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Discussion Paper

The Economics of Offshore Wind-Based Hydrogen Production in Saudi Arabia



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Key Points

Offshore hydrogen production from offshore wind energy is gaining global attention as an appealing solution for scaling up green hydrogen production. The technoeconomic feasibility of integrating offshore wind into hydrogen production has been explored in various regions, but no comprehensive study exists concerning Saudi Arabia's offshore wind potential. This work aims to assess the cost-effectiveness of producing hydrogen onshore versus offshore from wind power in the Red Sea. Via the use of a deterministic cost model, this study evaluates the levelized cost of hydrogen (LCOH) for both configurations. The results show that offshore wind farm costs and floating foundations are the major drivers of capital expenditure (CAPEX). While onshore electrolysis remains slightly less expensive than offshore electrolysis, both configurations require substantial cost reductions to compete with alternative onshore renewable energy sources.

- The LCOH of offshore hydrogen production from floating offshore wind ranges from $6.47 to $8.01/kg, reflecting the current high cost of such technology.
- Significant cost reductions in the main components of the system can reduce the cost range down to $4.57 to $6.07/kg.
- The development of Saudi Arabia's offshore wind-to-hydrogen sector will likely be a medium- to long-term target, requiring further cost reductions in offshore wind technology.
- Future innovations in decentralized hydrogen production can create new opportunities for cost reduction and scalability in the sector.

1. Introduction

The global push toward decarbonization and sustainable energy systems is driving innovation in how and where we produce and utilize clean energy. Hydrogen, a zero-emission fuel, is at the center of these innovations and can be utilized across various hard-to-electrify industries. Hydrogen production is categorized on the basis of the energy source used, with greater attention being paid to renewable energy-based hydrogen, known as "green hydrogen." This situation has driven research, for example, into how to integrate offshore wind energy into hydrogen production to leverage the vast potential of offshore wind for producing green hydrogen. Offshore wind is particularly appealing because of its high-capacity factors and consistent speeds, offering a reliable and large-scale energy source for hydrogen production, especially in areas with limited land availability. Globally, this concept is gaining traction as countries seek to align their energy strategies with decarbonization goals and establish themselves as leaders in the emerging hydrogen economy.

Countries that have established offshore wind industries are naturally proactive in exploring the promise of this combination. The North Sea, in particular, is seeing a collaborative approach to the development of these two technologies and linking them to energy hubs in countries such as Germany, Scotland, England, Denmark, and Norway (Farahmand, Günther, and Kristiansen 2024). Energy hubs, which allow for the coordinated management and optimization of different energy carriers within a single integrated infrastructure, including local renewable energy for green hydrogen production, have become increasingly relevant in the context of offshore wind. These hubs can effectively integrate wind power generation into hydrogen production, energy storage, and potentially other renewable sources, such as wave or solar energy. By enabling the direct conversion of wind energy into hydrogen at sea, these hubs can facilitate more cost-effective offshore hydrogen production than can the alternative of building high-voltage direct current (HVDC) networks for onshore hydrogen production, particularly in remote locations (Glaum, Neumann, and Brown 2024).

The growth of offshore wind has been driven by supportive policies, such as the European Union's (EU's) Offshore Renewable Energy Strategy, which aims to expand capacity to 60 gigawatts (GW) by 2030 and 300 GW by 2050 (European Commission 2020). Owing to its high-capacity factors and potential for large-scale deployment, offshore wind is ideally suited to meet the growing demand for green hydrogen. The ongoing advancements in floating wind technology further expand the geographical scope of offshore wind, enabling its deployment in deeper waters, where fixed-bottom turbines are not feasible. This situation opens new opportunities for countries with large amounts of offshore wind resources in deeper waters. Floating offshore wind farms (FOWFs), though currently more expensive than fixed turbines, offer greater wind resource potential and are the focus of ongoing research to reduce costs (Kang, Gbadago, and Hwang 2024). There are positive interactions between fixed and floating offshore wind technologies, such as knowledge sharing and collaboration. But negative interactions, such as competition for resources, resistance from established

turbine manufacturers, and challenges in infrastructure and labor availability, have also been found (Havinga, van der Loos, and Steen 2024).

