Advances in Reliability, Safety and Security, Part 10 – Kołowrocki, Kosmowski (eds.)
© 2024 Polish Safety and Reliability Association, Gdynia, ISBN 978-83-68136-22-7 (printed), ISBN 978-83-68136-09-8 (electronic)

Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

Brief Review Of Options And Risks In Offshore Green Hydrogen Production: German Case Study

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Abstract

This paper presented a brief review of offshore hydrogen production options in Germany and related risks. We describe the main electrolyzer technologies and design options for hydrogen production. The main technology alternatives are alkaline, PEM, and solid oxide electrolysis. Design options for the production are onshore electrolysis, electrolyzers in individual wind turbines, a dedicated offshore platform for electrolyzers, or an energy island. We chose a scenario with dedicated platform and PEM electrolyzers. The main factors were the lower losses related to transporting hydrogen instead of electricity, financial risks associated with artificial islands, and the suitability of pairing PEM electrolyzers with renewable energy sources. A main aspect of this work is the coverage of estimation of hydrogen production as well as the identification of hazards related to the baseline scenario. Many of the risks that are present in oil and gas platforms or offshore substations for offshore wind farms would be similar in hydrogen production platforms. Particular concerns for these platforms, though, include the scarcity of rare earth elements required for PEM fuel cells, the inexperience in operating these fuel cells in offshore environments, and the evaluation of situations where escaping gas could accumulate in production or storage facilities, posing a risk of explosion.

Keywords: hydrogen, offshore platform, PEM electrolyser, Germany

1. Introduction

The hydrogen strategy for the European Union recognizes hydrogen as a means of energy storage to cover seasonal variations and connect renewable energy production places to distant demand centers (EC, 2020). It can further replace fossil fuels in some carbon intensive industry processes and transportation. In North Germany, the regional strategy foresees using electricity from offshore and onshore wind farms to produce green hydrogen and store it in underground formations (North German States, 2019). Ports will act as centers to import and distribute green hydrogen, as German production will likely not cover the demand. Especially when the hydrogen is also supplied to other parts of Germany. This paper studies the options and risks associated with offshore hydrogen production. The main technology alternatives are Alkaline Electrolysis (AE), Polymer Electrolyte Membrane (PEM), and Solid Oxide Electrolysis (SOEC). Design options for the production are onshore electrolysis, electrolyzers in individual wind turbines, a dedicated offshore platform for electrolyzers, or an energy island. After reviewing these options, we will focus on an offshore platform.

This paper describes what risks may affect such facilities in terms of business continuation and resilience. Our main motivation comes from recent incidents on offshore infrastructures in the Baltic Sea. Nord Stream pipelines were damaged in 2022 (Sanderson, et al., 2023), and a gas pipeline and a telecommunication cable between Finland and Estonia were cut in 2023 (Police of Finland, 2023). We are further motivated by the new EU directive on critical entities (EC, 2022). It mandates Critical Infrastructure (CI) operators to perform a risk assessment and take measures to ensure their resiliency. In Germany, the current CI threshold for a gas production plant or transmission network is 5190 GWh/year (BMI, 2016). For electricity production, this value is 3700 GWh/year and the installed capacity of a power generating plant is 104 MW (BMI, 2021). So, today a gas production plant is a CI in Germany if it can produce gas with about 600 MW worth of energy in an hour.

But, these thresholds have lowered over time. The current threshold for electricity was set in place in 2022 (BMI, 2021). The previous threshold was 420 MW.

In accordance with this old threshold, our study considers a hydrogen production plant that is connected to a 400 MW Offshore Wind Farm (OWF). Many of the German OWFs were built considering the old CI threshold. So, 400 MW is a common installed capacity value in Germany. Also, having a low hydrogen production facility capacity respects the current German CI threshold. Especially when considering the variable production rate. Therefore, our case study platform for offshore hydrogen production may not be itself a CI. Yet, no guarantee exists that the current thresholds will not change. One can also consider a cluster of platforms which would be a CI. In all cases, specific challenges exist in protecting maritime infrastructures (Bueger and Liebetrau, 2023). Germany plans to be more reliant on offshore renewables. Thus, questions on risks and protection of these infrastructures are ever more relevant.

