State of Art in Offshore Hydrogen Production

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Contents

1 Introduction

The world is making a significant move towards cleaner energy sources and one of the prominent, reliable option is offshore wind power. Countries around the globe are recognizing the potential of this technology to decarbonize the energy system. Offshore hydrogen production will be one of the enablers of the further deployment of offshore wind as costs of transporting wind power by means of HVDC power cables will become less economically feasible at distances beyond 100 km from shore. At this point, several developments, pilots and demonstrations are performed and reported on offshore hydrogen production (OHP).

The Netherlands has set clear ambition to decarbonize its energy system through the rapid uptake of green hydrogen in the Dutch energy mix. For example, targets have been set to achieve 500MW of electrolysis capacity for domestic hydrogen production by 2025 and 3 – 4 GW by 2030. There are arguments that indicate that offshore hydrogen production can have an economic and societal benefit over onshore hydrogen production[1].

In line with that reasoning, the Ministry of Economic Affairs is planning to have two pilot projects for offshore hydrogen production. The first one (DEMO 1) will have a capacity of <50MW and is expected to be operational earliest in 2027, the second (DEMO 2) is aimed to have a capacity of 500 MW, being operational earliest in 2031. Additionally there are lower capacity pilots and demonstration projects under development like PosHYdon[2], Base Load Power Hub[3] and SeaLhyfe[4].

This report aims to summarize the current state of research, based on PESTLE aspects and provides an overview of the expected bottlenecks, high level roadmap of knowledge development activities needed to commercially implement 100+ MW scale offshore H2 production.

In chapter 2, the value of offshore hydrogen production is summarized. In chapter 3, the different envisioned concepts for offshore hydrogen production are listed, as well as the operational strategies that may affect the designs of these concepts. Chapter 4 consists of the technical state of art of key elements of offshore hydrogen production. In chapter 5, foreseen bottlenecks are listed, followed by a roadmap that highlights the most important activities to accelerate offshore hydrogen production.

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[1] Towards a sustainable energy system for the Netherlands in 2050 (tno.nl)
[2] Poshydon | About PosHYdon
[3] The wind park | Crosswind Hollandse Kust Noord (crosswindhkn.nl)
[4] https://www.lhyfe.com/press/offshore-hydrogen-production-on-a-new-scale-hope-project-and-its-consortium-selected-for-a-e20-million-european-commission-grant/

Abbreviation	Full form
AC/DC	Alternative/Direct Current
BOP	Balance of Plant
CAPEX / OPEX	Capital Expenses / Operational Expense
EIPN	Energy Infrastructure Plan North Sea
FLNG	Floating Liquified Natural Gas
FPSO	Floating Production Storage and Offshore
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LOHC	Liquid Organic Hydrogen Carriers
MW/GW	Mega/Giga Watt
NSEC	North Sea Energy Countries
OHP	Offshore Hydrogen Production
OSW	Offshore Wind Turbine
PEM / AEM	Proton Exchange Membrane | Anion Exchange Membrane
RED	Renewable Energy Directive
SOEC	Solid Oxide Electrolyzer Cell
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
WTG	Wind turbine generation

2 The value of producing hydrogen offshore

The value of (green) hydrogen as an energy carrier is currently well recognized. According to the IRENA (International Renewable Energy Agency)[5], hydrogen could account for up to 12% of global energy use by 2050. Many major industries and countries have drafted strategies and plans to boost renewable hydrogen development. The combined potential capacities of offshore and onshore renewable energy from solar and wind is much larger than can be directly absorbed as electricity in the energy systems. That abundance of renewable energy can be used to produce hydrogen, which provides an additional route to incorporate much larger amounts of renewable energy into the energy systems, rather than if wind and solar were only utilized as sources of electricity.

Hydrogen is a very versatile energy carrier. It can be used for the production of electricity again, but it can also be used for non-energetic purposes in industry (feedstock and industrial gas) and as a gaseous fuel in various applications that are difficult to electrify or require very high temperatures (cement, steel, glass, metal). In addition, electrolysis-based plants can represent a great source of flexibility on the demand side in supporting controlled integration of intermittent electricity supply into the electricity system [6].

For several reasons, offshore production of hydrogen has a large societal or system value. Many of the plans for current and near future development of offshore wind are still based on transporting generated electricity to shore and onshore conversion at the coast. With continued implementation, however, the landing of the many electricity cables is becoming an increasing challenge as well as space requirements for onshore conversion in or near densely built-up industrial areas. The foreseen increments in electricity infrastructure costs and related tariffs are an increasing point of attention as wind farms are built further out to sea[7]. Hydrogen offers a more favorable perspective on these points in terms of energy transport. Hydrogen infrastructure provides a greater capacity per landing point. The costs are lower, and existing natural gas infrastructure may be used. This stipulates an important role for offshore hydrogen production in the near future.

Although the system value of offshore hydrogen production is clear[8], the business case for individual offshore hydrogen production systems is not yet positive and under pressure[9]. The challenge for industry and governments is to put these business cases in perspective to the avoided costs for the energy system, such as transport and storage costs, and provide appropriate (financial) support or incentives to create a satisfactory end result for both industry and society.

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[5] Geopolitics of the Energy Transformation: The Hydrogen Factor (irena.org)
[6] Offshore hydrogen for unlocking the full energy potential of the North Sea – TNO White paper
[7] https://www.tennet.eu/news/ten-year-forecast-predicts-increase-transmission-tariffs-2027-onwards
[8] Towards a sustainable energy system for the Netherlands in 2050 (tno.nl)
[9] https://group.vattenfall.com/uk/newsroom/pressreleases/2024/ht1-conclusion

3 Current State of Art – Offshore Hydrogen Production

In short, offshore hydrogen production concept consists of converting demineralized seawater with using (renewable) electricity offshore into hydrogen by means of electrolysis and transporting that hydrogen to shore via pipelines. Offshore hydrogen production is hence not a straightforward technology. It is a combination of different technologies that are put under challenging conditions.

In the next sections, an overview in the general state of art on hydrogen production is provided in three aspects:

1) **Energy Supply** – The renewable energy source required to provide the renewable input power, in the right power level and form (direct current) as described in section 3.1
2) **Conversion to Hydrogen** – The concept used for hydrogen production (desalination, electrolysis technology, capacity, size, location, balance of plant design), as described in section 3.2.
3) **Hydrogen transport** – methods to bring the hydrogen to shore via repurposed or new built pipelines, either in a pure stream om blended with natural gas, as described in section 3.3.

3.1 Energy Supply

The production of green H2 requires a renewable electricity source to provide the input power into the electrolyzer system and other equipment used in the process. There are several options of energy source like wind, tidal, wave and solar to harness the energy from in an offshore environment. The most dominant source of renewable energy will be offshore wind farms, and to a smaller extent offshore solar farms. Although tidal and wave technologies could potentially provide renewable power as well, in the current technology, they are expected to play a minor role in developing offshore H2 in the North Sea region[10].

3.1.1 Offshore Wind Energy

Offshore wind is becoming a key renewable energy source that has a high TRL-level and is commercially mature to deploy in the world's seas. Therefore offshore wind energy is one of the most prominent renewable energy supply source for offshore hydrogen production. Offshore wind energy uses wind turbines to convert the wind into renewable electricity which in turn can be used to power up the H2 system to produce green H2. The majority of the

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[10] Offshore renewable energy (europa.eu)

currently installed offshore wind farms has been built at relatively shallow seas, where wind turbines are installed on monopiles that create a fixed connection to the seabed.

Inherently for wind energy, the produced power from an offshore wind farm is not constant. The power production depends on the local wind speed, and may differ significantly over various locations in the North Sea. A typical power output from such wind farm is presented in Figure 3.1. In this fictive example, there are a few hours of no wind, whereas over a year there can be full days or even weeks with little to no wind.

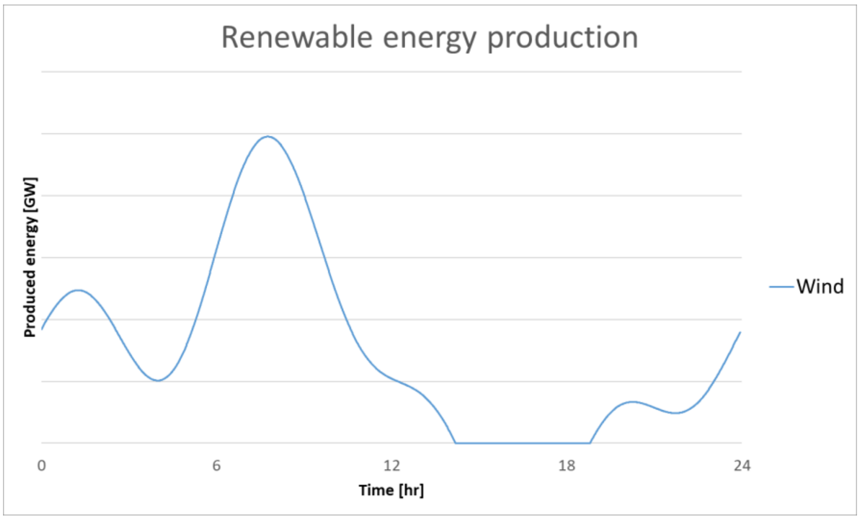

Figure 3.1: Fictive example of intermittent wind energy over a day.

The International Energy Agency (IEA) describes wind energy as a unique 'variable baseload' technology that helps to integrate the decarbonized energy system of future. By the end of 2022, the world had more than 60 GW of operational offshore wind capacity, with almost 9 GW installed in 2022 alone.[11] The Netherlands has reached its ambition to realize 5,5 GW of offshore wind power in 2023, the result of the energy agreement in 2013. The Dutch ambitions have been expanded towards 21 GW in 2032, 50 GW in 2040 and ultimately 70 GW by 2050.

In Europe, the countries in the The North Seas Energy Cooperation (the NSEC countries) and the UK all have ambitious plans with respect to development of offshore wind energy, see Figure 3.2. The combined ambitions of the NSEC countries show an envisioned installed capacity of 76 GW in 2030. The UK would add an additional 40 GW on the North Sea by 2030. By 2050, the total estimated installed capacity in the EU of offshore wind energy is close to 300 GW and the EU countries around the southern part of the North Sea agreed to supply 50% of that, hence 150 GW. Total installed capacity at the North Sea in 2050 is currently predicted to be over 300 GW.

Floating offshore wind farms may also become a source of energy for offshore hydrogen production in areas further offshore, with deeper water (>50 m). First floating wind farms have been commissioned, but not yet at the scale of the bottom fixed wind farms. Currently, the largest floating wind farm is considered to be the Hywind Tampen wind farm in Norway, consisting of eleven 8.6MW turbines. [12]

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[11] Global Offshore Wind Report 2023, Global Wind Energy Council.
[12] Hywind Tampen - Equinor, retrieved 12-04-2024.

For far offshore floating wind farms in deep water, the concept of a floating production, storage and offloading (FPSO) from the oil and gas sector is proposed. The idea is that the wind power is converted into hydrogen with electrolysis of seawater, create a liquid hydrogen carrier such as ammonia at the FPSO and have shuttle tankers ship it towards import harbors. These concepts are still in its early stage of development.

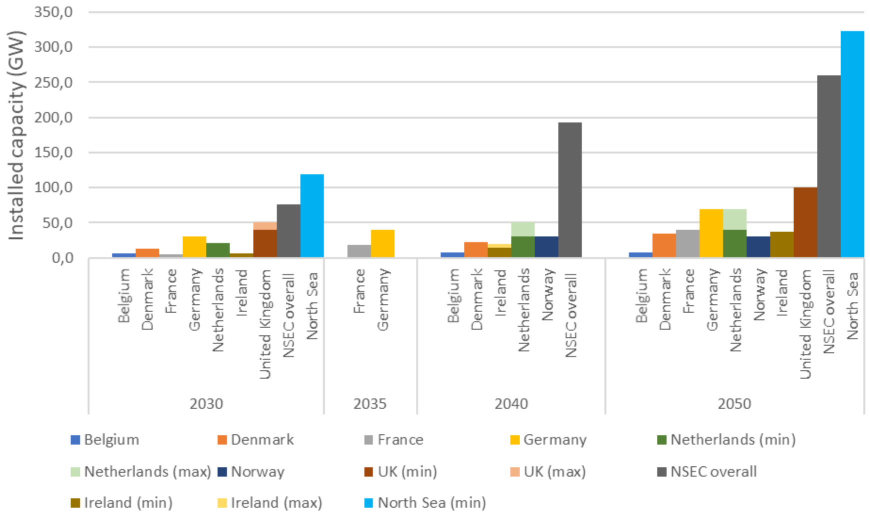

Figure 3.2: Predictions of installed capacities of offshore wind in Europe[13]

3.1.2 Offshore Solar Energy

As previously mentioned, harnessing solar energy for offshore hydrogen production represents a relatively new sector. Offshore solar energy production involves the installation of floating solar panels on the surface of oceans or seas to generate electricity, which is then used in the production of renewable hydrogen through electrolysis.

The floating solar installations and their locations are categorized based on wave category. There are 4 wave categories as follows:

- Category 1 – Floating solar on smooth water (TRL 8)
- Category 2 – Wave height of 1m- (TRL 6)
- Category 3 – Wave height of 2m- (TRL 4)
- Category 4 – Open sea (wave heights around 10m-) (TRL 3)

Open sea FPV installations will be under wave category 4. Today, most commercial floating solar installations are in locations of wave category 1 or 2. For the open sea category, steps are currently undertaken. Studies and pilot projects are underway for locations with higher wave heights, and offshore solar has been an explicit topic in the Hollandse Kust North (CrossWind 2022), West (OranjeWind 2023) and IJmuiden Ver Beta wind tender (2024). SolarDuck and RWE have recently installed an offshore floating solar pilot Merganser (0.5MWp), 12 kilometers from the Dutch coast in the North Sea[14].

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[13] North Sea Energy 2022, published 7 November 2022 (North Sea Energy (north-sea-energy.eu).
[14] SolarDuck and RWE successfully install offshore floating solar pilot Merganser off Dutch coast • SolarDuck

Similar to offshore wind, the produced power from offshore solar is intermittent, yet weakly correlated to the production profile of offshore wind. Hence, the two offshore energy sources have the possibility to complement each other, resulting in a larger number of hours in a year that there is a positive export power guaranteed (Figure 3.3) and a better use of the export power cable or electrolyzer. This can be of significant value for offshore hydrogen production, as systems may run at minimum load instead of needing to shut down regularly. Offshore electricity storage with batteries or innovative storage concepts may improve the continuous supply to offshore hydrogen production facilities further.