In the UK's latest Contracts-for-Difference (CfD) Allocation Round 6 (AR6), the strike price for offshore wind is set at £58.87/MWh (approximately $78/MWh), whereas floating offshore wind secures a higher strike price of £139.93/MWh (approximately $186/MWh) owing to the newer and less mature technology of the latter (DESNZ 2024). For the global offshore wind sector, auction design elements such as revenue stabilization mechanisms and strategic bidding behavior have successfully reduced costs and accelerated deployment. Jansen et al.'s (2022) review of historical auction bids reveals a trend of decreasing bid prices over time, driven by technological advancements, economies of scale, and increased competition. However, the analysis also emphasizes the challenges posed by strategic bidding and the risk of underbidding in highly competitive markets. In electricity markets, integrating hydrogen in offshore wind farms adds flexibility, reducing electricity imbalances and regulation costs because of the difficulty in accurately forecasting the amount of wind generation (Calado et al. 2024). Hydrogen offers significant opportunities for long- and short-term energy storage, enabling the integration of intermittent renewable energy sources into the grid without disrupting the market (Hill et al. 2024). However, while electrolyzers have the potential to provide flexibility services, their primary economic driver is solely hydrogen production (Lüth et al. 2024).

Yet, the integration of offshore wind and hydrogen production is not without its challenges. Although technical, environmental, and operational challenges exist, we focus primarily on economic challenges in this paper. The high costs associated with offshore wind infrastructure, electrolysis technology, and hydrogen transportation remain key barriers. These costs need to be carefully evaluated through technoeconomic assessment (TEA) to determine the viability of such projects. TEA provides a framework for assessing the economic and technical feasibility of integrating offshore wind into hydrogen production, considering factors such as capital and operational costs, potential revenue, and the impact of scale. This analysis is crucial for identifying the most cost-effective strategies, for guiding investments in this emerging sector and for determining the level of incentive support required to reduce hydrogen production costs.

This study aims to clarify the costs associated with offshore wind-to-hydrogen pathways, specifically in the context of Saudi Arabia. The economic analysis in this work compares the costs and efficiencies of producing hydrogen onshore via transmitted electrical power from offshore wind turbines with the alternative approach of producing hydrogen offshore and transporting it via pipelines. This study provides valuable insights into the technoeconomic aspects of offshore wind-to-hydrogen integration in the Red Sea region, highlighting the challenges of this technology, as Saudi Arabia aims to become a global leader in green hydrogen production. This work identifies the unique cost drivers for both onshore and offshore configurations and emphasizes the need for significant cost reductions to make these pathways competitive with alternative green hydrogen production methods. The various modes of hydrogen production with offshore wind power examined in this study are briefly described below.

The integration of offshore wind energy into hydrogen production can be achieved through the following two potential configurations, each with a distinct technological setup and infrastructure requirements: producing renewable energy offshore, converting it to hydrogen offshore, and then transporting hydrogen to shore, or producing renewable energy offshore, transmitting it to shore, and producing hydrogen onshore.

A. Centralized Onshore Electrolysis (Undersea Power Cables for Onshore Electrolysis)

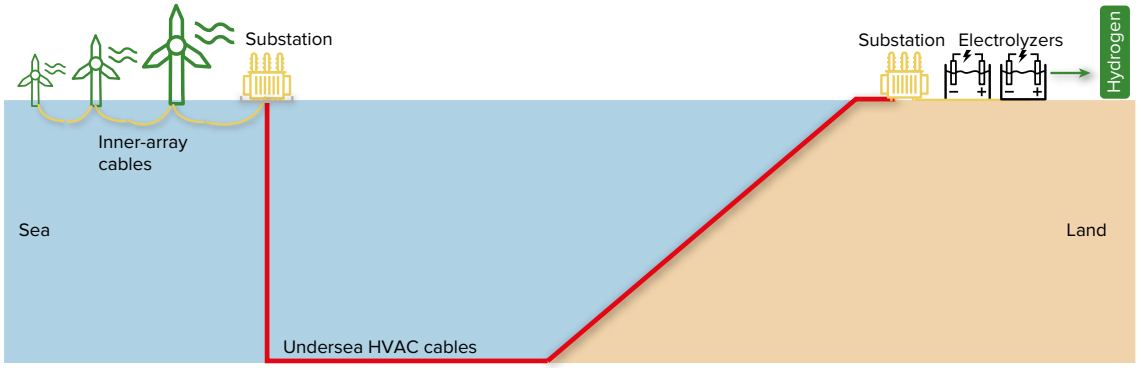
In this mode, the electricity generated by offshore wind farms is transported to onshore facilities, where hydrogen production takes place through electrolysis. This configuration typically involves the use of either high-voltage alternative current (HVAC) or HVDC undersea cables, depending on distance required. The onshore electrolysis production provides easier access to the desalinated water supply needed for the electrolysis process, as well as proximity to existing industrial and transport networks.