Rest of this paper is structured as follows. Section 2 introduces our reference scenario that considers PEM electrolyzers in an offshore platform. Section 3 provides risk identification for the reference scenario and Section 4 concludes the paper. Our future intention is to integrate hydrogen production into our existing OWF model (Niemi et al., 2024).

2. Reference scenario

As described in Section 1, many of the German OWFs have about 400 MW installed capacity. The current CI threshold for gas plant production is above this value. So, having a hydrogen production platform connected to an OWF with 400 MW installed capacity seems a plausible scenario. For example, Tractebel has announced developing a platform of this scale (Tractebel, 2019). The following subsections motivate our reference scenario. Section 2.1 describes potential electrolyser technologies and Section 2.2 design options. Section 2.3 provides a calculation of the amount of produced hydrogen. In brief, we consider PEM electrolyzers in an offshore platform that would generate 24500 tons of hydrogen per year, which corresponds to about 965 GWh/year.

2.1. Hydrogen production through electrolysis

Electrolyser splits water H_2O with electric current to hydrogen H_2 and oxygen O_2. Hydrogen is produced at the cathode and oxygen at the anode. The produced hydrogen has a high purity of about 99.99%. This paper describes three different technologies used in these electrolyzers. They are AE, PEM, and SOEC. The other technologies such as Anion Exchange Membranes (AEM) are considered too experimental for this assessment. (Taibi, Miranda, Carmo, and Blanco, 2020)

2.1.1. Alkaline Electrolysis

AE is the most mature solution for hydrogen production up to the megawatt range, and also the most used electrolytic technology at a commercial level worldwide (IEA, 2019), (Buttler and Spliethoff, 2018), (Carmo, Fritz, Mergel, and Stolten, 2013). AEs are easy to manufacture (Taibi, Miranda, Carmo, and Blanco, 2020). They consist of two electrodes immersed in an alkaline electrolyte of aqueous potassium hydroxide solution (KOH) of 20 - 30%. Pumps or natural circulation remove the product gas bubbles and heat. Electrolyte also serves as the gas-liquid-separator and it is stored in two separated drums for each product gas (Buttler and Spliethoff, 2018). The electrodes are separated by a diaphragm which keeps the product gases apart from each other (Carmo et al., 2013).

AEs have the benefit of using low-cost components for both electrodes and diaphragm (Patonia and Poudineh, 2022). Asbestos is used as the diaphragm and nickel materials as the electrodes (Chi and Yu, 2018). Platinum and ruthenium as well as cheaper metals such as manganese are used as catalysts. AEs are durable and tolerant to impurities while using robust cell separators. This design leads to a long system lifetime and low maintenance costs. It is claimed that a high scale of ‘green’ hydrogen can be produced with AEs at low investment costs (Patonia and Poudineh, 2022). They can operate at a minimum load of 10% to full design capacity and produce 99.5% pure hydrogen (IEA, 2019).

Despite all these advantages, AEs have several drawbacks. The ionic conductivity is supplied by the aqueous alkaline solution, which penetrates in the pores of the diaphragm. However, this makes the product gases to mix. This limits the lower power-operating range and the ability to operate at higher pressure levels (Taibi, Miranda, Carmo, and Blanco, 2020). The efficiency of the electrolyzer is reduced because of the diffusion of oxygen into the cathode chamber. The oxygen is catalyzed back to water on the cathode side, where hydrogen is produced.

At low load, also hydrogen diffuses to the oxygen chamber. Thus, the production rate is limited to avoid increasing the hydrogen concentration to unwanted and dangerous levels (Carmo et al., 2013). This issue can be mitigated with thicker diaphragms, but they lower efficiency. Some manufacturers use spacers between electrodes and diaphragms to further avoid the intermixing of gases (Taibi et al., 2020). However, this solution increases the ohmic resistances across the two electrodes. Thus, it drastically reduces the current density at a given voltage. The most severe drawback is that AEs are designed for operation at fixed process conditions and their current density must be altered slowly. Therefore, they are not a good option for balancing variable renewable energy sources. However, this issue can be partially solved by using batteries and control systems (Patonia and Poudineh, 2022).

2.1.2. PEM electrolysis

PEM electrolysis was introduced by General Electrics in the 1960s (Buttler and Spliethoff, 2018). The development of the first PEM systems was based on the solid polymer electrolyte concept to overcome the major drawbacks of AEs. It is now associated with proton exchange membrane facilities. They appear to be the most promising option for pairing hydrogen production with renewable sources (Patonia and Poudineh, 2022).

