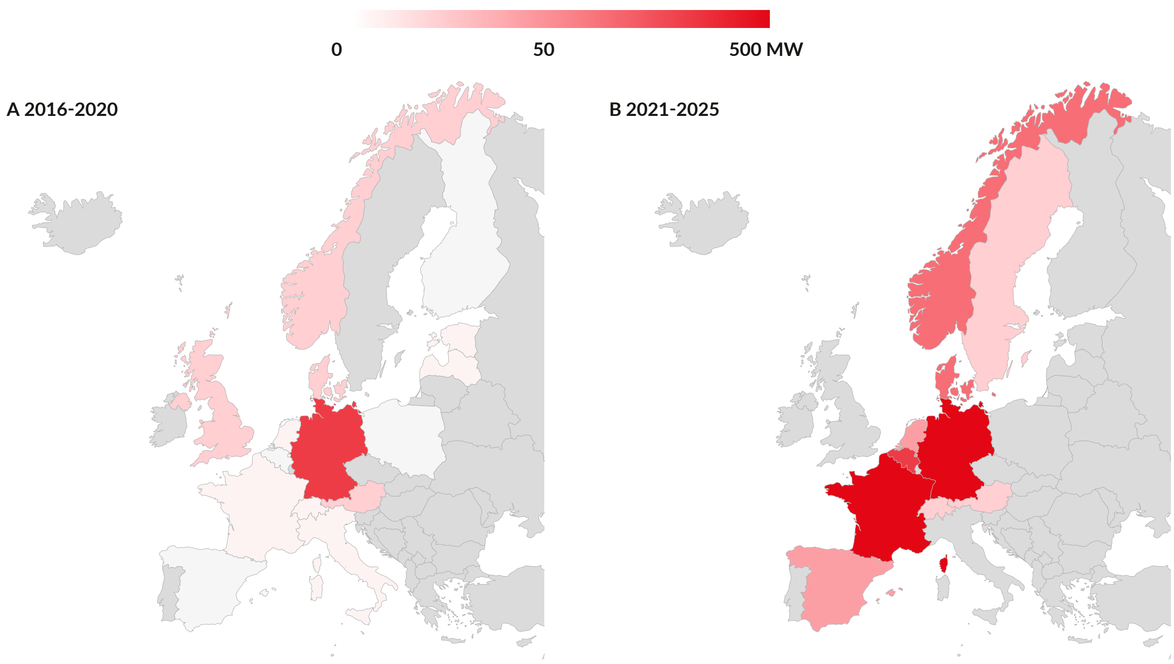
Figure 30. Cumulative planned PtH projects by year 2020 - 2040 in MW and # of projects



Source: Hydrogen Europe, *Clean Hydrogen Monitor 2020*. 2020. https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

According to the *Review of Power-to-X Demonstration Projects in Europe* study, the authors identified 220 projects (with total capacity of 2 GW – many have not specified their capacity), of which 105 assume a supply of energy directly from renewable energy sources.[59]

Figure 31. Newly installed capacities of PtX, (A) commissioned between 2016 and 2020, (B) planned for 2021-2025. Shaded countries installed capacity not specified, gray countries: no PtX projects.



Source: Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

The information about the PtX or PtH projects is not easy to obtain as these are usually projects with smaller capacity.

59 Wulf C., Zapp P. and Schreiber A., *Review of Power-to-X Demonstration Projects in Europe*, Front. Energy Res. 8:191, 2020.

Nevertheless, there are multi-megawatt projects which are worth listing:

- HyGreen Provence (France, 435 MW),
- H2V PRODUCT (France, 400 MW),
- H2V59 (France, 100 MW),
- Element Ein (Germany, 100 MW),
- Hybridge (Germany, 100 MW),
- Leuchtturm Hamburg (Germany, 100 MW),
- Norddeutsche Reallabore (Germany, 77 MW).

4.2. Hydrogen in strategic documents

According to GWEC, by the end of 2020, at least 33 countries (and the European Commission) had published or were preparing national hydrogen strategies.[60] This chapter will present the status of development of hydrogen strategies at the EU level and in the Baltic Sea Region countries.

European Union

After years of being considered a far-fetched niche technology, hydrogen is finally entering the mainstream. The European Union adopted its Hydrogen Strategy on 8 July 2020. It lays out plans to produce hydrogen based entirely on renewable electricity, such as wind and solar (with low-carbon hydrogen produced with fossil fuels tolerated in the short term to help scale up production).[61] Hydrogen is recognised as a major solution for decarbonising otherwise difficult industrial sectors – primarily the steel and chemical sectors, which traditionally rely almost entirely on fossil fuels and processes which cannot switch to electricity. In the long term, it can also be a plausible solution for shipping, aviation and heavy-duty road transport. Kadri Simson, the EU's energy commissioner presented the strategy, stating that "hydrogen is a vital missing piece of the puzzle to help us reach this deeper decarbonisation."[62]

The Commission expects that clean hydrogen may provide some 24% of the world's energy by 2050, with annual sales around €630 billion. The hydrogen value chain could eventually provide around a million jobs in Europe alone. But to produce sufficient renewable hydrogen with wind and solar energy will require drastic cost reductions in technologies such as electrolysers, which are expected to be fully mature by 2030 at the earliest.[63]