B. Centralized Offshore Electrolysis (Hydrogen Transported by Pipe or Ship)

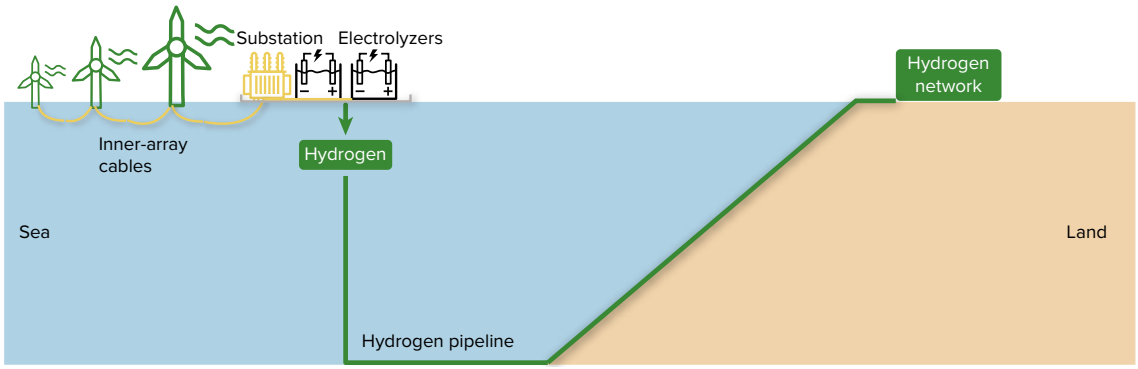
In this configuration, electrolysis occurs on a central offshore platform, where wind power is used to produce hydrogen via seawater. Platforms can accommodate systems ranging from 100 megawatts (MW) to 700 MWs (Venugopalan, Garcia Navarro, and Buijs 2024). The hydrogen produced is transported to shore via pipelines or specialized hydrogen carriers (ships). It is also possible for large-scale electrolysis to take place on artificial islands, accommodating multiple GW-scale hydrogen production units. These islands have the potential for both horizontal and vertical expansion to accommodate future increases in hydrogen demand.

In offshore hydrogen production, it is crucial to treat water properly because electrolyzers require very pure water to operate efficiently. Seawater, which contains high levels of salt and other impurities, cannot be used directly. Therefore, seawater must undergo a purification/desalination process. The purification process is crucial for preventing damage to equipment and maintaining efficiency during hydrogen production. Without this step, impurities in seawater can corrode the system or clog the components, resulting in expensive maintenance and reduced performance (Venugopalan, Garcia Navarro, and Buijs 2024).

Figure 1. Hydrogen integration with offshore wind farms.



(a) Centralized onshore electrolysis.



(b) Centralized offshore electrolysis.

Source: Authors.

Transporting offshore-produced hydrogen to shore can be accomplished via pipelines, most likely through newly built pipeline infrastructure; ship transport in various forms (compressed gas, liquid hydrogen, or hydrogen carriers such as ammonia) from centralized offshore electrolyzers; or the floating production, storage and offloading (FPSO[1]) concept. Each method comes with its own set of cost, infrastructure, and efficiency considerations.

2. Status of Offshore Hydrogen from Wind Power and Literature Review

2.1 Sample Global Projects

Offshore wind energy integration into hydrogen production is increasingly becoming a key strategic focus for many countries as part of their broader energy transition goals. Several countries are developing strategies to leverage offshore wind resources for large-scale hydrogen production. These strategies are often aligned with national decarbonization targets, energy security goals, and ambitions to become leaders in the emerging global hydrogen economy.

Germany is planning to integrate offshore wind power into hydrogen production as part of its National Hydrogen Strategy. The country aims to use its extensive offshore wind resources in the North and Baltic Seas to advance green hydrogen production. Germany is working on several pilot projects in the North Sea, including the AquaVentus initiative, which aims to produce 1 million tonnes (Mt) of green hydrogen from approximately 10 GW offshore wind power by 2035 (AquaVentus 2024). This initiative includes several projects, such as the AquaSector project, which plans to install a 300-MW electrolyzer capacity as a proof of concept. The AquaPrimus pilot project will focus on testing the integration of a 15-MW hydrogen wind turbine. Additionally, the AquaDuctus project will transport green hydrogen from offshore production sites to the mainland through a hydrogen pipeline. Helgoland, a small island in the North Sea, is set to become an energy hub within the AquaVentus initiative, serving as a central point for hydrogen production, storage, and distribution (RWE 2024).