In this technology, the two half-cells are separated by the proton exchange membrane. The electrodes are usually mounted on the membrane forming the membrane electrode assembly. Water is supplied at the anode and it is partly transported to the cathode side due to the electro-osmotic effect (Buttler and Spliethoff, 2018).

High efficiency is achieved thanks to a thin Perfluorosulfonic Acid (PFSA) membrane and electrodes with advanced architecture. The PFSA membrane is mechanically and chemically robust and withstands high pressure differentials. With the oxygen side at atmospheric pressure, the PEM cells can be operated at up to 70 bar. The PFSA membrane creates an acidic environment and high voltages. The oxygen evolution in the anode further creates a harsh oxidative environment hence requiring the use of materials that can withstand these conditions (Taibi et al., 2020). Noble metal catalysts like iridium and platinum are used for the anode and the cathode respectively. Titanium-based materials and protective coatings are necessary to provide long-term stability to cell components, optimal electron conductivity, and cell efficiency. As these rare earth elements are needed, PEM stacks are more expensive than AEs (Buttler and Spliethoff, 2018; Taibi et al., 2020).

PEMs have the most compact and simplest system designs (Taibi et al., 2020). However, they are sensitive to water impurities and can suffer from calcination. PEM electrolyzers can operate with low loads around 0-10% of the design capacity. The PEM separator is non-porous and allows for rapid cycling in flexible operational conditions. Thus, they can provide a speedy response suitable for electricity grid-balancing services. This capability makes PEM systems highly suitable for running on intermittent renewables and the most attractive technological option for the energy transition to ‘green’ hydrogen (Patonia and Poudineh, 2022).

PEM electrolyzers have a low cross-permeation leading to high purity of produced hydrogen (99.99% after hydrogen drying). Today, the electrode areas are approaching 2000 cm^2 though it is still far from future concepts of large megawatt (MW) stack units using single stack concepts. The reliability and lifetime characteristics of large-scale, MW stacks still have to be validated (Taibi et al., 2020).

2.1.3. Solid Oxide Electrolysis

Solid Oxide Electrolysis is expected to become the third main hydrogen production technology in the future (Patonia and Poudineh, 2022). It uses a solid oxide as the electrolyte material and has a high operational temperature of 650 to 1,000 oC (Luo et al., 2022). The technology is still far from maturity. It has been gaining interest since its inception in the late 1960s, due to its potential to significantly increase the efficiency of water electrolysis. SOEC has a high efficiency of around 80–90.8%. Compared to the other electrolysis technologies, it has an advantage because electrolysis is not limited by the Carnot efficiency (Patonia and Poudineh, 2022).

SOECs use relatively cheap nickel electrodes (Taibi et al., 2020). It is the only device that can directly electrolyze seawater to produce hydrogen. They further demonstrate long-term stability and ability to absorb CO2 greenhouse gases, which is a ‘negative carbon’ emission process (Luo et al., 2022; Patonia and Poudineh, 2022).

Despite these advantages, the high operating temperature is a challenge because it rapidly degrades cell components (Patonia and Poudineh, 2022). During shutdowns or ramping periods, thermo-chemical cycling hastens the degradation and decreases lifetimes. Additional challenges relate to sealing at higher differential pressure, and electrode contamination. The generated hydrogen fuses with water vapor requiring additional treatment to purify hydrogen.

Based on this information from these three technology options, we choose PEM for our reference scenario. Unlike AE, it can quickly change operational conditions and it is much more mature than SOEC.

2.2. Design options for an OWF powered hydrogen production plant

We consider four different alternatives on how hydrogen could be produced. The first option is to transfer the electricity to the shore and produce the hydrogen on land. The second option is to have electrolyzers for each turbine. The third option is to have an offshore platform for hydrogen production. Lastly, we consider an energy island.