There will be a gradual transition, following a phased approach:

- 2020-2024: The Commission will foster the setting up of at least 6 GW of renewable hydrogen electrolysers in the EU, and the production of up to a million tonnes of renewable hydrogen.
- 2025-2030: Hydrogen will become an integral part of the energy system. There will be at least 40 GW of renewable hydrogen electrolyser capacity and up to ten million tonnes of renewable hydrogen will be generated in the EU.
- 2030-2050: Renewable hydrogen technologies will reach full maturity and be deployed at scale across all sectors.[64]

In keeping with the Hydrogen Strategy, the Commission launched the European Clean Hydrogen Alliance with representatives from the private sector, civil society, governments and the European Investment Bank. Its aim is to scale up investment and foster demand for clean hydrogen.[65] Moreover, the Commission plans to formulate common standards, terminology

60 GWEC, *Global Wind Report 2021*, 2021. https://gwec.net/global-wind-report-2021/

61 European Commission, *A hydrogen strategy for a climate-neutral Europe*, Brussels 2020. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

62 *EU Commission charts path towards 100% renewable hydrogen*, EURACTIV, 8 July 2020. https://www.euractiv.com/section/energy/news/eu-commission-charts-path-towards-100-renewable-hydrogen/

63 *Powering a climate-neutral economy: Commission sets out plans for the energy system of the future and clean hydrogen*, European Commission website, 8 July 2020. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1259

64 ibidem

65 *European Hydrogen Alliance*, European Commission website. https://ec.europa.eu/growth/industry/policy/european-clean-hydrogen-alliance_en

and certification based on life-cycle carbon emissions, in line with the EU taxonomy for sustainable activities.[66] The NextGenerationEU recovery plan for Europe will include proposals for policy and regulatory measures to boost investor certainty, promote the deployment of hydrogen and help build infrastructure and logistical networks.[67] Finally, clean fuels – largely hydrogen – are also one of the three main pillars of the EU Strategy for Energy System Integration.[68]

A call for IPCEIs (Important Projects of Common European Interest – an EU initiative which shields specially worthwhile projects from EU rules precluding state aid[69]) was launched on 17 December 2020 by 22 EU member states and Norway to help kick-start the European hydrogen economy.

Germany

Germany sees hydrogen fuel as the best way to decarbonise sectors that cannot easily be electrified, such as aviation or heavy industry. The country is seeking to adopt a frontrunner position in hydrogen production and deployment, to become a global leader. To this end, the country adopted a national hydrogen strategy in June 2020 which puts a clear focus on green hydrogen (hydrogen produced from natural gas with carbon capture and storage is tolerated as a transitional measure).[70]

According to the strategy, Germany will build 5 GW of industrial hydrogen generation capacity by 2030. The strategy includes adding the necessary onshore and offshore renewable energy production to generate feedstock electricity. Another 5 GW of electroysers will be added by 2040 at the latest. Seven billion euros - in addition to already existing programmes - will be provided to expand hydrogen technologies, and EUR 2 billion more will be invested in hydrogen production plants in partner countries, largely for export to Germany. For instance, an agreement with Morocco will involve the construction of Africa's first industrial-scale green hydrogen facility, which will reduce annual emissions by 100,000 tonnes of CO_2 equivalent per year (despite being realised outside the EU, this amount can be counted towards Germany's emissions reduction targets). The strategy is also the first in the world to explicitly include other green fuels such as synthetic methane, kerosene, methanol and ammonia.[71]

Denmark

Denmark has set ambitious goals to reduce greenhouse gas emissions by 70% by 2030 (with the aim to become climate neutral by 2050).

Denmark sees potential in the hydrogen sector and is currently focusing on financing R&D projects. In 2017 the Danish Government allocated a budget of 5.1 million EUR for R&D and demonstration programmes on new renewable energy technologies, including hydrogen and fuel cells. Furthermore, the Danish Government has established a fund of 128 million DKK (16.6 million EUR) to support development and demonstration projects on energy storage. The fund was granted by the end of 2019.

According to Denmark's National Energy and Climate Plan, energy storage, including hydrogen solutions, may increase the stability and security of energy supply. However, the power-to-X technology requires more development.

Two power-to-X projects received grants and will commence large scale production and storage of green hydrogen. In December 2019, the Government reached a political agreement on the Finance Act 2020. Parties agreed, among other things, to allocate funds to support large-scale power-to-X technologies and to initiate a preliminary study on "energy islands".[72]

66 *EU taxonomy for sustainable activities*. European Commission website. https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

67 *Recovery plan for Europe*. European Commission website. https://ec.europa.eu/info/strategy/recovery-plan-europe_en

68 *Powering a climate-neutral economy: An EU Strategy for Energy System Integration*. European Commission website, 8 July 2020. https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf

69 *What's an IPCEI*. Hydrogen for Climate Action. https://www.hydrogen4climateaction.eu/whats-an-ipcei

70 Federal Ministry for Economy Affairs and Energy of Germany, *National Hydrogen Strategy*, 2020. https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

71 *German hydrogen strategy aims for global leadership in energy transition*. Clean Energy Wire, 10 June 2020. https://www.cleanenergywire.org/news/german-hydrogen-strategy-aims-global-leadership-energy-transition

72 Fuel Cells and Hydrogen 2 Joint Undertaking. *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans [Access date: 13.04.2021]