The SEN-1 area in the German North Sea is set to be the first region tendered specifically for offshore hydrogen production. Within this area, 300 MW of electrolyzers will be installed to produce green hydrogen, which will then be transported to shore through the AquaDuctus pipeline. In its Baltic Sea areas, Rostock's port infrastructure will be upgraded to support hydrogen storage and distribution. The HyTech Hafen Rostock Project will utilize offshore wind power to produce green hydrogen. This hydrogen will be used in various applications, including port operations, industrial processes, and transportation (Rostock 2024).

The Netherlands is investing heavily in offshore wind energy with hydrogen as part of its strategy to transition to a low-carbon economy. The country aims to have

11.5 GW of offshore wind capacity by 2030, with plans for further expansion in the future. A significant portion of this capacity will be used for hydrogen production. The NorthH_2 project aims to develop 4 GW of electrolysis capacity by 2030, powered by offshore wind farms, with plans to expand to 10 GW by 2040. Initially, electrolyzers will be placed onshore at the Eemshaven port, with future targets to produce hydrogen at sea once the technology matures (NorthH_2 2024). The Netherlands was the first country to pilot offshore green hydrogen production through the PosHYdon project, which integrated the following three energy systems in the Dutch North Sea: offshore wind, offshore gas, and offshore hydrogen. Green hydrogen is mixed with gas and transported via an existing gas pipeline to the coast (PosHYdon 2024).

Near the port of Rotterdam, the Holland Hydrogen I project aims to connect 200-MW electrolyzers with offshore wind to serve the industrial areas in the port (Shell 2022). Another key project for large-scale offshore wind development is underway north of the Wadden Islands in the North Sea, with a 500-MW electrolysis capacity expected to be operational by 2031. The project will source energy from approximately 4 GW of offshore wind power and use an existing natural gas pipeline for hydrogen transport (Enerdata 2024).

The UK is actively pursuing several offshore wind-to-hydrogen projects as part of its broader strategy to achieve net-zero carbon emissions by 2050. These projects are designed to leverage the UK's substantial offshore wind resources to produce green hydrogen. This hydrogen can be used to decarbonize various sectors, including industry, transportation, and heating. On its east coast, the UK has five hydrogen production hubs, with a targeted hydrogen capacity of 11.6 GW by 2037, of which 5.2 GW are projected to be green hydrogen. This approach aims to leverage the region's concentrated industrial energy demand, significant gas storage and offshore wind power (East Coast Hydrogen 2023). The Barrow Green Hydrogen Hub is a planned project in Cumbria that seeks to produce green hydrogen from 35-MW electrolyzers using solar power and offshore wind power from the Irish Sea. The hydrogen produced will be used to decarbonize local industries (Barrow Green Hydrogen 2024). The Deepwater Offshore Local Production of Hydrogen (Dolphyn) project focuses on developing technology that allows hydrogen production from seawater to take place directly on floating offshore wind platforms. This technology is in the trial phase, with a target to commercialize it before 2030 (Dolphyn Hydrogen 2024). The Dolphyn project in the UK has reported that decentralized hydrogen production via floating offshore wind and PEMEL systems are the most cost-effective approaches, with a levelized cost of hydrogen (LCOH) of approximately £2/kg at 100 km offshore (Kang, Gbadago, and Hwang 2024).

ScotWind is a major offshore wind leasing round managed by Crown Estate Scotland, which has opened up vast areas of Scotland's seabed for offshore wind development. Some of these projects are exploring the integration of hydrogen production. A study by the Net Zero Technology Centre (NZTC) on the Hydrogen Backbone Link has highlighted potential complementarities between the ScotWind leasing sites and a potential hydrogen pipeline from Scotland to Europe to utilize approximately 10 GW of wind power (NZTC 2023).

Denmark, known for its leadership in wind energy, is now focusing on green hydrogen as a key part of its energy transition strategy. The country is working on ambitious projects to produce green hydrogen from offshore wind. One of these projects is the Energy Island North Sea, which aims to create the world's first artificial energy island. The island will serve as a hub for offshore wind farms and green hydrogen production, connecting up to 10 GW of offshore wind capacity. The generated power can either feed into the grid or be used for hydrogen or other power-to-X products (DEA 2024).