There are two ways to connect an OWF to a hydrogen production facility at shore. For short distances, they can be connected using high voltage alternating current (HVAC) cables. This option is shown in Figure 1. However, increasing transmission distance makes them uneconomical. This distance can be increased if power is converted to high voltage direct current (HVDC) before transmission. HVDC cables have lower line losses, are cheaper than HVAC, and do not suffer from charging current constraints (Jansen et al., 2022). Using HVDC requires having a converter substation at the OWF. It is a suitable for long distance transmission. In Germany, OWFs are over 30 km from shore. So, both HVAC and HVDC have been used. High distance or high energy motivates the use of HVDC. Yet, the transportation of hydrogen has lower losses compared to electricity transportation by HVAC or HVDC. In Germany, the OWFs are not typically near the coast. Therefore, offshore production of hydrogen can be more economical than producing it onshore.

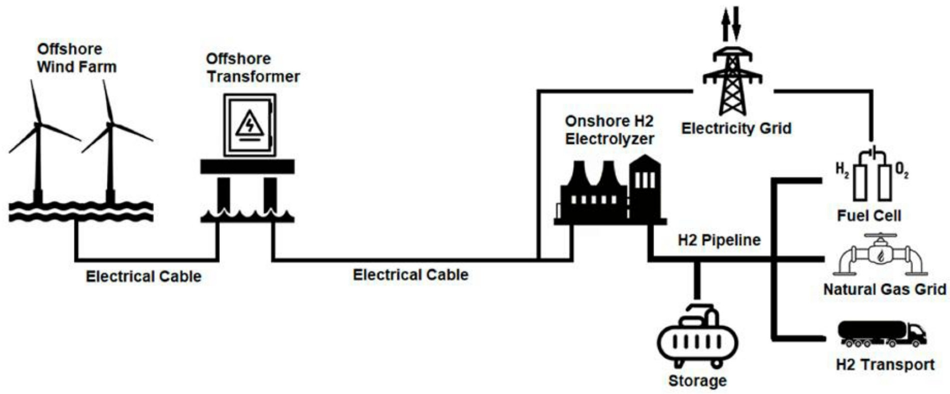

Fig. 1. Onshore hydrogen production with electricity produced in OWF (Calado and Castro, 2021).

Figure 2 depicts an option where hydrogen is generated in individual turbine platforms. The electrolyzer and the desalination unit could be located either inside or next to the tower of each wind turbine. The hydrogen produced is transported via a pipeline to the hub which is connected to many wind turbines. There the hydrogen is compressed and transported onward via pipelines (Singlitico et al., 2021). Several implementation plans exist. For example, Siemens Gamesa has patented designs for an offshore station with a turbine and an electrolyser (EP Patentnr. 4 067 534 A1, 2021), and housing the electrolysers within the turbine nacelle (EP Patentnr. 4 212 721 A1, 2022). RWE plans to build a demonstrator near Heligoland (RWE, 2023).

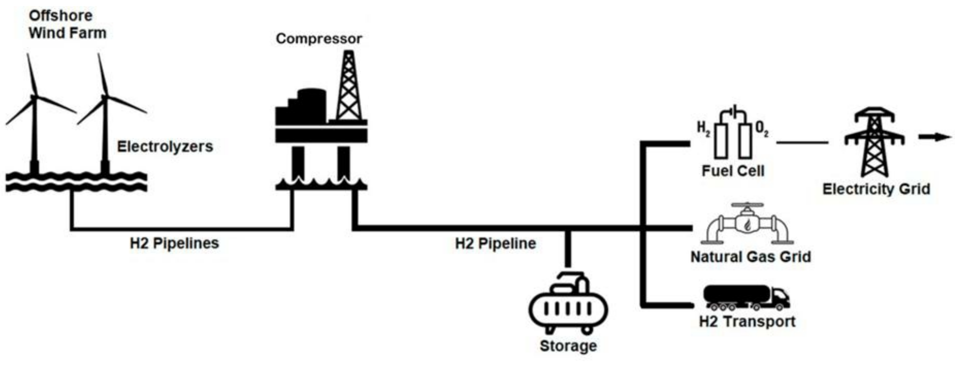

Fig. 2. Hydrogen production in individual wind turbines within OWF, with centralized compressor, modified from (Calado and Castro, 2021).