Estonia
Currently there is no hydrogen specific strategy in Estonia. In 2020 a resolution was proposed that the Estonian government develops a national hydrogen strategy to harness the potential of hydrogen technologies to reduce carbon emissions and decarbonise the economy.[73]

According to the Estonian National Energy and Climate Plan (NECP) a "Hydrogen Work Group" was set up in order to analyse the development of hydrogen and fuel cell applications in the energy system. It is also emphasised that the major obstacle in clean hydrogen deployment is the lack of regulations. Nevertheless, the NECP does not include specific objectives or targets for the production or use of hydrogen.[74]

Finland
Finland has ambitious goals to become carbon neutral by 2035 and carbon negative by 2050. Currently Finland does not have a separate hydrogen strategy but hydrogen is included (to a certain extent) in:

- the National Energy and Climate Strategy,
- the Medium-term Climate Change Policy Plan,
- Finland's plan on the deployment of alternative fuels infrastructure.[75]

In 2020 a National Hydrogen Roadmap for Finland was developed by the VTT research institute's hydrogen experts. The roadmap analyses Finland's strengths and opportunities and is to act as a knowledge base for shaping policy for Finland.[76]

Finland is not directly addressing hydrogen in its National Energy and Climate Plan, but it does include certain measures to promote green hydrogen production, mainly for transport use. The aim is to increase the share of biofuels (including hydrogen) in the overall transport fuels consumption in Finland to 30% by 2030 and to increase the number of gas-powered cars to 50 000 by 2030.

Lithuania
In June 2020, the Lithuanian government approved the country's post-Covid-19 stimulus strategy: The Plan for the DNA of the Future Economy. The Plan identifies 5 priorities, which will focus on:

- human capital,
- digital economy and business,
- innovation and research,
- economic infrastructure,
- climate change and energy.

Within the plan, EUR 2 million is earmarked for research into the use of hydrogen from renewable energy sources in the natural gas infrastructure.[77]

Furthermore, in November 2020, the Ministry of Energy and 19 organisations, including: ministries, business associations and large energy companies, have signed an agreement on the establishment of a hydrogen platform in Lithuania. The aim is to cooperate in the creation and development of hydrogen technologies, which will be crucial for achieving national and European energy and climate targets.[78]

73 *Resolution of the Riigikogu „Proposal to the Government of the Republic for the Development of a Hydrogen Strategy" 279 OE.* Parliament of Estonia website https://www.riigikogu.ee/tegevus/eelnoud/eelnou/b468d1c6-7d78-4a52-a523-f4738b74df10/Riigikogu%20otsus%20_Ettepanek%20Vabariigi%20Valitsusele%20vesinikustrateegia%20v%C3%A4ljat%C3%B6%C3%B6tamine_

74 Fuel Cells and Hydrogen 2 Joint Undertaking. *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans [Access date: 13.04.2021]

75 Fuel Cells and Hydrogen 2 Joint Undertaking. *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans [Access date: 13.04.2021]

76 Juhani Laurikko et al. *NATIONAL HYDROGEN ROADMAP for Finland*, 2020, Business Finland. https://www.businessfinland.fi/en/whats-new/news/cision-releases/2020/national-hydrogen-roadmap-guides-finland-towards-carbon-neutrality [Access date 13.04.2021]

77 *The Government Approves the Plan for the DNA of the Future Economy*, Ministry of Finance of the Republic of Lithuania website, 11 june 2020. https://finmin.lrv.lt/en/news/the-government-approves-the-plan-for-the-dna-of-the-future-economy

78 *Hydrogen platform being developed in Lithuania to promote advanced energy technologies* Ministry of Finance of the Republic of Lithuania website, 30 November 2020. https://enmin.lrv.lt/en/news/hydrogen-platform-being-developed-in-lithuania-to-promote-advanced-energy-technologies

According to Lithuanian National Energy and Climate Action Plan, Lithuania considers hydrogen as "a promising area for energy innovation and an opportunity to acquire new energy competences". Launching a hydrogen market would allow "the capitalization of research efforts, the creation of new businesses, economic growth and exportation opportunities". In the plan, hydrogen technologies and systems is among the 9 Key Strategic Value Chains relevant for European development.

Lithuania seems to consider hydrogen applications mainly from a research and development perspective. However, there are no specific objectives or targets for the production or use of hydrogen, nor hydrogen specific policies or measures.[79]

Latvia

Latvia does not have a specific strategy for hydrogen, however some elements related to hydrogen are included in the Latvian National Energy and Climate Plan. According to the NECP, Latvia will implement its research, development and innovation Smart Specialisation Strategy (RIS3) planned for the period 2021-2027. It will include "Innovative solutions in the field of RES technologies, incl. for production and use of biomethane, hydrogen and modern biofuels, smart use of biomass before combustion, use of solar energy in transport.". The NECP also includes research on retrofitting of the existing gas infrastructure for hydrogen purposes and development of a dedicated hydrogen infrastructure.