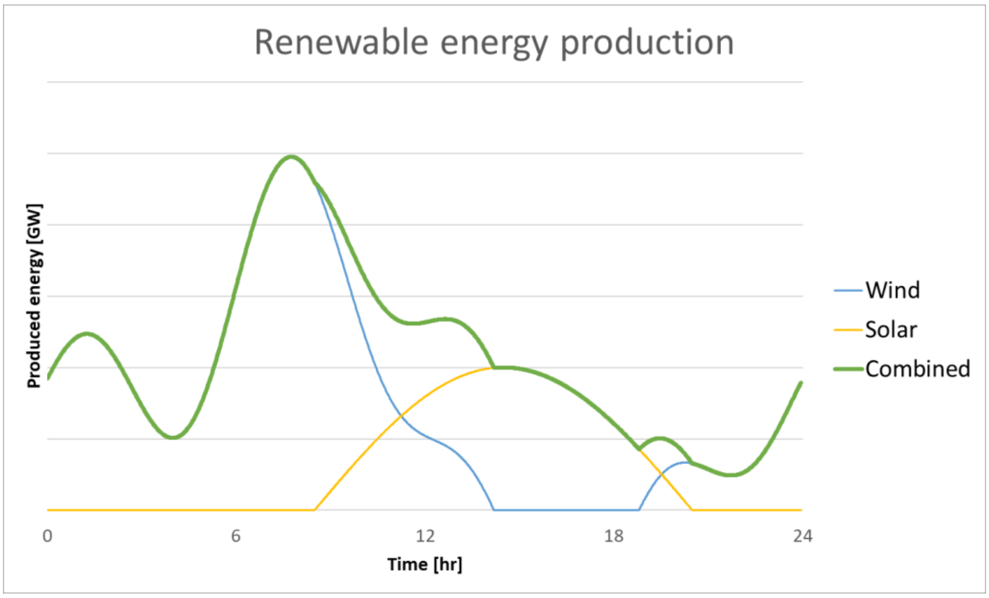


Figure 3.3: Potential complementary supply of energy from a combined offshore wind and offshore solar plant.

3.2 Hydrogen production

In this section, the different concepts are described that are currently envisioned to be installed for offshore hydrogen production. Although customized to the best configuration for each specific project, the most frequently seen design concepts are:

1. **De-centralized (in-turbine or at-turbine) Production**: In this case, the electrolyzer is connected to each individual wind turbine (optionally with a battery to store the electricity) and the produced energy is transported in H2 pipelines to a central collecting platform, where hydrogen compression is installed.
2. **Centralized Production**: The production of H2 is centralized either on a platform or an island where all the components of the H2 system are placed. This type of production could be further classified into 2:
    i. **Large scale electrolysis on a platform**: In this case, the wind turbines are connected to one or a combined number of platforms, on which the whole hydrogen production system including the electrolyzer and the Balance of Plant is located.
    ii. **Large scale electrolysis on an energy island:** In this case, multiple wind farms can be connected to an energy island where the electrolysis takes place at GW scale.

These production concepts are described in more detail to understand the current technology status and bottlenecks.

3.2.1 Decentralized Electrolyzer

The electrolyzer paired with its balance of plant (BOP), is located inside or next to the tower of each wind turbine. The produced hydrogen is then transported via pipelines that connects groups of turbines. On the hub (or manifold), the H2 is collected and compressed and transported to shore via pipeline.

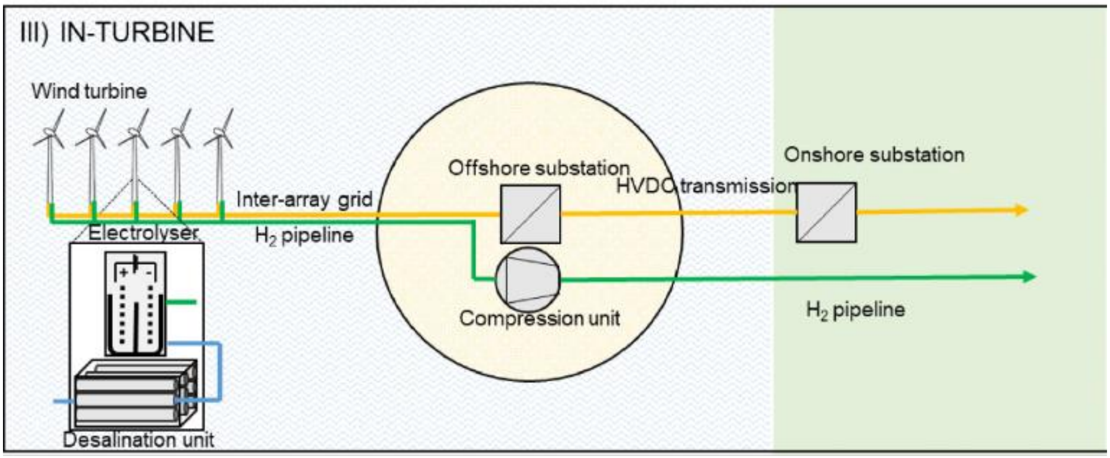
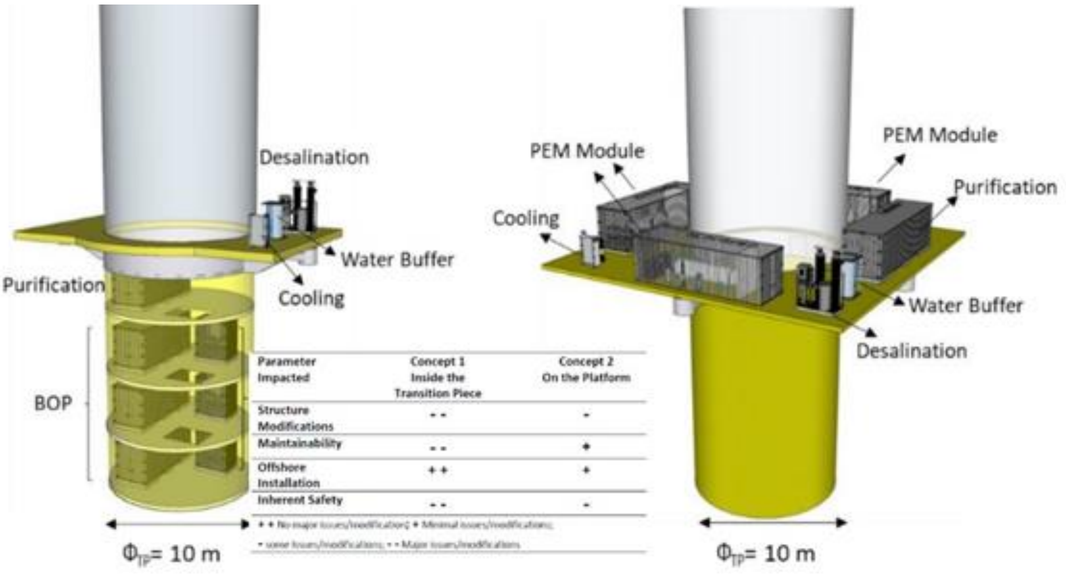


Figure 3.4: Decentralized Electrolyzer. The situation in the picture assumes a cable connection. In off-grid situations the cable may not be present.

Within the de-centralized electrolysis method, a distinction can be made between in-turbine and at-turbine electrolysis. The concept consists of different types of production and life support systems. The equipment's/systems include electrolyzer, riser, water lift pump, desalination units, battery and other facilities along with an AC/DC converter.

1. **In-Turbine Electrolysis:** It is a concept that converts all wind energy to hydrogen and therefore require fewer power conversion steps as no electricity is exported from the turbine, so the electricity produced in the turbine generator (690 VAC) could be directly converted to low-voltage DC for input to the electrolyser. In this concept, the electrolyzer and the associated Balance of plant is incorporated within the wind turbine.

2. **At-Turbine Electrolysis:** This is a concept that is based on the connection of an electrolyser to the transformer of a wind turbine (33+ kVAC) to an electrolyser system. As such, this concept allows production/export of both electricity and hydrogen. More power conversion steps are required, which could lead to more energy losses and a more complex integration with the electrolyser and with the electrolyser. In this concept, the electrolyser is installed as a separate system just outside the turbine (i.e., on the same foundation/monopile as where the wind turbine is), but connected to each individual wind turbine generator (WTG). Also desalinization, separation and conditioning of the hydrogen needs to be installed per WTG.



Parameter Impacted	Concept 1 Inside the Transition Piece	Concept 2 On the Platform
Structure Modifications	- -	-
Maintainability	- -	+
Offshore Installation	+ +	+
Inherent Safety	- -	-

+ + No major issues/modification; + Minimal issues/modifications;
- some issues/modifications; - - Major issues/modifications

Figure 5: In-turbine concept (in left) and At-turbine concept (in right)[15]

3.2.2 Centralized electrolysis on a platform/sub-station:

The electricity produced by a cluster of wind turbines or other energy sources are transmitted to a platform or a substation (a hub). This concept involves combining electrolysis on a platform to generate hydrogen from (desalinated) seawater. The offshore hydrogen platforms that are currently being envisioned can accommodate electrolyzer with capacities ranging from 100 to 700 megawatts (MW). Existing literature showcases case studies falling within the 100 MW range, which is considered the minimum capacity for economically viable hydrogen production using offshore platforms[16].

The platforms on which the electrolyzer are installed, could be a new platform or also an already existing platform. For large scale centralized offshore electrolysis, it is expected that new platforms will be constructed, smaller pilots during scale up can be implemented on existing platforms to save costs. Along with the electrolyzer, the platform also comprises other system required for the H2 system to function effectively, the balance of plant (BOP). This includes an AD/DC converter, sea water lift pump with desalination unit, H2 separator and drying system, a compressor, potentially a battery and other support systems.

Current state of art suggests that, for platform applications, a PEM electrolyzer is the preferred technology for hydrogen production, because of its high TRL, relatively small footprint and low weight. Additional to their compatibility, PEM Electrolyzer are currently foreseen to operate better with intermittent/fluctuating electricity more flexible than an alkaline electrolyzer.

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[15] Chico Moreno, F. D. (2021). *Design of an Electrolyzer Integrated in an Offshore Wind Turbine System*. [EngD Thesis, University of Twente]. University of Twente.

[16] wes-2023-143.pdf (copernicus.org)

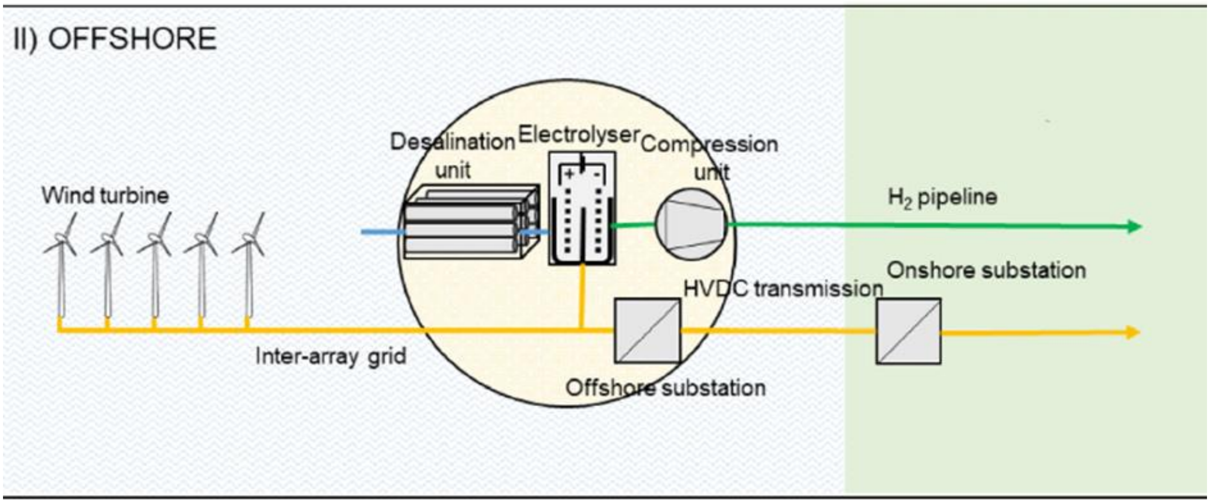

Figure 3.6: Figurative explanation of platform type electrolysis (1). The situation in the picture assumes a cable connection. In off-grid situations the cable may not be present.

3.2.3 Large scale electrolysis on an energy island:

The electricity produced by a cluster of offshore wind farms are transmitted to an (artificial) island to produce hydrogen using electrolysis of demineralized seawater. The energy island contains desalination units, electrolyzer and compressor to demineralize the water and then produce and compress hydrogen respectively.

Similar to the concept on a platform, it integrates electrolysis to produce hydrogen from seawater using offshore wind as energy source. The energy islands are much bigger than the above mentioned concepts (i.e.., turbine and platforms). They are suitable for large scale offshore windfarms and subsequent H2 production ranging from 1GW up to multiple GW. In addition, the scale is such that PEM-technology is not necessarily the preferred electrolysis technology or a combination of PEM and Alkaline technology can be applied.

There are already existing artificial islands build by many countries like Dubai for living but also countries like Canada for O&G purposes. Compared to the other 2 concepts, this concept has less limitations on the critical size and can use more mature technologies that are also developed at onshore electrolyzer plants. These islands can be scaled both by vertical and horizontal expansion.

Currently, the Danish government along with CIP P/S had plans to construct a “hydrogen island” on the Dogger bank, around 200 km off the Danish west coast. The plan was to connect this energy island with offshore wind of around 10GW capacity to produce around 1 Million tons of H2 per year and then to transport the H2 via pipelines to Northwest Europe . Recent information’s are pointing out to the fact that this project is shutdown.

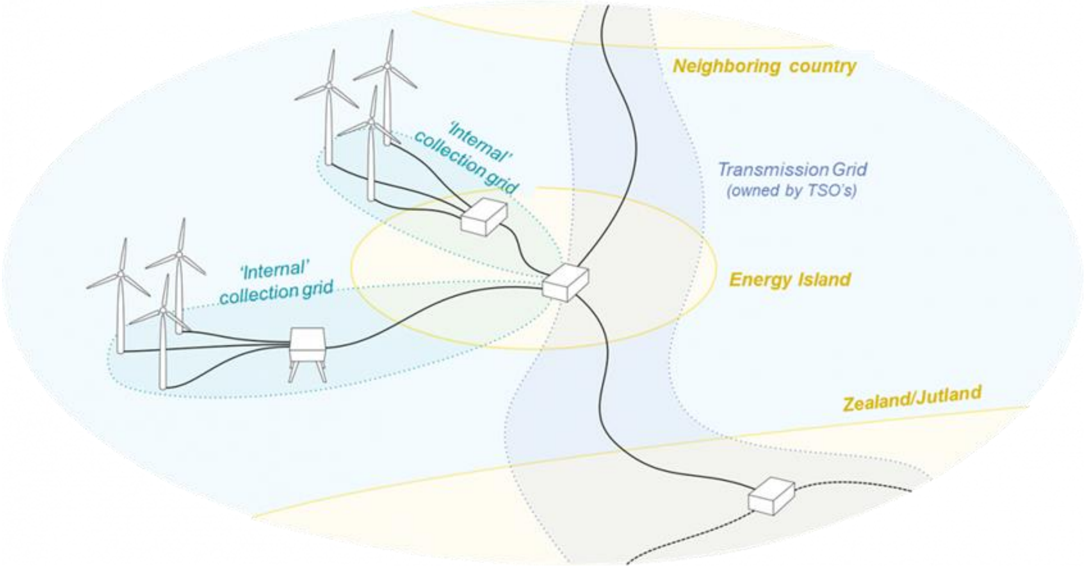

Figure 3.7: Concept diagram of energy island in the Baltic Sea

Additional projects are being investigated by Belgian government to construct an energy island in the Belgian part of North Sea, called the Elisabeth Island, although no hydrogen conversion is planned on this island. Denmark is also working on developing an energy island on the existing Bornholm island in the Baltic sea.