Figure 3 shows an offshore hydrogen production platform. Its function is somewhat similar to an offshore substation that transforms the energy produced by individual turbines. It is not clear if hydrogen production and substation should be combined or if these should be separate platforms. In all cases, electrolyzers need direct current that is not produced by wind turbines. Compared to having electrolyzers in individual turbines, a platform can provide economies of scale benefits (Singlitico et al., 2021). Individual systems do not need to be multiplied for each turbine and can be accessed in the same location, which can be beneficial for maintaining them. Again, several implementation plans exist. For example, Tractabel is developing a hydrogen production platform of 400 MW scale (Tractebel, 2019), Lhyfe has successfully tested a small floating platform (Lhyfe, 2023), and PosHYdon project plans to install an electrolyzer in a fixed offshore platform (Peters et al., 2020).

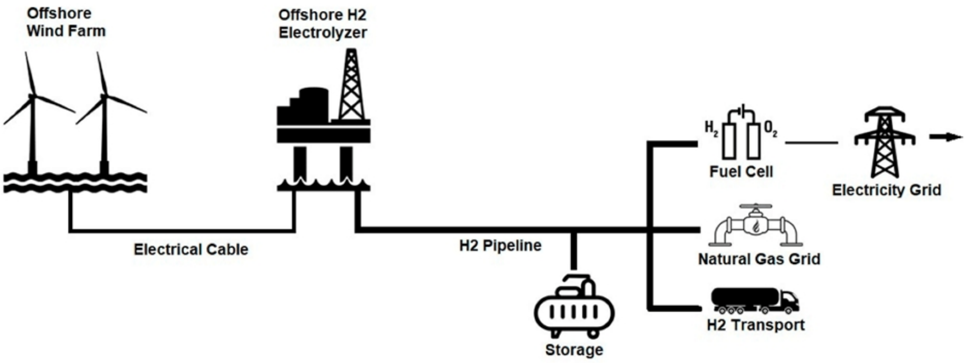

Fig. 3. Hydrogen production within an offshore platform (Calado and Castro, 2021).

Economics of scale benefits and ease of access may be even higher in an energy island. The idea is akin to onshore electrolysis, but the electrolyzers would be located on an island. Several plans exist in Europe. Germany is considering using Heligoland as an energy island (AquaVentus, 2021), while Denmark is considering building an artificial island in the North Sea (KEFM, 2023). Fig. 4 shows the German Exclusive Economic Zone (EEZ) in the North Sea with the existing and planned offshore wind farms. Most of these farms are located far distance from Heligoland, which would make the electricity transfer lossy. It is further estimated that an artificial island is economically beneficial only if the amount of production is high. In a Dutch example scenario, an artificial island with 4 GW of installed electrolyzers had a slightly lower capital expenditure than eight platforms with 500 MW capacity (Kawale, et al., 2022). There are legal and environmental concerns regarding artificial islands. These lead to regulatory risks that may significantly reduce the economic benefits if they are realized. For example, the island may need to be removed after use (van der Veer, et al., 2020).

Due to these factors, we chose a platform for our reference scenario. For us, it seems more feasible that one would use initially a platform for hydrogen production, rather than an artificial island. For example, the Danish plan for an energy island was postponed due to cost risks (KEFM, 2023). Therefore, we believe that, outside Heligoland, the large-scale hydrogen production will be initially implemented with platforms, in the German EEZ. Even if Germany does not have an offshore gas network like the Netherlands, a gas pipeline connects Germany to Norway (Dena and Gassco, 2023). It might be possible to reuse this pipeline to transport hydrogen and connect offshore production platforms to it.