The Latvian NECP does not include specific objectives or targets for the production or use of hydrogen, nor hydrogen specific policies and measures.[80]

Sweden

Hydrogen is a relatively new component in the general energy discussion and no national goals exist for its production or use. Driven by the steel industry and its strive to replace coal and coke, hydrogen has suddenly taken a place as a key technology to make this replacement possible. A vast amount of additional electricity will however be needed for maintaining hydrolysis as the preferred production method of hydrogen. Since replacing fossil fuels is the driver for this transformation only green hydrogen produced from renewable electricity will be accepted by the market. In January 2021, the governmental initiative "Fossil free Sweden" was produced.[81] The document gives some recommendations for next steps and this has already led to the Swedish Energy Agency being assigned to develop a national strategy for hydrogen. This work will be completed in the 2nd half of 2021.

Hydrogen is in Sweden (as well as in most countries) a common product used mainly in industry. New users and applications have recently shown gaps in regulations for example when establishing filling stations for vehicles.

Poland

A draft of a strategy titled "Polish hydrogen strategy until 2030 with 2040 perspective" has been put into public consultation in January 2021.[82] This document describes the ambitions of the Polish government in terms of hydrogen rollout across the Polish economy.

The strategy assumes among others:

1) installation of 50 MW until 2025 and 2 GW of electrolysers (able to produce 193.6 kt of H_2 / year) until 2030,
2) creation of 32 hydrogen fuelling stations until 2025,
3) commencement of operations of 500 hydrogen-fuelled buses (produced in Poland) by 2025 and 2000 by 2030.

The strategy also points out the necessity of legal changes and possibilities of financing the low-carbon hydrogen economy through, among others, contracts for difference.

79 Fuel Cells and Hydrogen 2 Joint Undertaking. *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans [Access date: 13.04.2021]

80 Fuel Cells and Hydrogen 2 Joint Undertaking. *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, 2020. https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans [Access date: 13.04.2021]

81 Fossil Free Sweden, *Strategy for fossil free competitiveness*, 2021. https://fossilfrittsverige.se/wp-content/uploads/2021/01/Hydrogen_strategy_for-_fossil_free_competitiveness_ENG.pdf

82 Ministerstwo Klimatu i Środowiska, *Polska strategia wodorowa do roku 2030 z perspektywą do 2040 r.* – project. 2021. https://www.gov.pl/web/klimat/rozpoczely-sie-konsultacje-publiczne-projektu-polskiej-strategii-wodorowej

Hydrogen is also part of the Polish Energy Policy until 2040 adopted in 2020. The Policy does not provide for specific actions related to hydrogen but states that hydrogen is one of the most anticipated innovations in the energy sector.

5. Key initiatives

There are numerous initiatives with the goal to increase deployment of hydrogen or offshore wind in Europe. The goal of this chapter is to investigate mainly initiatives coupling these two technologies.

5.1.1. Bornholm energy island concept

Bornholm is an Island located in the Baltic Sea southeast of Sweden and belonging to Denmark. It has 39 thousand inhabitants and an area of 588 km2. The Island's strategic position gives it advantages to serve as an energy hub between Sweden, Denmark, Germany and Poland.

Figure 32. Bornholm energy island concept

Source: Örsted

Building infrastructure at sea is more complex than onshore and comes at a higher cost. Using an island for this purpose is then a natural choice. Consequently, the German transmission system operator (TSO) 50Hertz and Danish TSO Energinet have signed a Letter of Intent to collaborate on the Bornholm Energy Island project. A pre-study will be launched to investigate having a grid connection point on the island, connecting planned wind farms in the area.

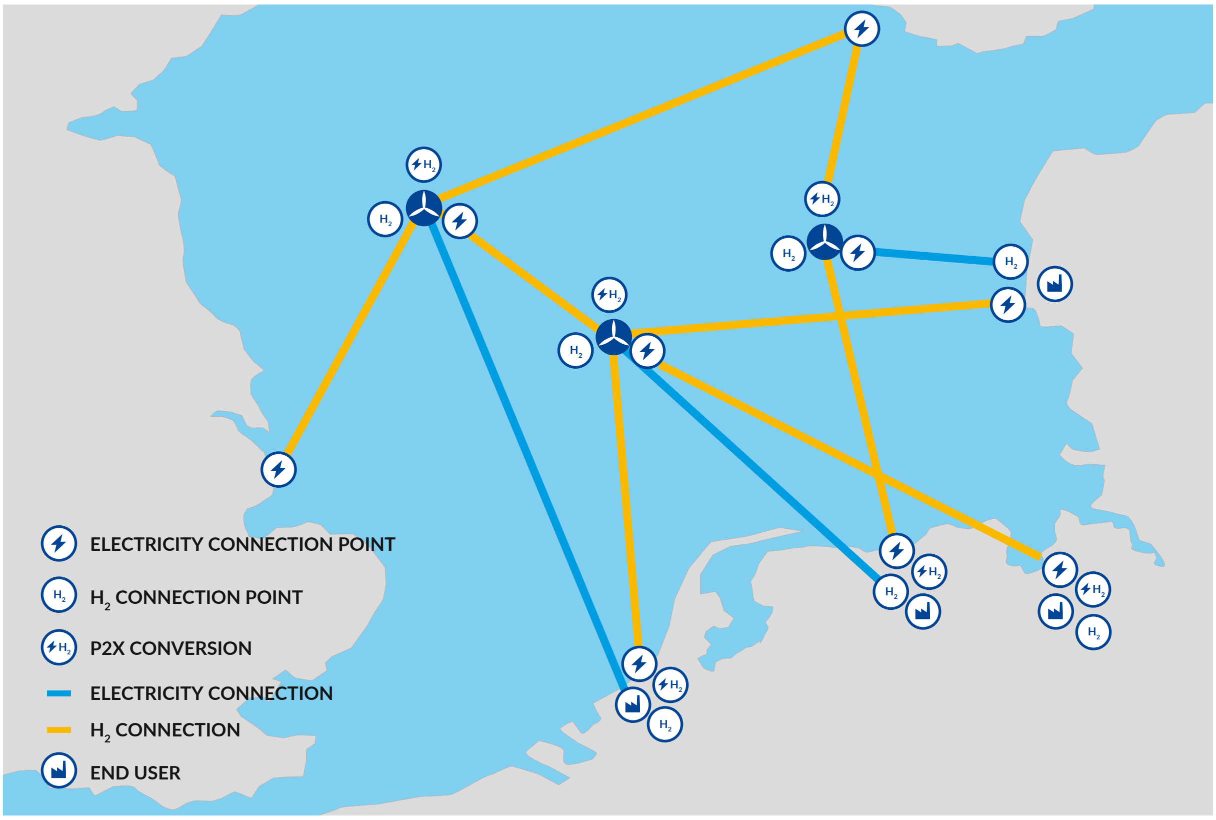
The agreement can be seen as a response to the Vision (clean stream project) presented by the Danish OWE developer Örsted in 2019. The Vision includes a first wind farm located at Rönne Bank but also large-scale hydrogen production to handle variations in electricity supply and demand. The Vision has been further studied in the EU funded, PROMOTioN project.[83]