Similarly, on its Baltic Sea coast, the Bornholm Energy Island project aims to connect up to 3 GW of offshore wind capacity to the energy island. The project plans to produce green hydrogen for domestic use and export. The H2RES Project aims to establish a small-scale electrolysis facility powered by offshore wind turbines. The 2-MW demonstration project will use two 3.6-MW offshore wind turbines to power green hydrogen production (Ørsted 2021).

Sweden is planning to build the Neptunus Energy Hub in the southern Baltic Sea. This energy hub is set to feature up to 3.1 GW of offshore wind capacity, and a portion of this electricity will be used to produce up to 370 kilotons (kt) of green hydrogen per year through offshore electrolyzers.

Additionally, the Polargrund Energy Hub, situated in the northern Gulf of Bothnia, aims to have a capacity of 3-GW offshore wind and will include electrolyzers that can produce up to 200 kt of green hydrogen per year. These projects are important parts of Sweden's strategy

to expand its renewable energy infrastructure and reduce carbon emissions, with operations expected to begin by the early 2030s (Enerdata 2024). In Vietnam, the use of 2 GW of offshore wind for hydrogen production by 2035 has been proposed. This proposal is part of the country's broader energy transition strategy, which includes significant offshore wind development and the integration of green hydrogen production to support its 2050 net-zero emission target (Enerdata 2024).

2.2 Literature Review of Offshore Wind and Hydrogen Production

Recent studies have focused on evaluating the technoeconomic feasibility of integrating offshore wind energy with hydrogen production to increase energy sustainability and reduce curtailment issues. Offshore wind farms face significant challenges related to high installation costs and grid connection difficulties, particularly due to the higher capacitance in underwater AC cables. While HVDC systems can mitigate energy loss, they have higher installation costs than do other systems. This situation has prompted the exploration of innovative alternatives, such as producing hydrogen at sea and transporting it to land without direct electricity grid connections (Calado et al. 2024; Kang, Gbadago, and Hwang 2024). In fact, some studies have reported that offshore hydrogen production is more cost-effective than is the construction of HVDC networks for onshore hydrogen production, especially in remote locations and for large capacities (Glaum, Neumann, and Brown 2024; Ibrahim et al. 2022; Wang et al. 2024). Conversely, wind farms located close to shore are likely connected to onshore facilities via power cables (Lüth et al. 2023).

Compared with underwater electrical cables, the transportation of energy via underwater hydrogen pipelines is an appealing option because of lower energy losses, lower costs, and improved scalability (Calado et al. 2024). This approach allows offshore wind farms to bypass grid connections entirely, increasing their feasibility and efficiency when combined with onsite hydrogen production in areas with high wind power density (Bonacina, Bordbar Gaskare, and Valenti 2022; Giampieri, Ling-Chin, and Roskilly 2024).

Promising developments in the offshore wind-to-hydrogen sector involve the use of ammonia as a renewable hydrogen carrier for long-distance interoceanic transport. Studies have suggested that the transportation costs of ammonia are lower than are the expenses associated with hydrogen conversion, storage, and reconversion. While liquid hydrogen is also considered promising because of its lower cost and greater flexibility in delivery, it faces significant energy loss during storage and transport (Díaz-Motta, Díaz-González, and Villa-Arrieta 2023; Bonacina, Bordbar Gaskare, and Valenti 2022). Ammonia, with its relatively high volumetric energy density and existing global infrastructure for storage and transport, is gaining attention as a critical component in the emerging hydrogen and green hydrogen economy (Díaz-Motta, Díaz-González, and Villa-Arriet 2023; Perez-Vigueras et al. 2023).

Proton exchange membrane (PEM) electrolyzers are well suited for offshore wind integration because of their high efficiency, rapid response to variable loads, and ability to adapt to the intermittency of wind power. Compared with other electrolysis technologies, the superior performance of PEM electrolyzers makes them ideal for offshore hydrogen production (Farahmand, Günther, and Kristiansen 2024; Guven 2024; Akdağ 2023; Luo et al. 2022). To produce hydrogen at sea, electrolyzers require high-purity water, which is typically obtained through reverse osmosis or other water treatment processes to ensure the necessary quality (Komorowska, Benalcazar, and Kamiński 2023). Desalination coupled with seawater electrolysis is feasible but requires significant technological advancements (Ramakrishnan et al. 2024).