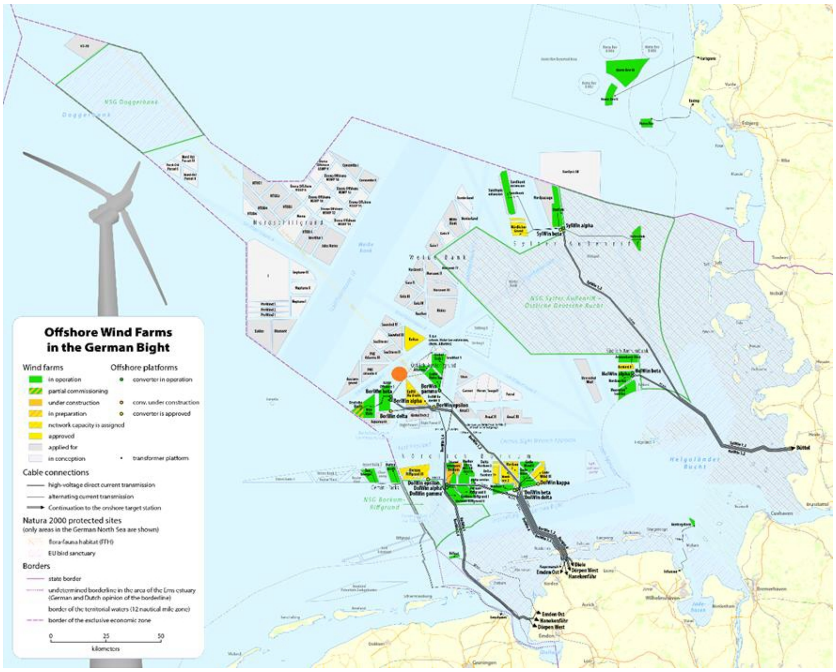

Fig. 4. Existing and planned OWFs in the German North Sea EEZ (Dörrbecker, 2020). The operating OWFs are marked with green and the planned ones with yellow and grey colors. The area chosen for our case study is marked with an orange circle.

2.3. Hydrogen production calculation

We assume that all the produced electricity from an OWF is used for hydrogen production. The assumption is based on a view that the cost of produced hydrogen would be too high if the production occurred only when the price of electricity was low (Singlitico et al., 2021). However, if 100% of electricity in a market is produced with renewables, economically it makes sense to produce hydrogen with excess electricity (Al-Ghussain et al., 2022), (Al-Ghussain et al., 2023). Yet, this will not be the case initially when a significant portion of the electricity within a market is not produced renewable.

Within OWF, power outputs of wind turbines depend on wind speed and turbine characteristics. We use the characteristics of the Vestas V164-9.5MW wind turbine. Its specifications are listed in Table 1 and the power curve is given in Figure 5. We used hourly wind speed data from the Copernicus ERA5 Dataset using values for 100 m altitude (Hersbach, et al., 2023). The location is at coordinates N54°26, E6°06, which is marked in Figure 4. The area was chosen because it has existing and planned OWFs, and it is over 100 km away from the shore and Heligoland. Our reference OWF consists of 42 turbines. So, it has 399 MW of installed capacity. Due to the wake effect, the full power production cannot be realized. We assume 15% losses due to this effect, based on (Gao et al., 2020). So, the produced power P_{OWF} is calculated with equation

$$P_{OWF} = 0.85 * 42 * P_{V164}(s_w), \quad (1)$$

where $P_{V164}(s_w)$ is the power produced by a Vestas V164 turbine as a function of the wind speed.
The amount of produced hydrogen M_{H2} is then calculated with equation

$$M_{H_2} = P_{OWF}/(E_{elec}/\eta + E_{add}), \quad (2)$$

where E_{elec} is the electricity consumed by the electrolyzer, and η is its conversion efficiency. We use the value 50 kWh/kg for E_elec from (Nguyen Dinh et al., 2021). However, we assume η to be 75% as this is the reported efficiency of the Siemens Silyzer 300 PEM electrolyzer (Dickschas, 2021). Electricity consumed by water purification, pressurization and other losses are considered in E_add. We estimate the energy consumption for these tasks to be 3 kWh for a produced kg of hydrogen (Nguyen Dinh et al., 2021). With these values, the platform can produce about 4870 kg of hydrogen per hour. When the wind speed data from years 2012 to 2022 is considered, the platform would have generated on average about 24500 tons of hydrogen per year. This value corresponds to about 965 GWh/year by using the higher heating value of 39.39 kWh/kg.

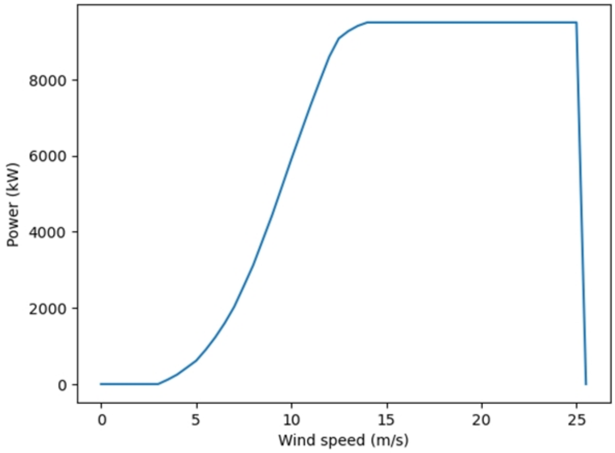

Fig. 5. Power curve of the VESTAS V164-9.5MW (The Wind Power, 2023).