The energy island usually consists of the following components to produce green H2: AC/DC converter, power rectifier, electrolyzer., desalination unit, hydrogen separator, compressor and a battery to store additional electricity.

The energy island has its own disadvantages. Constructing an energy island is relatively expensive considering the water depth making the construction challenging and additionally with the offshore conditions. The current ideal size of the island would be around 2 to 5GW to favor the major expected cost trends for the construction. In the future, the capacity will increase and an optimal hub size of around 10 – 15GW can be achieved.

3.2.4 Floating concepts

For concepts at deeper waters, further offshore, floating structures are investigated in first feasibility studies. First pilot projects for floating wind technology demonstrate the harvest potential at deeper waters. The first commercial floating wind projects are currently being developed, see section 3.1.1.

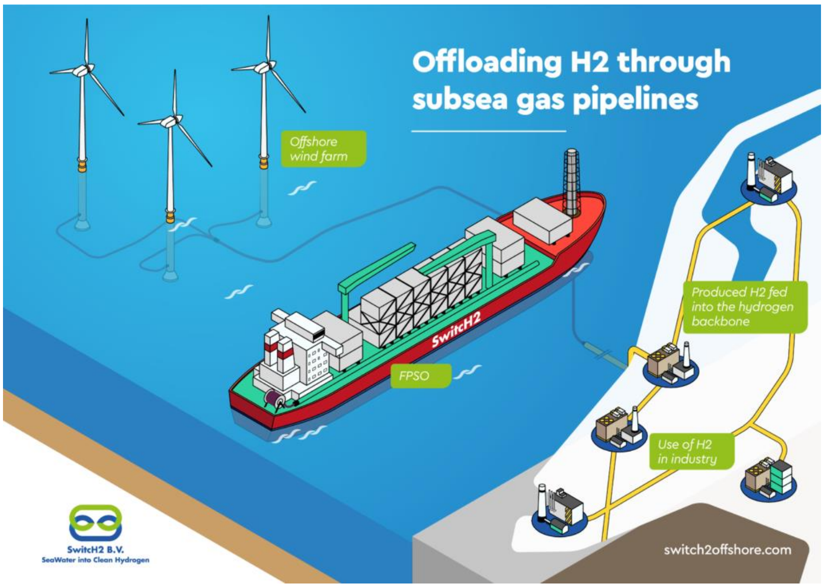

Figure 8: Floating Platform Offshore System (FPSO)

FPSO and FLNG technology have been developed and matured in the last decades. Deep water FPSO operations are now state of the art with sophisticated design, construction and maintenance strategies. Manageable scales and risks are well defined. Current facilities concern only fossil fuel resources however. No FPSO concept has yet been developed to produce hydrogen carriers, produced from renewable energy sources.

Although individual components of an hydrogen producing FSPO are at relatively high TRL, their combination into an integrated solution still poses several technical challenges (e.g. design of renewable interfaces) that can be considered more challenging than hydrogen production on a platform. The main challenges revolve around sizing, system integration, marinization and economics. A consortium of Marin, TNO and other partners have proposed a Green FPSO initiative to study this concept.

3.2.5 Operational strategies

The fluctuating power output from renewable sources has an impact on the electrolyzer operation, efficiency and material degradation. A connection to an offshore electricity grid or batteries may improve the operation of an offshore electrolyzer, as it can provide a baseload of power to keep the electrolyzer in a stable operation mode. During periods of low power production from renewables, the electrolyzer could use grid electricity, ensuring consistent operation and improved efficiency. The use of the grid is not trivial however, as the RED II/III regulations stipulate explicitly when produced hydrogen can be labelled as green hydrogen, depending on when the electricity to produce the hydrogen was generated.

The RED II (in particular Delegated Act 27(3), published in 2023[17], establishes the criteria where hydrogen production via water electrolysis can be counted as ‘green’ hydrogen that can be used to comply with the targets for the consumption of Renewable Fuels of Non Biological Origin (RFNBO). Generally speaking, there can be two main situations that arise in offshore hydrogen:

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[17] Delegated Act article 27.3 RED II

1) If hydrogen is produced via a direct connection to an offshore wind farm i.e., where there is no connection to the electricity grid (a so-called 'behind-the-meter' situation) then hydrogen can be counted as fully renewable only if the wind farm has entered in operation not early than 36 months before the hydrogen production facility.
2) If hydrogen is produced using electricity the wind farm while the wind farm is connected to the electricity grid (a so-called 'after-the-meter' situation), hydrogen can only be counted as green if at least <u>one</u> the following criteria are met:
    a. The electricity complies with <u>one</u> of the following criteria:
        i. 90% of the electricity grid of the corresponding bidding zone (in this case the Dutch electricity grid) is renewable; or
        ii. The emission intensity of the grid is lower than 18 gCO2eq/MJ (and the geographical and temporal correlation conditions are met, see below); or
        iii. Hydrogen is produced from renewable energy that would otherwise be redispatched i.e., to prevent curtailment
    b. The electricity complies with <u>all</u> of the following criteria:
        i. <u>Additionality</u>: electricity is purchased from a wind farm that came into operation no earlier than 36 months before the start of operation of the hydrogen production facility (an exception is made until 2038 if the hydrogen is produced starting from 2027); and
        ii. <u>Temporal correlation</u>: the electricity used for hydrogen production is produced within the same month (until 2029) or within the same hour (from 2030) as the hydrogen production; and
        iii. <u>Geographical correlation</u>: the electricity used for hydrogen production is produced in the same electricity bidding zone, an interconnected bidding zone (where the electricity price is higher), or in an offshore bidding zone

Similar to the onshore operation strategies[18], the following operation strategies or business strategies for the combination of a wind farm and the offshore electrolyzer can be determined:

- **Peak Shaving.** The peak shaving strategy uses the electrolyzer to shave the peaks off a wind farm's production. Electricity production has highest priority for this strategy, and hydrogen production is considered of lower priority. The electricity price is the main driver for running the electrolyzer. In general, the utilisation of the electrolyzer is relatively low, as the main focus is to exploit the renewable energy potential that would otherwise be curtailed because the electric grid cannot take a sudden peak in power. As electricity production has highest priority, the electric grid connection capacity will need to approximate the capacity of the wind farm, and is likely much larger than the electrolyzer capacity.

- **Baseload hydrogen production.** For this strategy, the electrolyser's hydrogen production is prioritized and any excess electricity production is sold on the market. The main focus is to have a continuous green hydrogen production. The grid connection required equals at least the capacity of the electrolyzer.

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[18] Offshore wind to hydrogen: flexibility provider in a Dutch electrified market | Flexible Offshore Wind Hydrogen Power Plant Module (grow-flexh2.nl)

- **Maximum profit operation.** In case of a well-established hydrogen market, and particularly when the electrolyzer operator and the wind farm operator are the same entity, this strategy could be seen more frequently. The profit optimisation strategy determines whether to produce hydrogen or to sell the electricity by looking at the forecasted hydrogen price to determine the most profitable production. This is the most flexible strategy: the prices of electricity and hydrogen will determine how the energy is transported to shore, through electrons or molecules. When the electricity price is high, it is more economic to sell the produced electricity and feed it into the electricity grid. However, when the electricity price is low or even negative, producing green hydrogen is more beneficial both for the system and for the operator since the hydrogen can be sold or converted as another energy carrier for a better price, or when stored at a later moment in time when the hydrogen price is even better.

- **Off-grid operation.** In this scenario, there is no dependency on an offshore electricity grid. Local electricity storage using e.g. batteries can still provide the appropriate minimum load in hours of insufficient wind energy production. Only hydrogen is being produced from the offshore wind park and transported to shore via pipelines. Startup of the system is supported by batteries.

The business case for each strategy is very different, particularly the balance between CAPEX and OPEX. The distance from shore, the availability of an offshore electricity grid or the relative size of the electrolyzer to the renewable power supply (wind farm) and national regulations are key factors that determine which strategy is most profitable.

3.2.6 Current development in offshore

The Dutch government has set an ambitious target of achieving 3 - 4 GW of electrolyzer capacity and 21 GW of offshore wind capacity by 2032. It is crucial to examine the initiatives of various governments and flagship projects to gain insights into the current state of offshore hydrogen production (OHP) utilizing wind energy as a primary source. The OHP technology is still in its development phase, which makes it difficult to pin point the exact state of art . To overcome this hurdle, in the forthcoming section of the report, our attention will be directed towards several flagship projects, with a specific focus on the technologies they deploy to make these projects a reality.

3.2.6.1 Currently running projects

Table 3.1: Projects that are planned within the near future.

Project Name	Location	Size	Status
PosHYdon	Dutch North Sea	1.2 MW	In operations on land
Cross wind - BLPH	Hollandse Kust Noord	2,5 MW	In construction. Operation Q2 2025?
Sealhyfe	Le Croisic, Nantes	1 MW	In operation offshore for a year (hydrogen not used)
Oyster	Grimsby, United Kingdom	>1MW	?

Project Name	Location	Size	Status
HOPE	Port of Ostend, North Sea	10 MW	FEED?

A brief explanation about each of the project is listed below:

1) **PosHYdon**: It is an offshore hydrogen production initiative operating within the Dutch North Sea.
    - This project is an initiative led by Nexstep, Neptune Energy, EBN and TNO and executed together with 15 partners
    - The capacity of this pilot project is around **1,2MW electrolyzer** on an existing offshore platform.
    - The energy to run this pilot is obtained from green electricity from the grid via a power cable from shore to produce hydrogen.
    - The hydrogen produced is transported in a blended stream with the natural gas to industrial users at the Maasvlakte area in Rotterdam
    - Objective – The main objective of this project is to accumulate valuable insights into integrating functional energy systems at sea, exploring H2 production in offshore environments, and testing the electrolyzer efficiency under fluctuating energy supply. Also hydrogen transport as a blend in an existing pipeline is studied.

2) **CrossWind** – **BLPH:** Innovative project that aims at building and testing a pilot scale Base Load Power Hub (BLPH) within the frame of Hollandse Kust Noord wind farm CrossWind.
    - This project is an initiative led by CrossWind, a joint venture between Shell and Eneco
    - The capacity of this pilot project is around 2,5 MW electrolyzer in a new offshore platform. Additionally the system hosts 1 MWe Battery Energy Storage System (BESS), 1200 Kg of H2 tank storage, 1 Mwe Fuel cell and 0,5MW floating solar.
    - The plant is planned to be operational in Q4 2025

3) **Sealhyfe:** Off the coast of Le-Croisc in France, at Centrale Nantes' offshore pilot site, SEM-REV, it's the first offshore hydrogen production facility in the world.
    - This project is an initiative led by Lhyfe, a company in green and renewable hydrogen.
    - The production capacity of this project is around 440 kg/day which equivalates to 1 MW electrolyzer. The hydrogen is vented to air offshore.
    - Objective – To make offshore renewable hydrogen become reality, by demonstrating the reliability of an electrolyzer at sea with a planned industrial deployment in 2023. The project is successfully finished in Q1 2024.

4) **HOPE:** Hydrogen Offshore Production for Europe (HOPE) is a project, where green hydrogen will be produced at sea and then exported onshore via composite pipeline.
    - This project is an initiative co-ordinated by Lhyfe and implemented by eight European partners: Alfa Laval, Plus, Strohm, EDP NEW, ERM, CEA, POM-West and DWR eco

    - The production capacity of this project is around 4 tonnes of green hydrogen a day with equivalence of around 10MW electrolyzer Capacity.
    - HOPE, will be located in the North Sea, 1 km off the port of Ostend in Belgium. The power will be supplied with a power cable from shore and the hydrogen will be brought back to shore via a flexible composite hose.

5) **Oyster**: The project aims to investigate the feasibility and potential of combining an offshore wind turbine directly with an electrolyzer. And transporting renewable hydrogen to shore.
    - This project consortium consists of ITM Power, Orsted, Siemens Gamesa and Element Energy.
    - The OYSTER project launched in Jan 2021 and will run to the end of 2024
    - Objective:
        - Developing & then validating performance of a fully marinized electrolyzer. And flexible power electronics for the electrolyzer. For integration with an OSW turbine.
        - Prepare for larger scale deployment integrated with offshore wind turbines.

3.2.6.2 Expected upcoming projects

The above mentioned projects are the ones that are envisioned in a short time span (ie, within next couple of years) with a smaller capacity. Other envisioned/larger projects that could start around 2030 are discussed next.

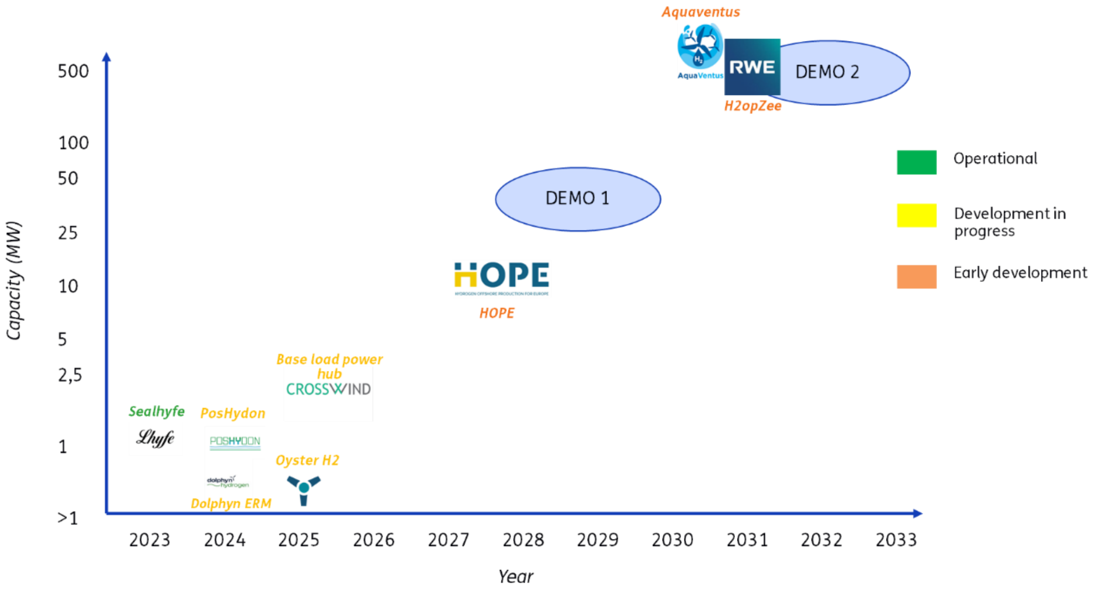

Figure 3.9: Offshore hydrogen production pilots and demonstration projects in NW Europe.