83 PROMOTioN project, *Deployment Plan for Future European offshore Grid Development. Short Term Project – Bornholm Island CleanStream Energy Hub*, 2020. https://orbit.dtu.dk/en/publications/d125-deployment-plan-for-future-european-offshore-grid-developmen

5.1.2. North sSea wind power hub

Plans for artificial energy islands in the North Sea have been discussed and evaluated for several years. In 2019, a European consortium consisting of Energinet, Gasunie, TenneT and the Port of Rotterdam released a set of preliminary studies that provided the basis for developing artificial energy islands offshore in the North Sea. The idea is that offshore wind farms are connected directly to far-offshore islands. Whereby these artificial islands serve as central hubs to distribute energy to several European countries and markets via radial connections. The goal is to connect up to 150 GW by the year 2040 and up to 180 GW by 2045 of offshore wind capacity to these islands and thus, contributing significantly to Europe's climate goals. Besides infrastructure such as HVDC converters, service and maintenance centres, the islands will also house power-to-gas facilities to bring energy to other sectors such as mobility and heating. Alongside building the complex technical infrastructure of such an endeavour, major challenges regarding regulation, market design and political implications have to be addressed.

Figure 33. North Sea Wind Power Hub concept



Source: © TenneT 2019 (https://www.tennet.eu/our-key-tasks/innovations/north-sea-wind-power-hub/)

5.1.3. Renewable hydrogen coalition (RHC)

Launched in November 2020 by WindEurope, SolarPower and Breakthrough Energy RHC is an initiative supported by 20 major companies in the field of renewable energy and Hydrogen. The group has developed a Policy Charter describing actions that will enable scaling up of the market of renewable hydrogen.[84]

5.1.4. German initiatives & projects

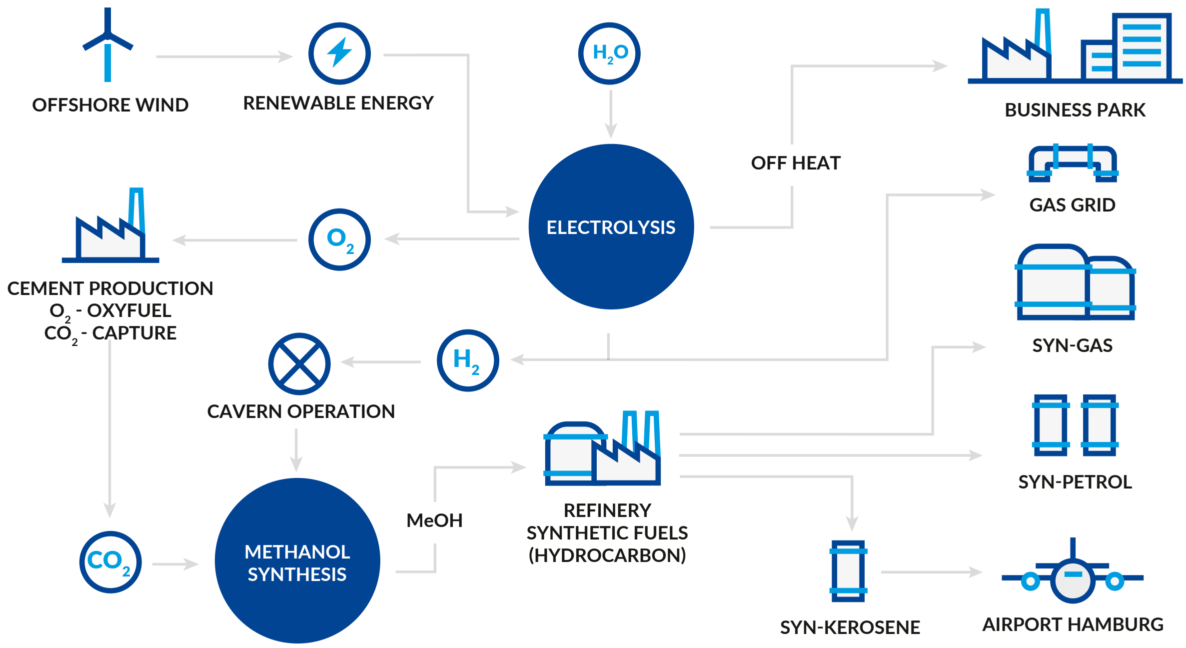
Besides multi-national initiatives like the North Sea Power Hub, there are also several national key initiatives with regard to offshore wind and hydrogen development. In Germany, several projects and initiatives have been launched. Three key initiatives are as follows:

84 Renewable Hydrogen Coalition, *Policy Charter for Making Europe The Global Leader in Renewable Hydrogen*, 2020. https://renewableh2.eu/wp-content/uploads/RHC-Policy-Charter-1.pdf

(1) Westküste 100

Several industry partners such as Ørsted, Raffinerie Heide, Stadtwerke Heide and Thyssenkrupp, among others, have formed the project „Westküste 100". Within the five-year project period, an electrolysis plant with a capacity of 30 MW will be installed. It will provide insights into the operation, maintenance, control and grid serviceability of electrolysers in preparation for the next scaling steps. The next step could be, for example, an electrolysis plant with the capacity of 700 MW, for which the electricity will be generated by an offshore wind farm. The hydrogen will be used to produce climate-friendly fuels for aircrafts and will be fed into gas grids. The German Ministry of Economic Affairs and Energy is funding the project.[85]

Figure 34. Westküste 100 concept

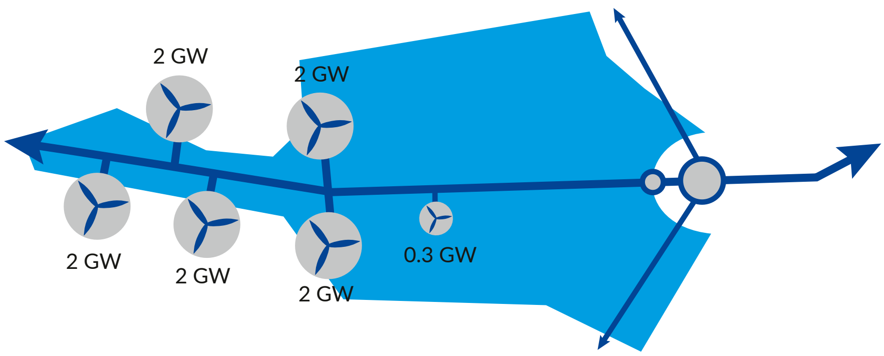


Source: www.westkueste100.de

(2) AquaVentus

The visionary project AquaVentus is another initiative that has been promoted and discussed in Germany. The project foresees 10 GW of offshore capacity for green hydrogen and its transport via pipeline to shore by 2035. Currently, 39 companies, research institutions and organizations are members of the AquaVentus initiative. The project is divided into five sub-projects. Each sub-project aims to deliver one central milestone, from developing the first prototypes to the large-scale production of hydrogen. The long-term vision of AquaVentus includes a cross-border hydrogen pipeline connecting Germany to other European markets, e.g. via the North Sea Energy Hub.[86]

Figure 35. AquaVentus project concept



Source: www.aquaventus.org

85 Further Information: www.westkueste100.de
86 Furher information: www.aquaventus.org

(3) H2Mare
The H2Mare project will explore offshore generation of green hydrogen and other power-to-X products via offshore wind turbines. The partners will integrate an electrolyser directly into a wind turbine, thus provide an innovative way to produce green hydrogen offshore (subproject "OffgridWind"). The direct coupling of wind turbines and electrolysers could minimize the costs of hydrogen production since no power grid connection is necessary. In addition, the project will deliver answers to open questions on safety and possible environmental impacts. The same applies to life cycle analyses and technology assessments. The project is funded by the Federal Ministry of Education and Research.