Table 1. Vestas V164-9.5 MW wind turbine specification (Vestas, 2023).

Parameter	Value
Rated power Output	9.5 MW
Rotor diameter	164 m
Blade swept area	21,124 m2
Frequency	50 & 60 Hz
Cut-in wind speed	3 m/s
Rated wind speed	14 m/s
Cut-out wind speed	25 m/s
Hub height	105 m/s
IEC Wind Class	IEC S

In reality, the electrolyzer capacity will likely be smaller than the power production capacity because the electricity production rate fluctuates (Jepma and van Schot, 2017). Assessing this capacity factor would require assumptions on the cost of the hydrogen production facility and the selling price of the hydrogen. These are needed to estimate the return of investment time depending on the size and the utilization rate of the production facility. We consider this assessment to be beyond the scope of this short review.

3. Risk identification for offshore hydrogen production

When looking at the dangers and risks of offshore installations, it's important to separate safety issues from security issues, as Iaiani et al. (2022) have done. We follow this approach in our discussion.

3.1. Safety perspective

Some studies exist regarding risks and safety related issues in green hydrogen production. However, many of them do not consider offshore production. Risks have been considered from a supply chain perspective (Markert et al., 2017; Azadnia et al., 2023), hydrogen production and storage installations perspective (Perelli and Genna, 2022), as well as focusing specifically on the explosion risk (Shi, et al., 2020). A risk assessment of offshore production of hydrogen has been conducted in the Netherlands (Rodenburg, et al., 2022). It presents a detailed risk assessment of offshore hydrogen production installations. This section identifies risks for our reference scenario considering these findings.

Significant experience exists within the offshore industry for carrying risk assessments (Brandsæter, 2002). While this experience comes from the oil and gas industry, certain risks are present in every offshore installation. Typical risks in the offshore industry are releases of hydrocarbons or other inflammable and/or toxic substances, well control problems, ship traffic, crane operations/lifting, extreme environmental conditions, structural failures including loss of water-tightness; and position keeping failure (Brandsæter, 2002). Out of all these, only the well control problems and consequences of toxic substance releases are irrelevant, as hydrogen is not toxic.

Two main scenarios for substance releases for a hydrogen production platform are a release of oxygen or hydrogen (Rodenburg, et al., 2022). Oxygen is generated when hydrogen is produced from the water. Exposure to pure oxygen risks human health, increases flammability, and degrades materials. Normally the oxygen concentration is 21%. Increasing the concentration higher than 40% leads to a 10% chance that the concentration is lethal and even a small increase e.g. 23% concentration increases flammability. These risks can be avoided by choosing a venting location where human presence is unexpected, and mixing the oxygen with air or heating the oxygen before release (Rodenburg, et al., 2022). Heated oxygen rises and does not concentrate near the platform.

Hydrogen is an explosive gas and an accidental release of it can cause a fire or in obstructed areas an explosion. As hydrogen is lighter than air the most likely scenario is an upward moving jet fire or cloud fire if the ignition is delayed. Therefore, it is important to design the platform such that potential leaks can be detected and safely vented out. Similar to the oxygen venting position, one must choose a location where human presence is unlikely. As hydrogen is not intended to be stored within the platform, a leak can be stopped by stopping the hydrogen production. However, due to the small molecule size, the permeability and leakage of hydrogen through materials is relatively high. Some materials may degrade due to the presence of hydrogen. Therefore, suitable materials need to be used and process pressures should be monitored.

An offshore hydrogen production platform will likely be uncrewed. Thus, the risk of death or injury of personnel is only present during the installation phase and maintenance interventions. In our reference scenario, we consider the platform to be fixed to the seabed, which eliminates the chances for the position keeping failure. However, structural risks still exist, which can be caused e.g. by a ship collision, extreme weather, or structural fatigue.