Table 3.2: Envisioned larger projects

Project Name	Location	Reference	Scale
H2opZee	Dutch North Sea	Demonstration project	300 – 500 MW
AquaVentus	Different locations	Industry-led projects expected funding from governments	100 MW – 1 GW
NortH2	Initially in Eemshaven and then at sea in the next phase	Industry led project	In total 10 GW of which a part offshore H2
DEMO 1	Hollandse Kust Region	Tender by government	< 100 MW
DEMO 2	North of Wadden Island	Tender by government	500 MW

A brief explanation about each of the project is listed below:

1) **H2opZee:** It's a hydrogen project in the Dutch part of the North Sea. The idea is to build electrolyzer with a capacity of **300 to 500 MW** far out at sea to produce hydrogen.
    - H2opZee stems from an initiative of TKI Wind op Zee. RWE joins forces with Neptune Energy to develop this hydrogen project at sea.
    - **The aim of this project,** is to start the demonstration site for 500 MW green hydrogen offshore at the end of 2030.
    - It's a demonstration project at sea for green hydrogen in the Netherlands.

2) **AquaVentus:** The overarching goal of AquaVentus is to install 10GW of green hydrogen generation capacity from offshore wind energy in the North Sea by 2035 and to establish an associated transport infrastructure.
    - It's an association with more than 100 companies, research institution and organization
    - 4 sub-projects along the value chain namely:
        - Development of offshore wind turbines with integrated hydrogen production – **AquaPrimus**
        - Large scale offshore hydrogen park – **AquaSector**
        - Central offtake pipeline – **AquaDuctus**
        - Research platform – **AquaCampus**

3) **NortH2**: The project investigates the feasibility of large-scale production, storage and transport of green hydrogen.
    - NortH2 is a consortium of Eneco, Equinor, RWE and Shell Netherlands.
    - Ambition is to make no less than **2 to 4 GW available by 2030** and grow to more than **10 GW around 2040**.
    - The electrolysis will initially take place in Eemshaven and in a later phase at the sea.

4) **DEMO 1**
    - Less than 100MW offshore hydrogen project to be realized earliest by 2027
    - Tender information to be released by 2024
    - Location - Hollandse Kust Region Wind farm

5) **DEMO 2**
    - Around 500MW capacity offshore hydrogen project to be realized earliest by 2031
    - Location – Ten Noorden van de Wadden wind farm
    - The current pipeline running near the Demo 2 zone is being investigated for its feasibility of being reused for hydrogen transport

3.3 Transport to shore

After the offshore production of H2, it needs to be transported to shore for further utilization and eventual delivery to end-users. Three types of transport to shore are going to be discussed in this document:

1) Transport to shore by pipelines
2) Transport to shore by ship
3) Floating, Production, Storage and Offloading (FPSO) Unit

3.3.1 Pipeline Transportation:

To bring hydrogen to shore via pipelines, either new pipelines will have to be built, or use shall be made of existing pipelines. Either option has its distinct benefits over the other[19][20].

In case the hydrogen is produced at locations far away from (available) trunk lines, then new built pipelines is foreseen. The benefit of a new pipeline is that the design will be dedicated to the produced capacities of the platforms in the area, in terms of material, diameters and routing.

In case existing trunk lines are routed relatively close to the offshore hydrogen production platform, then there is reason to investigate the possibility to make use of that trunk line. Making use of existing pipelines (including the landing point) will be more economic, will have a lower ecological impact and the permitting processes are expected to be shorter. Current expectation is that, at least for the Dutch offshore sector, existing natural gas trunk lines will remain essential for natural gas transport until after 2030, but rerouting parts of the existing lines may open the possibility to use one for dedicated hydrogen transport.

An alternative option for hydrogen transport through pipelines is to blend the hydrogen in the natural gas stream. This is assumed to be a feasible option in the near future. Blending hydrogen into the existing natural gas pipelines can be considered as an attractive solution for the transportation of the renewably produced hydrogen in DEMO 1 project. This however has a significant impact on the value of the green hydrogen as in a blend the hydrogen is valued to its caloric value, about one third of that of a cubic meter of natural gas. Green certificated can add value to the green hydrogen produced.

The reason this technology being feasible in the near future, is because the hydrogen backbone is not yet established and in the meanwhile, this provides the possibility to transport hydrogen for the producers and the end users. Once blended, there are two options: either 1) to directly sell the hydrogen-natural gas blends or 2) to de-blend the hydrogen from the natural gas stream. De-blending is simply gas separation. The most common technologies for hydrogen de-blending are: Pressure Swing Adsorption (PSA), Cryogenic Distillation and Polymeric Membrane Separation

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[19] 23-0026 DNV Rapport EZK - Onderzoek naar hergebruik van mijnbouwlocaties en infrastructuur
[20] DNV 2023. Specification of a European Offshore

3.3.2 Ship Transport:

Transporting the offshore produced H2 to shore via ship transport could be a crucial link in places where there exists no pipelines or difficult terrains, such as very deep water or long distance transport (well beyond 100 km).

Hydrogen can be transported by ships in the form of gas, liquid or by more dense carrier such as NH3 or MeOH. The project size and the transporting distance are the main parameters to consider in assessing hydrogen transport costs[21].

- **Gaseous Form of Transportation**: For transportation by ships, hydrogen needs to be transported into a form with higher energy density and then reconverted at the importing terminal. The least energy-intensive option would be to compress it. To make the whole process green, the ship also has to run with H2 as their fuel. In an extensive research done by IRENA on considering the transport distance & the project size, it was concluded that transporting compressed hydrogen is not attractive for large scale, long distance trips[22].

- **Liquid Hydrogen Transport**: The liquefaction of hydrogen is already performed commercially today, but only on a very limited scale. With the Suiso Frontier, there is a well working prototype that is expected to run commercial services between Japan and Australia from the mid 20's[23]. For this to reach a commercial level as of LNG, the technology still has to be scaled up by several orders of magnitude. Additionally, the liquefaction process is an energy consuming process. Existing liquefaction plants may consume around 30 – 36% of the energy contained in H2. On top of that, during transport of Liquid H2, boil-off will lead to a significant loss of the H2 as well.

- **Ammonia (NH3):** H2 is converted to NH3 by a process called Haber-Bosch. HB process uses Nitrogen & Hydrogen to produce NH3. Once NH3 has been synthesized, then it is transported from the production location to an import harbor via ships at cryogenic conditions (-33 C) or pressurized (7 bar). Once in the landing point, it could be converted back to H2 by cracking or be used directly as NH3 for industrial uses.

- **Liquid Organic Hydrogen Carriers (LOHC):** LOHC's absorb & release hydrogen through chemical reactions. When H2 is absorbed into the liquid organic carriers, a hydrogenation catalyst is used. Once hydrogenated, then its transported via ships. LOHC usually have properties similar to diesel and can be transported as liquids. Once at the landing point, the hydrogen is then releases onboard using a dehydrogenation catalyst.

- Other options that are considered for hydrogen transport are Methanol, Ethanol, Syngas or Salts. All options have considerable advantages and disadvantages considering technology maturity, conditions for storage and transport, safety, energy density and energy losses.

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[21] IRENA_Global_Trade_Hydrogen_2022.pdf
[22] IRENA_Global_Trade_Hydrogen_2022.pdf
[23] Insight: Too cold to handle? Race is on to pioneer shipping of hydrogen | Reuters

4 State of the art of electrolysis systems

Having established a clear understanding of the concepts and offshore hydrogen production sources in the preceding section, the primary objective of this section is to dive into the technical details of an offshore hydrogen system. The aim is to assess the fundamental requirements and the state-of-the-art of all pivotal components within an electrolysis system. The focus will be on delving deeper into the technical aspects of the crucial components needed to produce hydrogen offshore: exploring the various components, their functionalities, and evaluating their current technology readiness level (TRL) . The main technical aspects to be discussed in this section are the electrolyzer technology, electrolyzer systems, and the waste streams generated during electrolysis. Finally, this section will showcase some of the challenges identified so far around offshore hydrogen (production) systems.

4.1 Electrolyzer technology

The easiest and most cost-effective method to produce hydrogen directly from electricity is through water electrolysis, a process that uses electricity (and sometimes heat) to separate water (i.e., to “electrolyze” water) into hydrogen and oxygen. This is achieved within a device called an electrolyzer. When this electrolyzer is powered by renewable sources, the resulting hydrogen is termed “green hydrogen”. Figure 4.1 shows a schematic of a water electrolysis cell.

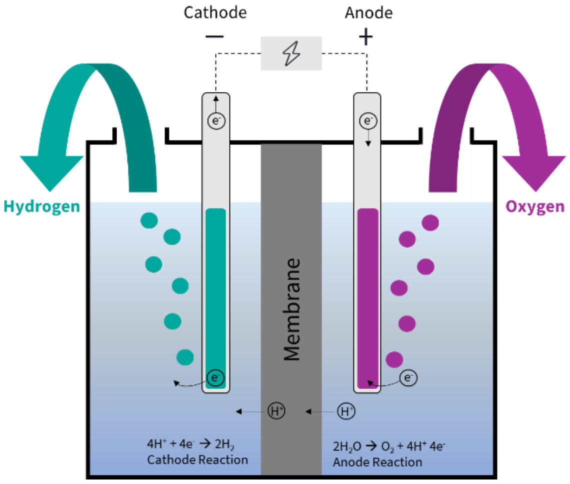

Figure 4.1. Generalised schematic of a water electrolysis cell. A cell is the working unit of an electrolyzer.

The main components of an electrolyzer are:

1) **Electric circuit**: connects a source of electric power (e.g., a wind turbine) to the rest of the cell
2) **Electrodes**: catalysts where the water splitting takes place

  - a. Anode: the electrode where oxygen is produced
  - b. Cathode: the electrode where hydrogen is produced

3) **Electrolyte**: a substance that connects electrically both electrodes, thus closing the electric circuit
    - a. Depending on the type of electrolyzer, the electrolytes can be either water-based solutions or solid substances such as a polymer or a ceramic material.

There are three main types of electrolysis technologies:

- Alkaline electrolysis
- Proton Exchange Membrane (PEM) electrolysis
- Solid Oxide electrolysis (SOEC)

In addition, there are innovative concepts under development, such as Battolyser and Anion exchange membrane (AEM) electrolysis.

In all types of electrolyzer the same overall process takes place:

$$9\,L\,H_2O + Energy \rightarrow 1\,kg\,H_2 + 8\,kg\,O_2$$

The minimum amount of energy needed for the water electrolysis to take place is a function of the operating temperature; this minimum amount of energy corresponds to the Higher Heating Value of hydrogen and is roughly equal to 40 kWh/kgH2. This means that no matter which electrolysis technology is used, the minimum energy needed is exactly the same. However, the actual use of energy can be significantly different for each technology.

Furthermore, the core principle of the three main electrolysis technologies is the same: energy is used in order to split water into hydrogen and oxygen. They all have the same three components, where the difference is in the types of components that each technology uses. The materials used in each type of electrolysis technologies in turn dictate parameters such as the operating temperature and operational flexibility.

The basic unit of an electrolyzer is called, a ‘cell’, as shown in Figure 4.1; an arrangement of cells is called a ‘stack’. The combination of a stack and balance of plant is referred to as a ‘system’.

The output of an electrolysis cell/stack/system is measured in power units e.g., kW, MW, GW, etc. This is both related to both the power input needed and the amount of hydrogen that can be produced:

$$1\,MW_{electrolyser}(installed\ capacity) = 200\frac{Nm^3H_2}{h} = 17{,}8\frac{kgH_2}{h} = 156\frac{tonH_2}{year}$$

4.2 Comparison of different electrolysis technologies

Table 4.1 provides a comparison of the most common electrolysis technologies.

Table 4.1. Comparison of the differences and similarities of the three main types of electrolyzer technologies.

Property	Alkaline electrolysis	PEM electrolysis	SO electrolysis
Minimum energy consumption	~40 kWh/kgH2 (regardless of the type of energy needed)		
Actual energy consumption	~47-55 kWh/kgH2		
Operating temperature	60-80ºC	60-80ºC	700-1000ºC
Main type of energy needed	Electricity	Electricity	Electricity + heat
Operational flexibility	Limited operational flexibility but not as flexible as PEM	Can be ramped up and down between 5-25% and 100% capacity in seconds	Preferred for constant operation
Type of electrolyte used	Alkaline water solution (water + KOH)	Acidic polymer	Oxide-conducting ceramic
Types of electrodes used	Nickel, cobalt, iron	Platinum, iridium	Nickel, zirconium, yttrium, lanthanum
Cost ranges[24]	200-1000 €/kW	600-2000 €/kW	>3000 €/kW
Technology readiness level (TRL)	9 (used industrially at multi-MW scales e.g., in margarine production)	7-8 (small-scale projects at MW scales)	4-5 (pilot projects at kW scales)
Examples of vendors and original equipment manufacturers (OEMs). Note: this is not an exhaustive list.	Thyssenkrupp-nucera John Cockerill McPhy Asahi Kasei Longi	Siemens Energy Plug Power NEL ITM Power Cummins/Accelera	Bloom Energy Ceres Power Sunfire SolydEra Haldor Topsoe

Alkaline electrolysis is the most mature of the electrolyzer technologies, with several large-scale plants operated for decades. Alkaline electrolyzer were historically used as a source of hydrogen for e.g., hydrocracking processes (refining) well before natural gas as a feedstock for steam methane reforming became the mainstream (grey) hydrogen production technology. Alkaline electrolyzer are still used nowadays in the food industry i.e., to produce high-purity hydrogen for the hydrogenation of vegetable fats in the production of margarine. It is also the selected technology that is considered in several large scale onshore electrolyzer systems for green hydrogen production. The main advantage of alkaline electrolysis is the use of inexpensive materials, which alongside the commercial maturity positions it as the cheapest electrolysis technology in the market.

PEM electrolysis is a technology that has been in development since the 2000’s. The origin of the technology comes from the advances in PEM fuel cells e.g., for mobility applications that

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[24] These cost ranges are very wide because they represent the current state of the market where the prices are changing rapidly due to economies of scale and also market speculation.

took place in the 1990’s in the automotive industry. The main feature of PEM electrolyzer is that they offer a higher degree of operational flexibility than alkaline electrolysis, which makes them the most attractive technology for direct interconnection with renewables e.g., in offshore hydrogen production.