5.1.5. Other projects

The NorthH2 consortium

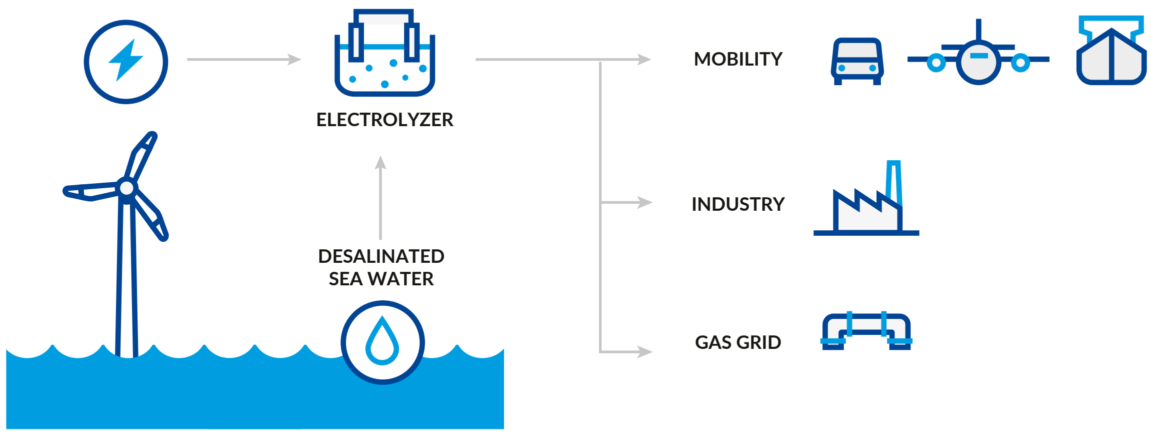
One of Europe's largest wind to hydrogen initiatives is the NorthH2 project.[87] The idea is to use electricity from OWFs outside the Netherlands and produce green hydrogen onshore using existing energy infrastructure. The consortium includes: Equinor, RWE, Gasunie, Groeningen Seaports and Shell Netherlands. Target is a capacity of 4 GW hydrogen in 2030. The first stage will be onshore production, but offshore is foreseen in coming stages.

The project is looking into the full value chain from building OWFs (in the North Sea), producing hydrogen but also storage and distribution networks in north-west Europe.

Siemens - Gamesa and the Oyster project
The joint company and turbine manufacturer Siemens-Gamesa (SG) are developing an integrated hydrogen production system in their largest offshore wind turbine SG14-222 DD. Expected benefits are lower losses and lower production cost. The first prototype is expected in 2025.[88]

Funded by 5m€ from the European Commission (within the Fuel Cells and Hydrogen Joint Undertaking - FCH2-JU) SG, Element Energy and ITM Power have built a consortium with the aim to develop and build an integrated MW-scale OWE and hydrogen production system. The first demonstrator is planned to be in operation in mid 2022.

Figure 36. Integrated wind turbine hydrogen production, Siemens-Gamesa



Source: Siemens Gamesa

Tractebel H2 concept
Another engineering company looking into possibilities for hydrogen production at sea is the global actor Tractebel. German energy and offshore engineers are developing a concept for hydrogen production on an offshore platform. The team is using existing platform designs and adopting them for 400 MW scale hydrogen project. Little details are known to date, but the company has announced innovative features such as integrated desalination of seawater.[89] Tractebel is part of the Engie Group.

87 NorthH2 webpage. https://www.north2.eu/en/
88 Siemens Gamesa webpage. https://www.siemensgamesa.com/products-and-services/hybrid-and-storage/green-hydrogen
89 Tractebel webpage. https://tractebel-engie.com/en/news/2019/400-mw-offshore-hydrogen-production-takes-system-to-new-levels

Dolphyn project

In early 2020, the UK based consultancy company ERM, received £3.12M funding for its Dolphyn project. The unique feature with its integrated OWE and hydrogen system is that it is based on a floating turbine. The first prototype is expected to be a 2 MW turbine pending an investment decision in Q2-2021 with a first run in 2024. The consortium behind the Dolphyn project has recently been expanded to include NEL from Norway and Doosan from South Korea.[90]

Neptun Energy

Another marine named company, Neptun Energy, is looking into the possibilities to convert offshore oil/gas platforms to hydrogen production sites. Locating these in an OWF give access to green electricity at low cost. With a history as a traditional oil and gas company they have high competence in offshore activities. A first pilot is evaluated using an existing Neptun platform in the sea outside the Netherlands. This specific platform is located between the Luchterduinen OWF and the shore.[91]