From a reliability viewpoint, offshore hydrogen production depends on the availability of following inputs and systems 1) electricity from OWF, 2) desalinated water, 3) electrolyzers, 4) compressors, and 5) a pipeline for transport. Operational experience has been cumulated from all these systems. However, PEM electrolyzers have not been utilized to large extent in offshore environment. Therefore, the high reliability and maintainability of these systems in this environment remains to be demonstrated. This situation may improve with the experience gained from pilot projects, e.g. the PosHYdon experiment (Peters et al., 2020).

After hydrogen arrives to shore it could be stored or distributed further. A study considering bunkering of alternative fuels in the Port of Amsterdam found that storing gaseous hydrogen is relatively safe compared to many alternatives e.g. liquid natural gas (Wessels, 2021). A hydrogen gas leak will likely immediately result in a jet fire. The report therefore excludes the risk of explosion in bunkering. However, the report notes an explosion in a Norwegian refueling station which may dispute this assumption. An explosion may still occur if the jet flame is congested or if there is an ignition source within the gas (Liang et al., 2019). For example, the study on explosion risks within a hydrogen production facility also assumed that the gas would be congested within it (Shi et al., 2020).

3.2. Security perspective

In the context of security considerations for offshore hydrogen production platforms, a notable parallel exists with offshore substations (Tecklenburg et al., 2023). In a survey conducted among 31 professionals within the offshore wind energy sector, Gabriel, Tecklenburg, and Sill Torres (2022) identified several security risks that are also relevant for offshore hydrogen production platforms. These scenarios include the threats of cyber-attacks, sabotage, and terrorism. The critical infrastructures vulnerable to such adversities encompass the production platform itself, the subsea pipelines connecting the platform to the shore, and the power and data cables. This analysis underscores the imperative for a robust security strategy that encompasses both physical and cyber dimensions to safeguard these essential components of offshore hydrogen production infrastructure.

When considering the platform, cyberattacks or sabotage can result in loss of operational control, or partial to complete destruction. Such risks are elevated due to the explosive nature of Hydrogen. Threats may originate from both external and internal sources, such as unauthorized access by individuals or actions by maintenance personnel. Regarding terrorism, the potential for deliberately targeted ship or helicopter collisions, as well as threats from explosives and drone attacks, must be considered (Köpke et al., 2023). Pipeline as well as power and data cables share similar security scenarios, i.e. sabotage by maliciously intended destruction via anchors or fishery nets and explosive threats. Recent incidents, like the explosions at Nord Stream (Soldi et al., 2023) emphasis the relevance of these scenarios.

To mitigate these risks, maritime surveillance employing optical and radar systems, along with monitoring through the Automatic Identification System (AIS), has proven effective (Soldi et al., 2023). Furthermore, Distributed Acoustic Sensing (DAS) technology offers precise monitoring capabilities for areas encompassing subsea pipelines and cables (Thiem et al., 2023). However, the effectiveness of such surveillance strategies necessitates the integration of suitable response measures. This involves the mobilization of official entities such as police forces, as well as private security services, to ensure comprehensive protection. Aside the physical and cyber risks, one should also consider risks to the supply chain. In case of Hydrogen production, one has to put special emphasis on the rare earth elements of PEM electrolyzers, which may lead to exposure to new geopolitical risks (Kamran et al., 2023).

4. Conclusions

This paper presented a short review of offshore hydrogen production options in Germany and related risks. There are plans for small scale demonstrators in offshore wind turbines. But from the societal viewpoint, the large-scale production scenarios are the most interesting ones. These include production in an offshore platform, Heligoland, or an artificial island. Producing hydrogen in Heligoland is rather similar to a production scenario in an onshore location and it only makes sense for OWFs located near the island. An artificial island scenario has high financial risks. Therefore, we focused on hydrogen production within an offshore platform. In this scenario, risks are similar to those of oil and gas platforms or offshore substations for OWFs. However, the environmental risks are much lower compared to those in the oil and gas industry. The main questions are the availability of rare earth elements needed for the PEM fuel cells, which may pose geopolitical risks, lack of operational experience of these fuel cells in offshore locations, as well as assessing scenarios where the leaking gas may get congested within a production or storing facility leading to an explosion risk. Our future intention is to integrate hydrogen production into our existing OWF model to further study resiliency of the offshore hydrogen production (Niemiet et al., 2024).

Acknowledgements

This paper uses data from Copernicus Climate Change Service information. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

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