SOEC technology finds its origins in the development of solid-oxide fuel cells. SOECs’ ability to split water using electricity and heat makes it an interesting technology to applications where waste heat (150ºC-200ºC) is available from industrial sources. The use of waste heat leads to a decrease in the net electricity demand for water electrolysis in SOEC where an electricity consumption of 33-36 kWh/kgH2 is expected, whereas to meet the total energy consumption (47-55 kWh/kgH2), waste heat (in the order of 11-22 kWh/kgH2) can be used from e.g., industrial processes or nuclear power plants. The lower consumption of electricity of SOEC with respect to AEL and PEM electrolysis (where the main source of energy is electricity) makes it a potentially attractive technology for water electrolysis in co-location with industrial waste heat.

There are other electrolysis technologies that have less maturity than alkaline, PEM, and SOEC, and that can be understood as a combination thereof:

- Anion Exchange Membrane (AEM) electrolysis is a technology recently developed that can be seen as a combination of alkaline electrolysis (low-cost materials) and PEM electrolysis (high operational flexibility). This technology is at an early commercial stage.
- Protonic Ceramic Cell (PCC) electrolysis is a new technology that can be seen as a combination of PEM electrolysis (acidic electrolyte) and SOEC (ceramic material), where the goal is to decrease the operating temperature with respect to SOEC. This technology is at early lab-scale stages.

Out of all the technologies mentioned above, PEM electrolysis seems to be the most suitable for offshore hydrogen solution due to its operational flexibility and relative compactness (low footprint per unit hydrogen produced).

4.3 Electrolysis systems

The basic layout of an electrolysis system is shown in Figure 4.2. In general, the components of an electrolysis system are as follows:

- Electrolyzer stack
- Fluid Mechanical Balance of Plant (BoP)[25]
- Electrical Balance of Plant (BoP)

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[25] Balance of Plant (BoP) is a term generally used in the context of engineering to refer to all the supporting components and auxiliary systems of a plant needed to deliver the energy, other that the production unit itself (electrolyzer in this case).

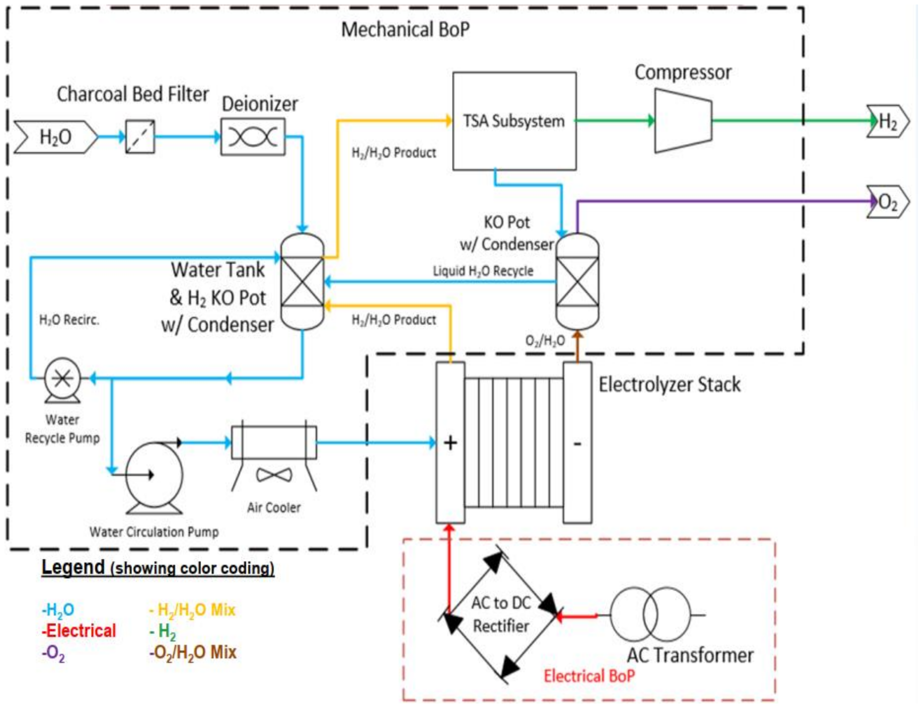

Figure 4.2. Example process flow diagram of an electrolysis system. Besides minor differences, all kinds of electrolysis systems have similar layouts[26].

Additional BoP components such as chemical storage, ventilation systems and oxygen and heat recovery systems exist, but their use will depend on the application and the location of each individual electrolysis plant.

4.3.1 Fluid mechanical balance of plant

The fluid mechanical BoP of an electrolysis system is divided in three main components:

- Water treatment and demineralization
- Drying and separation of the H2/O2 and water stream.
- Hydrogen purification
- Hydrogen compression

4.3.1.1 Water treatment

As mentioned before, for every kilogram of hydrogen produced, a minimum of 9 liters of water is required. This requirement can increase to 10-15 liters due to potential water losses in a typical system e.g., as a result of cooling losses or inefficiencies in some balance of plant components.

Unless direct sea water electrolysis is considered (a technology that is researched but still at low technology readiness level), the type of water required in an electrolyzer is often referred to as “ultrapure water” i.e., water with a minimal amount of contaminants (dissolved material, ions, etc.). The specification for water purity varies per technology and manufacturer, but

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[26] Source of the figure: Brian D. James et al. Analysis of Advanced H2 Production & Delivery Pathways. Presentation given during the US Department of Energy’s Annual Merit Review 2020 https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review20/p102_james_2020_o-pdf.pdf?sfvrsn=5b168db8_0.

it is generally agreed that ultrapure water in the context of electrolysis is water that has a resistivity of at least 10-20 MΩ-cm[27], which corresponds to between 0,01 and 0,05 mg/l of dissolved matter in water and 0,05-0,1 µS/cm maximum allowed conductivity. Pollutants in the water can lead to: corrosion of metals, deactivation of catalysts and electrolytes, blocking of water flow channels, etc.

In typical electrolysis systems the water treatment is done in two steps; Table 4.2 shows a summary of the water purification steps in electrolysis systems.

Table 4.2. Typical steps of water purification in electrolysis systems.

Water treatment step	Dissolved matter content at inlet	Dissolved matter content at outlet	Typical energy consumption
Purification/desalination	150-35.000 mg/l	10 mg/l	0,04 kWh/kgH2
Water polishing	10 mg/l	0,01-0,05 mg/l	0,0025 kWh/kgH2

Water purification is done to decrease the dissolved matter content as much as possible. Typical freshwater supply in the Netherlands has a total dissolved matter content of 8°dH, which corresponds to ~150 mg/l, whereas seawater has a typical dissolved matter content of 35.000 mg/l, which stipulates the importance of water treatment in offshore conditions, when the sea is the source of water for electrolysis. There are two main types of processes used: mechanical purification (e.g., reverse osmosis) and thermal purification (e.g., multi effect distillation). Figure 4.3 shows an example of a water treatment process.

- Reverse osmosis is a process that uses pumps and water-permeable membranes in order to force water through the membrane, leaving the dissolved matter behind.
- Multi-effect distillation is a process that uses low-temperature heat to evaporate water and subsequently condense it.

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[27] This corresponds to, respectively, Grade 1 water as per the ISO standard 3696:1987 and Type 1 water as per the ASTM International standard D1193-06(2018). Cf. https://forum.atlashighpurity.com/blog/astm-and-iso-water-quality-standards-for-laboratory-grade-water

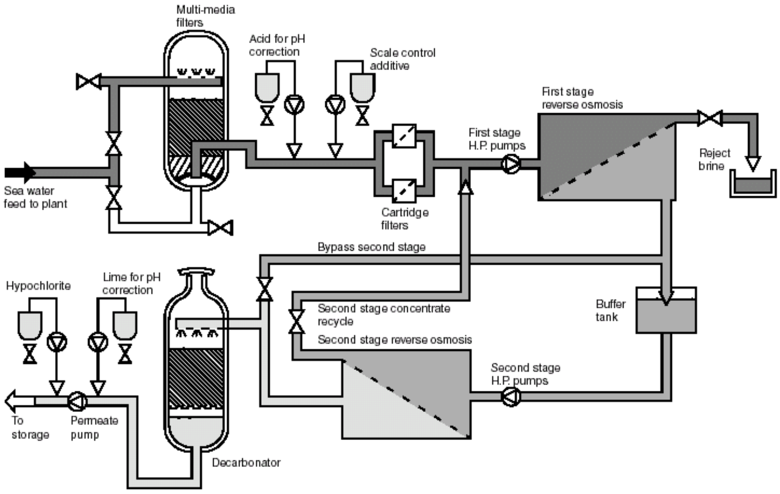

Figure 4.3. Example process flow diagram of a seawater treatment process.

Often an extra step after water purification is needed to achieve the purity required by electrolyzer mainly because dissolved ions are typically not removed from the water in the first step. The second step of water treatment in electrolysis systems is called ‘water polishing’. This is done via two kinds of processes: chemical polishing (e.g., mixed-bed ion exchange) and electrical polishing (e.g., electrodeionisation or electrodialysis).

- Mixed-bed ion exchange columns use substances called ion-exchange resins, which are polymeric beads that, when in contact with water, remove the ions in the water.
- Electrodeionisation (also called electrodialysis) uses electric charge to force ions away from the water.

4.3.1.2 Hydrogen Purification

The products of water electrolysis are hydrogen and oxygen. Due to the inherent permeability of gases in the system, there will always be a small amount of oxygen in the hydrogen side and hydrogen in the oxygen side. This means that the hydrogen production side of an electrolyzer (the cathode) consists of a mixture of hydrogen, oxygen, and water.

Hydrogen purification is needed to achieve the required hydrogen purity, which can vary per type of end user. Table 4.3 shows an overview of the purity requirements of different hydrogen end users.

Table 4.3. Hydrogen purity specifications of different end users.

Hydrogen purity specifications	Type of end user	Total amount of allowed contaminants
98%	Hydrogen as fuel for heating processes	20.000
99,5%	Hydrocracking	5.000
99,97%	Fuel cells	300
99,999%	Lab-grade hydrogen	10

The technologies needed to purify the hydrogen are typically aimed at removing first the oxygen and then to remove the water. This is done for safety reasons: oxygen contents of

~5% in hydrogen can lead to explosive mixtures that need to be mitigated as early in the process as possible.

Table 4.4. Overview of the hydrogen purification steps.

Hydrogen purification step	Content at inlet	Content at outlet	Typical energy consumption
Step 1: oxygen removal	Ppm level (depends on operating pressure)	0	Strongly depends on technology
Step 2: water removal	~17.000 ppm	<5 ppm (depending on end-user specification)	Strongly depends on technology (~0,5 kWh/kgH2 for TSA)

Oxygen removal is done either via chemical processes (e.g., catalytic conversion) or mechanical processes (e.g., membrane purification).

- Catalytic conversion relates to the use of a catalytic bed to force the reaction of oxygen with hydrogen to form water.
- Membrane purification consists of forcing the hydrogen-water-oxygen mixture through a hydrogen-permeable membrane in order to separate the hydrogen from the rest of the components.

Once oxygen is removed, water is the second removal step. Depends on the type of oxygen removal used, additional water can be generated (e.g., via catalytic conversion). The most common types of processes used for water removal are physicochemical (e.g., Temperature Swing Adsorption) and thermal (e.g., chilling).

- Temperature Swing Adsorption (TSA) is a process that uses an adsorbent that can remove the water from the hydrogen-water mixture. Figure 4.4 shows an example of a TSA unit for a hydrogen-water mixture.
- Chilling consists of the use of low-temperature chillers in order to condense the water from the hydrogen mixture.

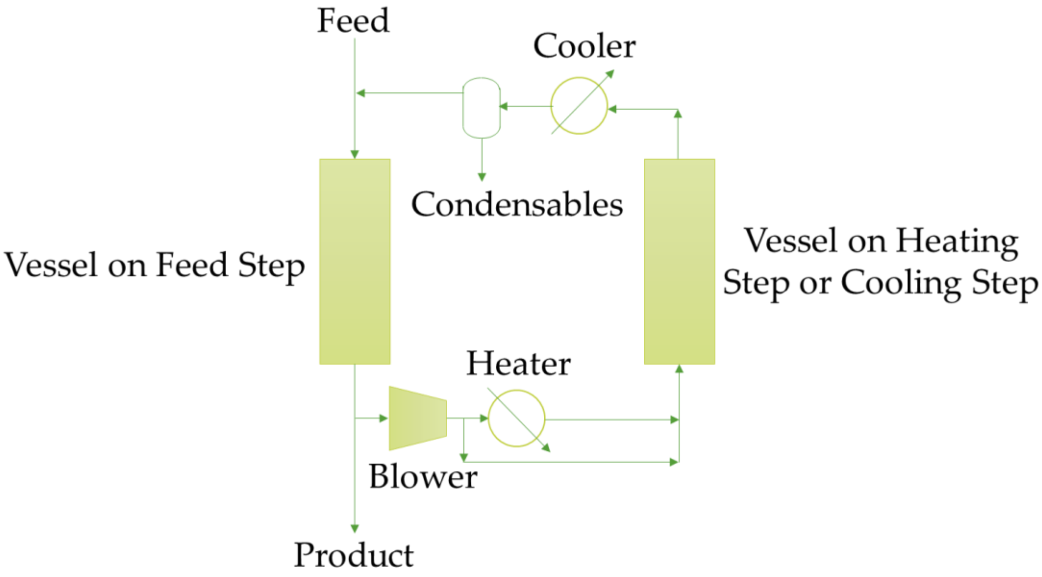

Figure 4.4. Example of a Temperature Swing Adsorption (TSA) process.

4.3.1.3 Hydrogen Compression

Once hydrogen is purified, it needs to be compressed to either be injected to pipelines or used in end-user processes. The type of compression needed for hydrogen strongly depends on two main parameters:

- Pressure ratio (output pressure divided by inlet pressure)
- Hydrogen flow

Generally speaking, there are two main scenarios that define the choice of compression, listed in Table 4.5.

Table 4.5: Hydrogen compression scenarios

Scenario for the choice of compression	Electrolyzer capacities	Pressure inlet-outlet	Energy consumption (typical ranges)
Scenario 1: small hydrogen flows, large pressure ratios	Small (MW-scale)	30-900 bar (hydrogen refueling station)	5-10 kWh/kgH2
Scenario 2: large hydrogen flows, low pressure ratios	Large (GW-scale)	30-50 bar (injection to hydrogen pipeline)	2-5 kWh/kgH2

The main types of compressors are positive displacement compressors (e.g., reciprocating compressors), dynamic compressors (e.g., centrifugal compressors), and non-mechanical compressors (e.g., electrochemical).