6. Barriers and opportunities

	Barriers	Opportunities
Regulation & Policy	• Still too few green hydrogen projects being developed, especially in Poland and the Baltic States in comparison to other EU countries. There is a considerable disproportion of efforts and political commitment. Western European countries like Germany and France have multi-MW green hydrogen projects in the pipeline whereas others are lagging behind. • OWE ambitions across the Baltic Sea countries do not necessarily follow their potential. As an example, Sweden or Finland with very high technical potential for OWF deployment are not focusing on offshore solutions. On the other hand, Germany has limited offshore areas available in the Baltic Sea but very ambitious green hydrogen goals. • Lack of hydrogen strategies – very few countries have developed dedicated hydrogen strategies. In the Baltic Sea Region only Germany has fully adopted a dedicated hydrogen strategy while Poland developed a draft. • Hydrogen faces many regulatory issues such as: permitting issues (complexity or absence of rules), injection of hydrogen to the grid (standards based on natural gas), safety regulations etc.[92] There is still a significant amount of work to be done to overcome these barriers.	• Strong European Union decarbonisation policy – the European Green Deal as well as the goal for climate neutrality by 2050, supported by dedicated EU hydrogen and offshore energy strategies provide a strong stimulus for policy changes across Europe. • Already identified barriers – many regulatory barriers are already identified on national levels (see results of the HyLAW project)[93], they can be addressed through changes in national legal frameworks.
Market conditions	• Costs – In order to compete with grey hydrogen, green hydrogen needs to reach cost of production below 2 EUR/kg. A major part of the cost reductions will come from lower renewable electricity prices. Despite a very successful cost reduction trend in offshore wind industry in the past decade, further cost cutting will be necessary for successful coupling with electrolysers. • Low demand for green hydrogen – demand for green hydrogen is still very low to reach economics of scale and needs to increase through uptake in new sectors such as: mobility, heating, steel production, chemical industry, energy production etc. The lack of demand stems primarily from the price barrier – fossil-fuel based solutions are cheaper. There is also a technological-access barrier, where hydrogen-ready solutions (for example storage infrastructure, turbines, fuelling stations) are yet to reach maturity and be deployed. • Business models – there is a need to develop new business models that will prove economic viability of green hydrogen production and uptake by the private sector. This also relates to hydrogen production from offshore wind – there is a considerable need for proof of concept.	• Significant cost reduction in RES – dropping renewable energy prices are the key driver for LCOH reduction. Energy from offshore wind is foreseen to drop by one third in the next 10 years. • With electrolysers onshore, connected to the grid, there is a possibility to take advantage of price variations to produce hydrogen at times of surplus. Using a mix of different RES, with different production profiles, could lead to increased number of load hours for the electrolyser and therefore lead to cost reductions. • High carbon emissions allowances costs – prices over 50 EUR per tonne of CO_2 give a strong market signal. Even if in the past the emission trading scheme may have been contested it cannot be ignored by the industry which will have to start looking for green energy sources. • Market leadership – Europe is a market leader in offshore wind with over 70% of global installed capacity. Similar technological leadership can be built in green hydrogen industry.
Regional cooperation (Baltic Sea Region)	• Insufficient regional cooperation – there is still insufficient cooperation in the region e.g. there is no regional offshore wind strategy (although first political commitments are made)[94] nor hydrogen strategy and very few real cross-border initiatives. Hybrid projects and offshore grid development may be a game changer. • Baltic Sea Region is highly diversified – although diversity is generally favourable this might be seen as a barrier due to different levels of ambition regarding hydrogen and offshore wind energy development.	• Favourable conditions for offshore wind and hydrogen production – Baltic Sea is one of the basins with highest offshore wind energy potential. The Baltic Sea Region also includes two leading producers of hydrogen (grey) in Europe (Germany and Poland). The region is also rich in potential green hydrogen recipients such as steel industry, refineries, chemical industry, transport sector etc. • Planned OWE projects - there are considerable plans for OWE development in the Baltic Sea Region, Poland alone is planning to build 11 GW until 2040 and Denmark plans to use Bornholm as an energy island.

90 ERM webpage. https://ermdolphyn.erm.com/p/1

91 *The world's first offshore green hydrogen plant*. Neptune Energy webpage. https://www.neptuneenergy.com/esg/new-energy/poshydon-hydrogen-pilot [Access date: 20.04.2021]

92 Floristean A. et al. *Deliverable 4.2 List of Legal Barriers*. HyLAW project.2019. https://www.hylaw.eu/sites/default/files/2019-01/D4.2%20-%20List%20of%20legal%20barriers.pdf

93 ibidem

94 *Baltic Ministers endorse commitment for closer cooperation on offshore energy*. European Commission website, 30 September 2020. https://ec.europa.eu/info/news/baltic-ministers-endorse-commitment-closer-cooperation-offshore-energy-2020-sep-30_en [Access date: 15.06.2021]

7. Recommendations

Regulation & Policy

- Hydrogen deployment requires clear strategies at national and regional levels. Currently very few countries adopted hydrogen strategies which specify clear and ambitious goals for hydrogen production and uptake. This is critical to pave the way for technology development. One of the solutions might be to make use of future NECPs which should include green hydrogen production and consumption in order to plan for renewable energy deployment matching increased electricity demand.
- Significant promotion efforts should be made to disseminate information about the green hydrogen potential and barriers (significant knowledge already exists) among policy makers. This should enable adjustment of the legal framework needed for green hydrogen development. In addition green hydrogen from offshore wind should be stressed out as a field which requires serious investigation as it can become a significant contributor to reaching climate neutrality by 2050 (considering high offshore wind potential in the Baltic Sea Region). Results from demonstrative projects should be widely disseminated.

Market conditions

- New business models should be analysed in order to prove commercial viability of green hydrogen production (including hydrogen from offshore wind) in various sectors e.g. transport, steel or chemical industry, heating etc.
- Further investigations (studies etc.) and demonstrative projects related to power-to-x from offshore wind should be launched to prove feasibility and competitiveness of these concepts. Offshore wind energy should be considered a strategical technological match for hydrogen production due to: potential large scale deployment, cost reduction of offshore wind, potential for offshore wind to become a reliable energy source with hydrogen used for balancing.
- More demonstrative and large scale green hydrogen projects are required in order to reduce the green LCOH, this includes not only production facilities, but also use of green hydrogen (or derivatives like NH_4) downstream i.e. in shipping, energy sector, industry applications etc.

Regional cooperation (Baltic Sea Region)

- A regional strategy for offshore wind and hydrogen development which will make use of the Baltic Sea Region diversity and opportunities such as high offshore wind and hydrogen potential, presence of industry etc.
- Knowledge exchange should be promoted among the Baltic Sea Region countries to overcome differences such as regulatory issues, support schemes, strategy approach but also to promote green hydrogen projects.
- The Baltic Sea Region would benefit from more cross-border initiatives and agendas. Establishing of a Baltic green hydrogen hub stimulating regional cooperation and exchange of knowledge as well as promoting new business models in various sectors would be strongly recommended.

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