- Reciprocating compressors capture a certain volume of gas and decrease its volume using materials such as a piston or a diaphragm. Figure 4.5 shows the schematics of a reciprocating compressor.
- Centrifugal compressors use a rotating head (called an impeller) to increase the velocity of a gas, and then subsequently convert the velocity into pressure. For high purity hydrogen streams that are expected in dedicated offshore hydrogen pipelines, centrifugal compression is currently not considered to be feasible with state of the art techniques[28].
- Electrochemical compressors use electricity to move hydrogen from a large to a small chamber using a hydrogen-permeable membrane. The TRL level of these types of compressors is still relatively low, and the capacities are limited to flow rates far lower than flow rates foreseen from 100MW+ electrolyzer.

Considering the current state of art on hydrogen compression, it is likely that offshore compression will be performed by reciprocating compressors. The inherent free forces and moments, in combination with their frequencies will pose however significant challenges to the structural integrity of platforms and surrounding equipment.

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[28] TNO Boek/rapport (recip.org)

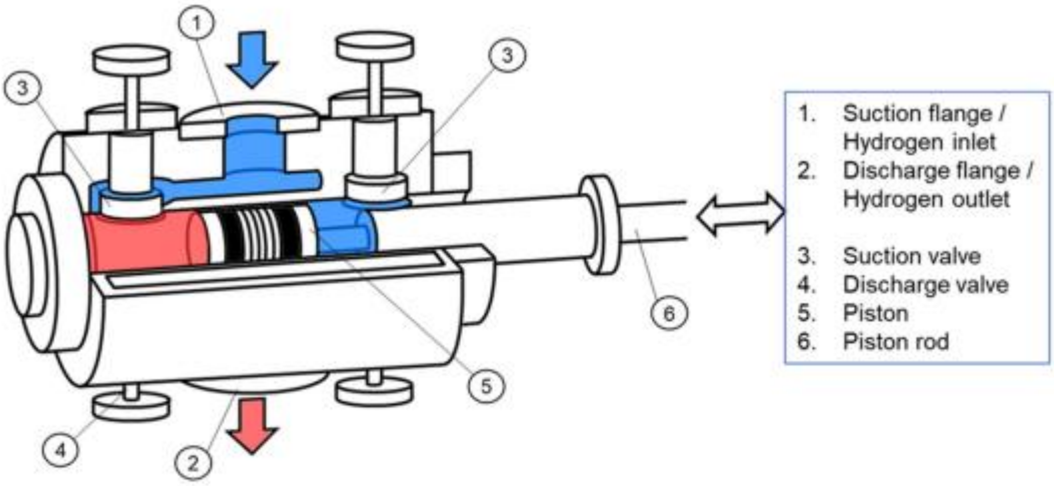

Figure 4.5. Schematic representation of a reciprocating compressor.

4.3.2 Electrical balance of plant

The electrical BoP of an electrolysis plant consists of the following steps:

- High-voltage AC/ low-voltage AC conversion
- Low-voltage AC/low-voltage DC conversion

4.3.2.1 High-voltage AC/ low-voltage AC conversion

The type of electric power conversion needed by an electrolysis system depends on where in an electric network it is connected. Table 4.6 shows an overview of the different voltage levels in an electric network.

Table 4.6. Overview of the different voltage levels in an electric network.

Type of AC connection	Voltage ranges	Examples
Low voltage	70-600 VAC	Household connections
Medium voltage	0,6-33 kVAC	Distribution lines
High-voltage	33-380+ kVAC	Transmission lines
Wind turbine	690 VAC	Typical output voltage of a wind turbine before injection to a network

Depending on the scale (kW/MW/GW), electrolysis systems can be placed either on medium voltage or high-voltage grids, meaning that electric power conversion is needed between grid connection and electrolyzer. For the particular case of a wind turbine, whereas wind turbines typically output power with 690 VAC, next to the turbine (e.g., at the base of the tower) there is usually a transformer that upgrades the voltage output to medium voltage (33-36 kV). Figure 4.6 shows a schematic representation of power conversion in a typical wind turbine.

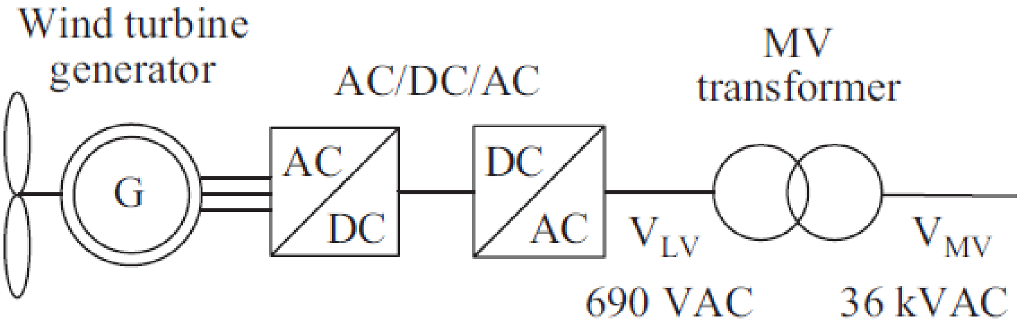

Figure 4.6. Schematic representation of the power conversion in a wind turbine.

AC/AC power conversion is done using a transformer. A transformer is a device that consists of two coils made of wire around a magnet, where the number of windings of the wire will be proportional to the amount of power converted. There are many types of transformers; they are differentiated in terms of power (small-, medium-, and large-power transformers), type of cooling (dry-type and liquid-cooled transformers) and application (isolation, noise-reduction, phase-shifting, step-voltage, grounding). Figure 4.7 shows an image of a 36 kV, liquid-cooled transformer for offshore wind turbines.

Figure 4.7. Example liquid-filled transformer for offshore wind turbines (36 kV).

4.3.2.2 Low-voltage AC/low-voltage DC conversion

Electrolyzer require a Direct Current (DC) to operate. Therefore, an AC/DC conversion is needed; this step is called 'rectification'. A rectifier is a device that converts an oscillating two-directional AC into a single directional DC. Rectifiers can take wide variety of physical forms, from vacuum tubes diodes and crystal radio receiver to modern silicon-based design. The main challenge of electrolysis systems is that the requirement of high current and low voltage is challenging due to low efficiencies of high-current rectifiers. There are two types of high-current rectifiers: thyristor-based rectifiers with hybrid filter (THRF) and diode rectifiers with DC chopper (CPRF). Currently, AC/DC converters based on thyristors dominate the market for industrial applications.

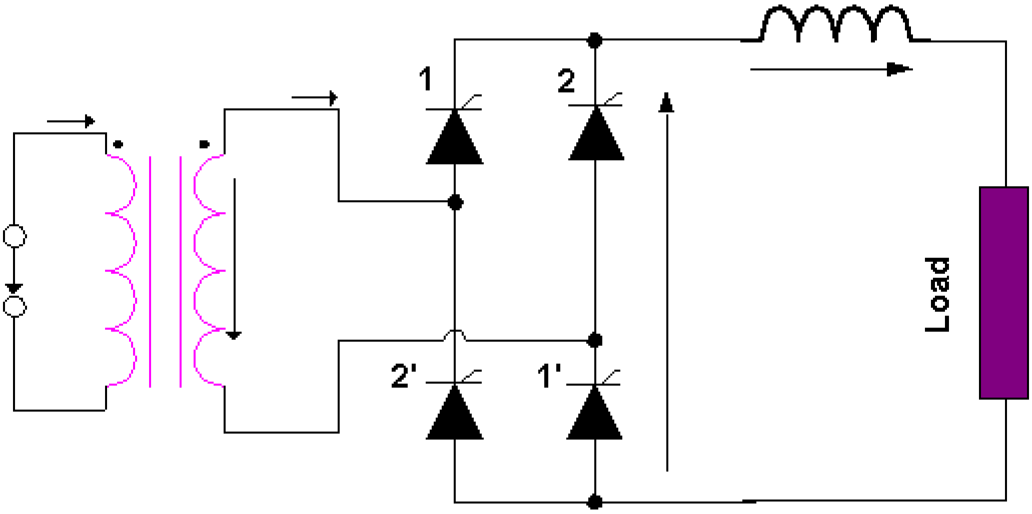

Figure 4.8. Example of a thyristor-based AC/DC rectifier.

4.4 Waste streams of an electrolysis system

Next to hydrogen, the outputs of an electrolysis system are oxygen, heat, and salt or saltwater/brine. If not valorized e.g., used for a different application, these outputs are considered waste streams; therefore, the environmental impact of their disposal should be considered, particularly when operating an electrolysis system offshore.

4.4.1 Brine Disposal

As discussed before, a water treatment process needs to remove approximately 35 g/l of dissolved matter from water. A reverse osmosis process requires between 1,4 and 1,8 liters of seawater for every liter of purified water produced, meaning that for every liter of water, between 400 and 800 ml of waste water is produced. This means that the resulting concentration of total dissolved matter in the wastewater will be between 44 and 88 g/l. Any salt concentration higher than 50 g/l is defined as brine, meaning that for every 1 liter of water produced, there will be up to 2 liters of brine produced. Table 4.7 shows the calculations of brine production per liter of water purified and per kg of hydrogen produced.

Table 4.7. Calculations to show the amount of brine produced per unit of water and hydrogen in an electrolysis system.

Reference	Seawater inlet in reverse osmosis	Dissolved matter content to be disposed of	Wastewater outlet from reverse osmosis	Resulting amount of brine equivalent produced (water with 50 g/l salt)
1 liter of pure water	1,4-1,8 l	35 g	0,4-0,8 l	0,9-1,8 l of brine
1 kg of hydrogen	13-16 l	315 g	3,6-7,2 l	8-16 l of brine

According to Table 4.7, for every kg of hydrogen produced, a total of between 8 and 16 liters of brine need to be disposed of. Pumping brine back into the ocean can cause an increased salinity, which leads to decreasing dissolved oxygen content in the ocean, causing potentially hypoxic conditions that can threaten marine life. Brine could also be valorised e.g., by mineral recovery. The North Sea contains critical raw materials (CRMs) in varying quantities of elements such as lithium, strontium, and magnesium. There is potential for combining CRM recovery from offshore brines, although this is a research avenue that has not been developed yet.

4.4.2 Oxygen Disposal

Besides salt from water, oxygen is produced in an electrolysis system. As we showed above, for every kg of hydrogen produced, 8 kg of oxygen are also produced, meaning that for every MW of electrolysis installed capacity there can be up to 140 kgO2/h produced.

Oxygen gas is already used in different production purposes including industrial, medical, food processing and others. The gas can come in various qualities depending on the purpose. In current electrolysis systems (onshore), oxygen is released into the atmosphere due mainly to safety considerations: oxygen can greatly accelerate corrosion and oxidation processes as well as increase the likelihood of explosive atmospheres if handled next to flammable or explosive gases such as hydrogen. Furthermore, release of oxygen into the environment may also have side effects worth considering.

Oxygen can also be valorized e.g., in combustion processes. Combustion processes that use pure oxygen instead of air (also known as oxyfuel combustion) can lead to significant increases in thermal efficiency, as well as more complete combustion (leading to a decrease in carbon monoxide emissions) as well as decreasing nitrogen oxide emissions (since the nitrogen from the nitrogen oxide emissions in combustion comes from the air). Furthermore, there can be a potentially advantageous effect of injecting oxygen back to the ocean: increasing oxygen content of the ocean can lead to increase of marine life presence around the site of injection.

4.4.3 Heat Production

Electrolyzer produce waste heat at a rate between 7 and 15 kWh/kgH2. Depending on the electrolysis technology (in particular depending on the operating temperature) the heat is typically released via cooling water, steam, or other coolant, with temperatures between 60-80ºC (for alkaline and PEM electrolyzer) and up to 700-1000ºC (for SOEC). Typically, heat produced during electrolysis is disposed into air using liquid-to-air cooling i.e., fans that blow air into radiators. Large-scale electrolysis systems do not have liquid-to-air using fans and radiators but using cooling towers, such as can be found in e.g., nuclear power plants. Another option for waste heat disposal is to have liquid-to-liquid cooling in a nearby body of water. The main challenge around (potentially) disposing waste heat directly in the ocean is the impact on oxygen concentration: increased ocean temperature leads to less dissolved oxygen, which is detrimental to marine life.

Recovery of heat from an electrolyzer is potentially interesting to increase the total system efficiency (if heat is used to power the balance of plant of electrolysis systems) and to enhance the business case of hydrogen production (if heat is sold to downstream processes). A particularly interesting application for the residual heat of low-temperature electrolyzer (e.g., PEM) to power thermal-based water purification (e.g., multi effect distillation) and physicochemical-based hydrogen purification (e.g., TSA), both of which can in theory be operated with the waste heat of an electrolyzer.

4.4.4 Summary of waste streams in an electrolysis system

Table 4.8 summarizes the waste streams that are produced in an electrolysis system.

Table 4.8. Summary of waste streams produced in an electrolysis system.

	Brine	Oxygen	Heat
1 kg of hydrogen produces	8-16 l (50 g/l brine)	8 kgO2/kgH2	7-15 kWh/kgH2
Potential impact on marine life	Negative	Positive	Negative

4.5 Challenges around deploying offshore hydrogen production systems

Electrolysis systems with all the components and waste streams as described in the previous section, form together only a piece of the puzzle when it comes to deploying electrolysis systems offshore. Next to the hydrogen production, there are several other subsystems that need to be considered, including offshore wind power and hydrogen (transport) assets. Integrating electrolysis systems with intermittent renewable power production sources e.g., offshore wind power, is a topic that has gained attention at European levels in order to decarbonise the economy.

Since the topic of offshore hydrogen production is a recent topic that has gained significant attention, there is relatively little experience with offshore hydrogen. So far, only a few demonstration projects have been initiated to assess the feasibility and elucidate the challenges of offshore hydrogen production: initiatives such as the SeaLhyfe and the PosHydon projects have taken the initial steps to test offshore hydrogen production (using PEM-based electrolysis systems). So far there have been a few challenges and lessons learned around offshore hydrogen production:

Reliability. Besides the relatively low experience of the industry with PEM electrolysis, some BoP components have been identified as potential bottlenecks for deploying offshore hydrogen production with unmanned operation. Processes such as water purification (in particular reverse osmosis) have a track record of regular maintenance required to operate. This poses a challenge regarding unmanned operation: since the costs of manning an offshore platform are high, maximizing the time in between human intervention (called ‘touch time’ in the offshore oil and gas industry) is needed in order to create a positive business case for hydrogen offshore.

Hydrogen transport. Unlike the onshore Dutch natural gas network, the offshore natural gas transport network does not have significant redundancy, meaning that developing offshore hydrogen transport would mean either lowering the utilisation of the offshore network for natural gas and re-using that infrastructure, or developing new infrastructure for hydrogen. There are pro’s and cons for either option, when it comes to costs, ecology, timelines and other aspects, and the uncertainty on what the total required transport capacity of such infrastructure shall be make this an important challenge.

Potential utilisation of offshore assets. The North Sea has a significant number of assets related to oil and gas e.g., platforms, pipelines, underground reservoirs. Given that most (if not all) assets are linked to the production of oil and/or natural gas and such production wells have a finite capacity, there are potentially many assets offshore that can be revalorized e.g., to have offshore hydrogen production activities. This revalorization can result in a potential business case for offshore asset owners, which may contribute to a positive business case of offshore hydrogen production if this is done strategically. Furthermore, offshore underground hydrogen storage can be developed to contribute to energy storage and flexibility needs that are increasingly seen as essential for future energy systems.

5 Bottlenecks to 500MW offshore hydrogen production

The previous chapters focused primarily on offshore hydrogen production from a technical point of view, by examining the Technical state of art. Whether large quantities of hydrogen will be produced offshore does not only depend on Technological aspects, but also depends on other aspects, such as Political, Economical, Societal, Legal and Environmental and aspects, which all 6 abbreviate to PESTLE.

The upcoming section is going to be split into 6 categories, based on the PESTLE aspects and are going to focus on the state of art & the bottlenecks for each aspect. The basis for outlining the forthcoming bottlenecks was derived through a multi-faceted approach.

- **Internal Brainstorming with TNO Experts:** TNO initiated an internal brainstorming session with our experts utilizing the back casting technique to foresee potential bottlenecks that might arise during the progression of DEMO 2.

- **Knowledge Workshop with 70+ Industrial Partners via HEROW Platform**: TNO leveraged the HEROW platform to organize a knowledge workshop involving over 70+ industrial partners from diverse backgrounds. The objective was to conduct a back casting session, drawing insights from these varied perspectives across the value chain.

- **Unified Aim for Back casting Sessions:** Both the TNO-led sessions and the HEROW-organized workshop shared a common focus and objective centered around "500MW offshore H2 production by 2031."

- **Literature Study by TNO:** TNO also conducted an extensive literature review to gain deeper insights into existing studies and research focusing on similar topics. This step was undertaken to augment the understanding based on the current body of knowledge available in the field.

The next sections indicate several bottlenecks that are defined from the above sources of information. It shall be noted that there are currently many actions undertaken by many players in the hydrogen economy to mitigate these bottlenecks or find solutions to them.

5.1 Political Aspect

The political aspect primarily involves governmental policies, international relations, and regulatory frameworks, among other factors. Political decisions play a crucial role in shaping the trajectory of emerging technologies like Offshore H2 production. The political landscape can significantly impact project outcomes and is a key factor in the success of technologies we're discussing. The upcoming sections of the report will detail current efforts taken to enhance offshore H2 production and the challenges that needs attention.

5.1.1 Current state of art

The Dutch government with their ambitious goals are playing a significant role in shaping H2 economy worldwide. In the recent past, the focus has also shifted towards offshore H2 production & quite some initiatives has already been commenced with offshore production. Some initiatives that are significant for the growth are:

- **Letter to the Parliament -** The letter to the parliament on “demonstratie projecten waterstof op zee” dated 10th June 2024 emphasizes on hydrogen as an energy carrier for wind energy. This letter was sent from the Directorate-General for Climate & Energy to the President. This letter dives deeper into the DEMO 1 & 2 projects and how the ministry tries to achieve it goals and way forward. This document provides a boost for offshore hydrogen production and the stern belief the Dutch government enforces on the technology.

- **Ostend Declaration:** Together with many other North Sea countries, an ambitious target for offshore wind of around 120GW by 2030 has been set for the North Sea. The objective of this declaration is to “Deliver cross border projects & anchoring the renewable offshore industry in Europe”. This declaration signed on the 24th April 2023, will be of crucial importance in the development of offshore hydrogen production.

5.1.2 Bottlenecks

As it could be inferred from the previous section that the government is positive for the development of offshore hydrogen production. In spite of the support, there may be some bottlenecks that can be incurred during the developmental phase. Below mentioned are some bottlenecks that could be a potential threat for the complete development. The corresponding bottlenecks are categorised based on their level of urgency, with the initial one’s very urgent & the latter ones not so urgent.

- **Regulatory Frameworks:** These are the legal mechanisms that exists on both national & international levels. As far as the author’s knowledge, not a lot of attention has been provided yet to establish these regulatory frameworks for offshore hydrogen. Creating a regulatory framework for production is important as it helps to reduce the inefficiency of the process & helps in the standardization of the process. While creating this framework, high priority has to be given to RED III (Renewable Energy Directive) compliances & their monitoring strategies. The RED III is a dynamic legislation aimed at gradually moving the EU towards its climate targets.

- **Hydrogen Transport:** Similar to production framework, the hydrogen transport framework is also essential to ensure proper transportation to the shore. The creation of such frameworks will make sure that the transportation is done in a standardized procedure & should address topics such as H2 purity in the pipeline, rules & regulations for offshore TSO’s. The Energy Infrastructure Plan North Sea (EIPN) that was announced in the letter to parliament on 16th September 2022 will help to set up this regulatory framework by providing a guiding picture of the necessary development of infrastructure for offshore wind. The EIPN is expected to be ready in early 2024.

- **Decommissioning:** Focus on regulatory frameworks for de-commissioning the H2 operations is also something that needs attention in the near future rather than now. For the whole operation to be circular & green, its important to address the circularity of the materials involved in the operations including wind turbines, platforms, electrolyzer etc., The regulatory framework has to ensure that the whole process is circular & assessment of environmental impacts.

- **Subsidies & Funding Mechanism:** Additional to the regulatory framework, it's of primary urgency to make a decision on the funding mechanisms for demonstration projects. The government of NL, should clearly communicate with the industrial/interested parties about how the funding & subsidies are going to work for demonstration projects of bigger scale. "How is the CAPEX & OPEX for these demonstration projects are going to be covered and What would be the ideal funding mechanism", are some of the questions that still needs some clarity for the success of demonstration projects.

- **H2 Downstream Economy:** The whole focus of this report has been related to offshore H2 production. But, it's also essentially important to support the H2 downstream processes. H2 downstream processes includes end users like Mobility sector, industrial sectors or chemical plants. As mentioned earlier, it's essentially important to support these processes economically for a successful development of offshore H2 production. It could arise as a potential problem for production if failed to provide necessary measures for downstream processes.

5.2 Economical Aspects

The economic aspect involves costs, investments, market trends, and financial factors. Success in a demonstration project relies on addressing not only technological challenges but also economic and environmental considerations. Overcoming economic challenges is essential for ensuring the success of the demonstration project. The upcoming sections of the report will detail current economical efforts made for offshore H2 production and the challenges that need attention.

5.2.1 Current state of art

Presently, studies assessing the value of H2 in our energy system have conducted initial business case analyses, revealing LCOH values ranging from 9 to 16 EUR/kg for onshore hydrogen production[29]. Furthermore, the results of the first auction, held in 2024, of the European Hydrogen Bank (EHB, a recent subsidy instrument for hydrogen production in Europe) showed LCOH values from 132 projects all around Europe[30]. The prices of the projects that bid for subsidies range between 5,80 and 13,50 EUR/kg, where the average LCOH of the proposed projects in the Netherlands was 9,80 EUR/kg[31].

There are uncertainties regarding how costs will evolve in the future. Predicting the business case in a fully developed hydrogen economy is challenging. The perceived financial risks and upfront pioneering costs are deemed high, underscoring the importance of political support in navigating these challenges.

5.2.2 Bottlenecks

There are some bottlenecks that hinder or can be foreseen as a problem during the development of demonstration projects. Some of the bottle necks that the author foresees are described in brief below. The corresponding bottlenecks are categorised based on their level of urgency, with the initial one's very urgent & the latter ones not so urgent.

- **Economical Business Case**: Developing a sufficiently strong economic business case is crucial. This holds for commercial system in the further future, but to a certain extent also for a demonstration project in offshore hydrogen production. Initiating such projects often involves significant capital expenditures (CAPEX) alongside operational costs (OPEX) for maintenance and other activities. Without an acceptable economic return, the development of offshore hydrogen production becomes challenging. Therefore, industry and governments shall remain in dialogue to overcome these hurdles and ensure the feasibility, scalability, and success of offshore hydrogen production projects, as well as ensuring that the demonstration projects DEMO 1 and DEMO 2 provide the correct learnings at an adequate scale in order to diminish the risk towards scale-up but also to ensure a fair competition for future tenders.
- **Supply Chain cost increase**: The recent increase in the supply chain costs within the offshore wind industry poses a significant threat to the economic feasibility of

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[29] TNO-studie levert nuttig startpunt voor kostprijsdaling van hernieuwbare waterstof - NLHydrogen

[30] The results of the first EHB subsidy auction mark a historical milestone in the hydrogen market: they contain the results of actual hydrogen prices calculated across a plethora of projects in Europe, showcasing the differences across countries in a non-committing (unless the subsidy is obtained) but realistic manner.

[31] EC (European Commission) 2024. Results of the Pilot Auction for Renewable Hydrogen. Presentation. For more information about this subsidy auction the reader is referred to the following reference: European Hydrogen Bank auction provides €720 million (europa.eu)

offshore hydrogen production. The interconnected nature of these sectors highlights the need for strategic interventions, including supportive policies and collaborative efforts, to ensure the continued economic viability of offshore hydrogen production in the face of supply chain challenges in the offshore wind industry.

- **Supply Chain development**: the currently foreseen number of projects or large scale demonstration projects is not yet sufficient to convince many parties in the value chain to invest heavily in creating products specifically for offshore hydrogen production, particularly since the growth of onshore hydrogen production will also require vast investments.
- **Dependency on Foreign Economics:** Dependency on foreign economies can act as a bottleneck for offshore hydrogen development due to various factors. Reliance on external markets for crucial components, technologies or financing can expose offshore development to various uncertainties & supply chain disruptions.

5.3 Societal Aspects

The societal aspect touches upon topics like (but not limited to) public perception, human capital & impact to the community. Overcoming societal challenges is essential for ensuring the success of the demonstration project. Societal factors, such as political guidelines, regulation, environment, and public acceptance, may both enable and hamper technological development. The upcoming sections of the report will detail current societal efforts made for offshore H2 production and the challenges that needs attention.

5.3.1 Current state of art

There is broad support for the energy transition away from fossil fuels, and hydrogen is recognized as a potential player in this shift, serving as a parallel path for decarbonization alongside electrification. According to the author's knowledge, currently, there is no significant societal opposition to hydrogen in general, though there might be reservations for specific applications. It's important to note that a few noteworthy incidents could swiftly alter this perception.

5.3.2 Bottlenecks

As mentioned in the state of art, so far there is no significant societal opposition for offshore H2 production. But, it's also important to maintain this way, as public perception plays a prominent role in making or breaking a project. Some probably bottlenecks foreseen are described briefly below.

- **Societal dislike of Hydrogen:** As mentioned earlier, public perception plays a prominent role in the development of offshore hydrogen. One or few newsworthy incidents could alter the course of the societal likes/dislikes. Therefore, care has to be given to the safety objectives of the H2 operations. In a research done by Radboud University[32], it mentions that factors like cost, unequal benefits & technical immaturity could be critical issues to address.
- “**Not in my back yard” (NYMBY)**. It is a characterization of opposition by the residents to a proposed development. The Dutch public, in the recent times, showed some resistance against onshore wind, biomass & geothermal energy. For offshore wind energy, the resistance has been to a lesser extent, but this may change at any instance. Stakeholders will need to keep the public opinion into consideration with respect to offshore hydrogen, and should address the changes in sentiment with care.
- **Human Capital:** Green H2 supply chain requires a skilled workforce. The lack of skilled human resources poses a risk to the development of offshore hydrogen production. Offshore hydrogen production often involves complex technologies & processes, requiring workers with specialized skills in areas such as engineering, process optimization & safety management. Additional to this, the offshore hydrogen production industry is relatively new, and there might not be sufficient pool of experienced professionals. Addressing the human capital issue is essential and has to be done as early as possible. To make sure that this issue doesn't come up, a combination of efforts has to be made, including targeted education & training programs along with industrial collaborations.

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[32] content (ru.nl)

5.4 Technical Aspect

The technical aspect touches upon topics like (but not limited to) technological development, Research & Development. The idea of this aspect is to examine the level of technological advancements, innovation there has been within a specific domain. Understanding the current state of art & bottlenecks is crucial for a successful development of offshore hydrogen production. The next part of this section will focus only on bottlenecks as the current state of art has been elaborately explained in Chapter 4.

5.4.1 Bottlenecks

- **Knowledge Sharing:** Sharing knowledge is really important for the success of offshore hydrogen projects. Since this type of hydrogen production is still quite new, industries need to exchange information to learn from each other. However, a challenge could arise because, being a new technology, some parties may prioritize economic interests over sharing technology. It's crucial that the industrial partners share what they've learned for a rapid succession of the domain.

- **Efficient operation:** As mentioned in section 4.5, for a hydrogen system to function efficiently, it has to be made sure that all the individual components operated systemically. So far, there has been only few projects of smaller scale that has been demonstrated. For projects larger than 100MW, this could be a bottleneck if not provided greater attention to.

- **Unmanned Operations:** Unmanned operation means all plant equipment's is controlled remotely and there are no operating crew permanently required on site. The bottlenecks in unmanned operation are around technological, regulatory & safety challenges.

    - **Technological Challenges:** For a platform to be unmanned, there has to be a robust & reliable automation systems, sensors and mechanics that can handle the offshore complexities.

    - **Regulatory Challenges:** Developing new regulations to ensure that unmanned operation comply with safety & environmental standards. When creating new regulatory frameworks or updating the existing ones, care has to be given for this challenge.

    - **Safety Concerns:** Safety & security of unmanned facilities, especially in emergency situations could be a crucial bottleneck.

5.5 Legal Aspects

The Legal aspect touches upon topics like (but not limited to) Licensing & Permitting, Legal framework & Contractual agreements. It plays a significant role in shaping industry dynamics, influencing corporate behaviour and setting boundaries for economic activities.

5.5.1 Current state of art

As a result of the offshore natural gas production, there is already a large set of standards and legislation concerning the production, transport, and utilisation of energy carrying gasses. There are a few aspects however where applicable, widely-recognized standards are still not yet available or will need to be modified significantly to switch from natural gas to hydrogen application, for example for the design for offshore H2 pipelines or the hydrogen concentrations that shall be transported in the pipelines. Also for hydrogen production, there is no governing (minimal) set of standards that need to be complied with for all electrolyzer OEMs. The formalization of standards and legislation is in process, but it may take years before they are accepted and applied in industry, on a global scale.

Safety is an important topic related to standards and legislation, which in fact could be treated in all aspects in PESTLE. Proper standards and legislation will assure safe operation of the hydrogen production assets offshore, for example when it comes to minimum flow to avoid hydrogen cross over, reuse of existing pipelines and the effect of hydrogen embrittlement. Safety is considered a very important item in the whole hydrogen value chain, and is therefore researched extensively in programs like the WVIP or North Sea Energy

5.5.2 Bottlenecks

The intersection of political and legal aspects is evident, where political decisions evolve into legal frameworks. The success of offshore hydrogen production relies on the harmonious interaction between political and legal elements. The bottlenecks in legal aspects mirror those in the political, as detailed in Section 4.1.2 under regulatory frameworks. Additionally, as described in the state of art on legislation, a bottleneck is whether the standards and legislation will be available on time.

5.6 Environmental bottlenecks

The Environmental aspect touches upon topics like (but not limited to) Marine biodiversity, carbon footprints & environmental impacts. The environmental aspect recognized the importance of sustainability, natural resource management & the impact of human activities in the environment. It is crucial to closely monitor this aspect, as it serves as the interface between environmental considerations and business strategies..

5.6.1 Current state of art

Environmental considerations have become increasingly influential, especially in areas like wind tenders. Balancing the impact on the environment with societal benefits is crucial. As offshore hydrogen production is currently limited, involving Non-Governmental Organizations (NGOs) in early-stage research programs proves beneficial. This inclusion fosters better alignment among various stakeholders operating in the North Sea, ensuring that environmental concerns are addressed collaboratively.

5.6.2 Bottlenecks

In offshore hydrogen production, there are some environmental aspects of the operation that can act as bottlenecks, that may cause some hindering in the efficiency & sustainability of operations. Some bottlenecks are provided below.

- **Environmental Permitting:** Offshore hydrogen production operations occur in the midst of marine environments rich in biodiversity, demanding careful consideration to prevent harm to the natural ecosystem. Anticipated challenges include:
    - **Waste Management**: The by-products of hydrogen production, such as heat, brine, and oxygen, pose environmental challenges. Proper handling and disposal of these by-products are essential to avoid serious effects.
    - **Water Usage and Disposal**: Hydrogen production requires a significant amount of seawater, and the processing results in brine with high salt concentration. Managing both water usage and the proper disposal of brine is crucial, as highlighted earlier.
    - **Hydrogen Emission**: Hydrogen is considered an indirect green house gas because although it does not cause a warming effect on its own, it interacts with airborne molecules like OH- ions to prolong the lifetime of atmospheric methane – a highly potent GHG – and increase the production of ozone (O3), another greenhouse gas. Some research has been going on within Hy Delta3 & GNVL regarding this topic.

These challenges pose potential threats to the development of offshore hydrogen, affecting both the environment and society. To navigate these hurdles efficiently, special attention must be given to environmental issues during the permitting process. This involves assessing how interested parties plan to address and overcome these challenges, ensuring sustainable and responsible offshore hydrogen operations.

- **Nature Inclusive Buildings:** Nature Inclusive buildings refer to structures that intentionally incorporate and interact harmoniously with the nature & environment. Offshore hydrogen production operations occur in the midst of marine environments rich in biodiversity making its absolutely essential to be inclusive of nature during the construction of the platforms & also during the de-commissioning. The Dutch government in the WindopZee project addressed the importance of "nature inclusive construction" by setting up Offshore Wind Ecological Program (WOZEP)[33] to specifically investigate the effects of construction & operation of wind farm on nature. The program also asked the developers of wind farm to build them in a way that is nature inclusive. This initiative should not only stop with wind farms but also continue and extend to offshore hydrogen production.

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[33] woz_publiek_flyer_gb_05-2022.pdf

6 Knowledge development roadmap

In order to develop large scale offshore hydrogen production, several bottlenecks will need to be resolved. Key bottlenecks have been summarized in Section 5. The road towards a healthy, vivid hydrogen economy that includes offshore hydrogen production is still a number of steps away. Before hydrogen will be produced offshore, several boundary conditions will need to be sorted out concerning onshore hydrogen production, transport, storage and consumption, from an economical, legal and political stand point. At the moment of writing this report, several parties in the value chain are continuously working to make this happen.

The scale up of offshore hydrogen production will rely on the development of proper boundary conditions for onshore hydrogen production, transport, storage and consumption. These are considered outside of scope of this report. The roadmap on knowledge development for offshore hydrogen production focuses on the additional knowledge that needs to be built on the offshore topics only.

Three items are considered critical for successful upscaling of offshore hydrogen production:

- **Economical aspects**: Currently the business case of individual projects is not yet considered positive. This is due to the status of the current energy market (e.g., low prices of fossil fuels) but also due to the status of the hydrogen market (e.g., high prices of electrolyser systems and other critical components) and due to high contingencies expected by project developers in order to invest in first-of-its-kind projects. Subsidies will therefore be required to divide the risk between the tax payer and the developer, who can have a potential gain from taking this risk. In order to improve the business case, both CAPEX and OPEX of these offshore hydrogen production facilities will need to decrease significantly. Although other sectors like the offshore wind sector have seen cost reductions as a result of learning curves, first demonstration projects and possibly actual projects will need support in order to achieve an acceptable business case, de-risk offshore hydrogen, facilitate further scale-up and replication projects, and to allow learning curves to be created and fulfilled.
- **Ecological and safety aspects**: a clear distinguisher for offshore hydrogen production compared to onshore is ecology. The impact of installing hydrogen production assets and connecting hydrogen infrastructure will have an ecological impact, as well as the operation of both. The impact of brine disposal and heat disposal will need to be investigated thoroughly before scaling up can be done, and more importantly it shall be investigated if these waste streams can be utilized rather than seen as waste. Similar to current natural gas production and transport, the safety aspects and related standards and norms shall also be updated for large scale hydrogen production and transport, already from the first moment of hydrogen production. The learnings from the demonstration projects should help elucidate what the specific ecological risks are of offshore hydrogen, how different they are from current offshore wind and offshore oil and gas, and recommend mitigation paths for the government (e.g., to set rules for future tenders), project developers (e.g., to follow the rules in a cost-

effective manner) as well as for technology developers and research institutions (e.g., to guide innovations and technology development in order to revise or adapt existing technology).

- **Technical aspects**: As stated in Section 4, many of the individual components in hydrogen production have a high Technical Readiness Level. The components and waste streams form together only a piece of the puzzle when it comes to deploying electrolysis systems offshore. Since the topic of offshore hydrogen production is a recent topic that has gained significant attention, there is relatively little experience with offshore hydrogen. Main aspects to be considered in the roadmap towards large scale hydrogen production are considered to be:
    - Intermittent renewable energy supply: Currently, electrolyzer systems cannot optimally accept the intermittent supply of renewable energy. Effort will need to be put in either designing for higher flexibility of intermittent hydrogen production, or in designing backup power supply systems, or grid connections.
    - Offshore compatibility, which is a combination of optimizing a system that requires a compact design as a result of small available footprint and high endurance under harsh offshore conditions. The design of such system may therefore look quite different from an onshore design, even if the same electrolysis technology is selected.
    - Unmanned operation, which also shall reflect in a robust design. As a result of unmanned operation, resulting from a desire to minimize OPEX by long mean time between failures of components, as offshore maintenance is considered costly. The final systems may also look different compared to (current) onshore systems, also on a component design level, when it comes to complying with offshore-specific technical specifications and requirements.
    - Hydrogen transport to shore. Especially when produced volumes of hydrogen increase, the knowledge gaps on safe and reliable offshore compression stations shall be evaluated thoroughly. Depending on whether a blended stream of hydrogen and natural gas will be foreseen, additional lessons in blending and particularly separation (deblending) will need to be learned.

Considering the items above, there is still a significant share of things to be learned. Although some of these learnings can be done by studies on paper, it is important to realize that some things are learned better by doing. Learnings shared in public presentations in the HEROW[34] platform support this statement, by e.g. the PosHYdon project (e.g. on permitting and standards) or in the Baseload Power Hub project (e.g. on how the design of the platform has significantly changed over the design stages of the projects). The Dutch government has specified a list of expected learnings from their two proposed Demonstration projects[35].

In order to learn about offshore hydrogen production, current pilots and foreseen pilot/demonstration projects play an important role. The most important learnings and the minimum scale at which these shall be learned is projected in Figure 6.1. The figure indicates the most important learnings:

- The scale (minimum capacity) at which this learning shall be evaluated. The circle indicates the minimum scale, the line indicates that the same learning shall be evaluated for larger capacities, as new knowledge gaps will likely surface for larger capacities. The capacities in the figure indicate typical sizes of pilots that are currently

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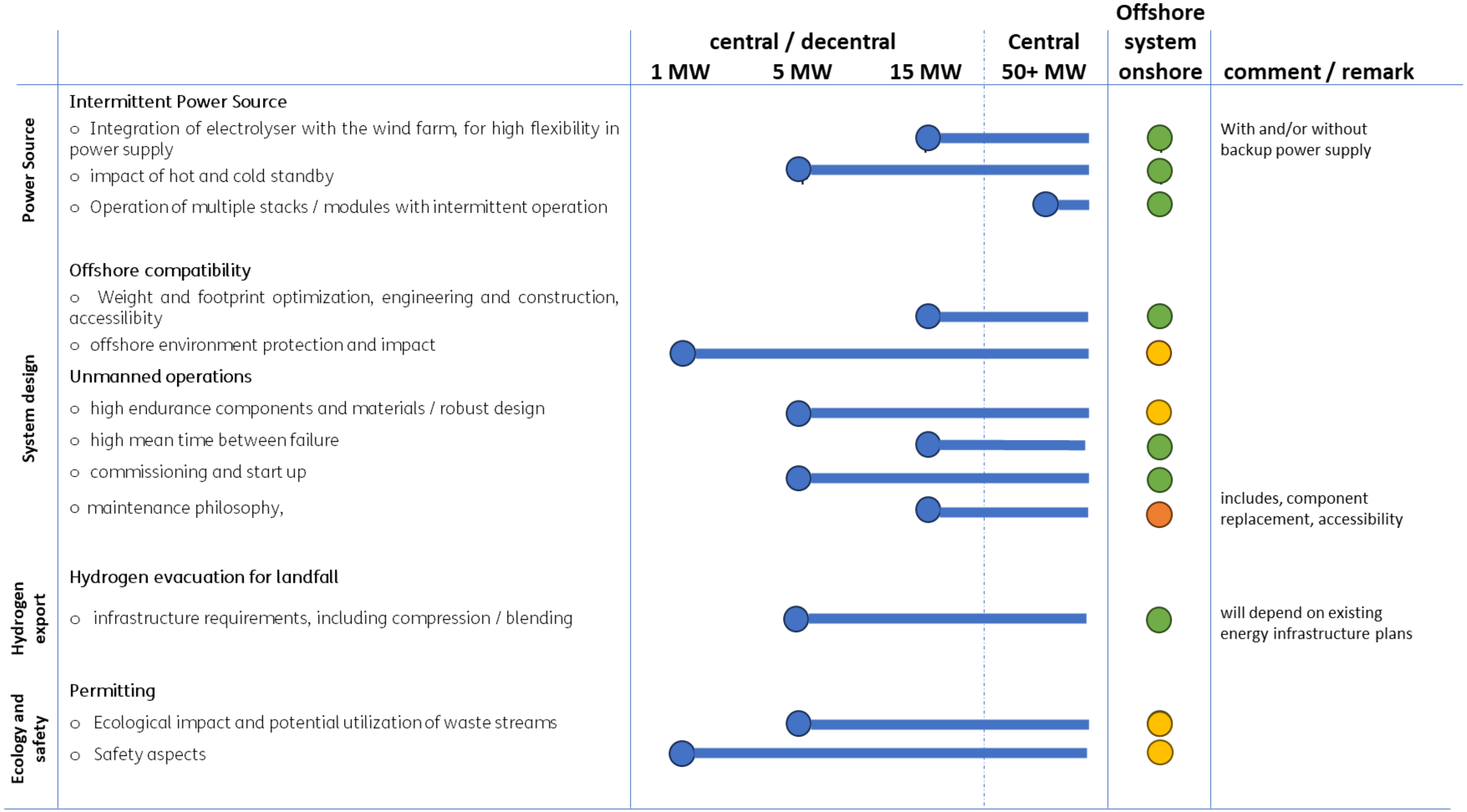
[34] HEROW (topsectorenergie.nl)

[35] Bijlage marktconsultatie - Learning objectives demonstration offshore hydrogen (rvo.nl)

seen, or that are recommended to consider. The 1 and 5 MW scale pilots are already here, as can be read in Section 3.2.6. The size of 15 MW is selected as this may be maximum size where experience for both central and decentral electrolysis can be built up. Larger capacities will focus on centralized electrolysis, powered by multiple power sources.

- An indication of whether it is necessary to learn this offshore. It is important to assure that the volumes of produced hydrogen can be monetized. Relying on an offshore infrastructure to transport the hydrogen to shore is a large risk to many developers in the pilot and demonstration stage of offshore hydrogen production. To mitigate this risk and speed up the process of learning, one could argue whether specific learnings shall be learned only from certain electrolysis capacities onward. In addition, some learnings do not have to be learned (far) offshore, but can also be learned onshore or near shore (e.g. at harbors). The green circles indicate that this can be learnt onshore (on systems that replicate offshore systems), red indicates that it can only be learnt offshore. Orange circles indicate that not all can be learnt onshore, but shall at least be demonstrated near-shore. Testing/demonstrating near shore may mitigating risks and associated costs regarding installation of the platform and/or the export of hydrogen to shore.

Although the concepts of central and decentral production of hydrogen have their distinct properties (as presented in Chapter 3), the first number of pilots and demonstration projects with relatively small capacities (<20 MW) will provide valuable lessons for either concept.



		central / decentral			Central	Offshore system onshore	comment / remark
		1 MW	5 MW	15 MW	50+ MW		
Power Source	Intermittent Power Source						
	○ Integration of electrolyser with the wind farm, for high flexibility in power supply			●━	━━	🟢	With and/or without backup power supply
	○ impact of hot and cold standby		●━	━━	━━	🟢	
	○ Operation of multiple stacks / modules with intermittent operation				●━	🟢	
System design	Offshore compatibility						
	○ Weight and footprint optimization, engineering and construction, accessibility			●━	━━	🟢	
	○ offshore environment protection and impact	●━	━━	━━	━━	🟡	
	Unmanned operations						
	○ high endurance components and materials / robust design		●━	━━	━━	🟡	
	○ high mean time between failure			●━	━━	🟢	
	○ commissioning and start up		●━	━━	━━	🟢	
	○ maintenance philosophy,			●━	━━	🟠	includes, component replacement, accessibility
Hydrogen export	Hydrogen evacuation for landfall						
	○ infrastructure requirements, including compression / blending		●━	━━	━━	🟢	will depend on existing energy infrastructure plans
Ecology and safety	Permitting						
	○ Ecological impact and potential utilization of waste streams		●━	━━	━━	🟡	
	○ Safety aspects	●━	━━	━━	━━	🟡	

Figure 6.1: Knowledge roadmap for offshore hydrogen production

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