The integration of hydrogen production into offshore wind shows promise, but several challenges need to be addressed. Farahmand, Günther, and Kristiansen (2024); Komorowska, Benalcazar, and Kamiński (2023) have highlighted the need for substantial investments in infrastructure, such as pipelines and storage facilities, to manage the produced hydrogen. Additionally, the above authors have noted that regulatory frameworks and market mechanisms need to evolve to support the large-scale deployment of these systems. Distributed hydrogen production, which eliminates the need for centralized onshore facilities, has been demonstrated to be more cost-effective than other types of hydrogen production, especially in marine environments (Kang, Gbadago, and Hwang 2024).

In recent studies, Bonacina, Bordbar Gaskare, and Valenti (2022) and Díaz-Motta, Díaz-González, and Villa-Arriet

(2023) have investigated the environmental sustainability of producing hydrogen via offshore wind. Both studies have concluded that offshore wind-powered hydrogen production has a lower environmental impact than conventional hydrogen production. Despite its significant potential and low environmental impact, the offshore wind sector faces high installation costs and the challenges of operating under harsh environmental conditions (Rezaei, Akimov, and Gray 2024). Some research on electrolysis has emphasized the use of surplus renewable energy. This approach increases production costs because both hydrogen and electricity need to be exported. Recent studies have suggested that relying solely on excess wind energy is not economically viable. Instead, dedicated offshore wind farms for hydrogen production should be prioritized (Hill et al. 2024; Bonacina, Bordbar Gaskare, and Valenti 2022).

The uncertainty in cost assumptions presents a significant challenge for offshore wind-hydrogen systems. The LCOH is highly sensitive to the electricity costs associated with offshore wind farms (Bødal et al. 2024). Existing technoeconomic studies have often lacked clarity in terms of hydrogen production costs. Additionally, electrolyzer efficiency is sensitive to fluctuations in input power, necessitating dynamic models to accurately estimate hydrogen production costs (Rezaei, Akimov, and Gray 2024; Hill et al. 2024). This ambiguity emphasizes the need for more detailed and transparent analyses to assess the financial feasibility of offshore wind-hydrogen systems.

2.3 LCOH from Offshore Wind

The TEA of hydrogen production from offshore wind energy is an important area of focus in current research. A consistent theme across several studies is the evaluation of the LCOH under different scenarios and timelines. Studies such as that of Groenemans et al. (2022) have demonstrated that directly coupling PEM electrolysis (PEMEL) systems with offshore wind turbines can potentially lower the LCOH to $2.09/kg via pipelines, compared with $3.86/kg from traditional electrolysis using transmitted electricity, assuming an accelerated price reduction in the main components. Similarly, Giampieri, Ling-Chin, and Roskilly (2024) have conducted a detailed case study on the UK, using simulation models to analyze the costs and technical requirements of hydrogen production, storage, and transportation in various offshore wind-to-hydrogen scenarios, revealing that compressed hydrogen, which is produced offshore and transported via pipelines, is the most cost-effective scenario, potentially lowering the LCOH from 6.6 $/kg at present to approximately $2.9/kg by 2050.

Kang, Gbadago, and Hwang (2024) have examined the feasibility of hydrogen production by FOWFs off the Korean Peninsula highlighting that liquid hydrogen production becomes more cost-effective at scales up to 250 MW, with the LCOH holding at approximately 11 $/kg. The above study has suggested that specific regional conditions and synergies can further enhance the economic viability of offshore wind-to-hydrogen systems. Bonacina, Bordbar Gaskare, and Valenti (2022) have explored the viability of creating offshore liquefied hydrogen production plants powered by wind energy for the purpose of refueling ships, aiming to reduce carbon emissions in the naval sector. The above study employs an analytical model combined with an economic prefeasibility analysis and uses MATLAB simulations to assess the performance and economic metrics of different plant configurations, with a focus on the optimal sizing of wind farms and hydrogen production capacity. The above study has revealed that the LCOH can be below $4.37/kg for a wide range of plant capacities, suggesting that offshore liquefied hydrogen production plants are economically feasible.

Rezaei, Akimov, and Gray (2024) have modeled the cost and efficiency of hydrogen production from offshore wind power in Australia via a dynamic system that accounts for real-world factors such as economies of scale, learning by doing, and the variable nature of wind power input. The study has revealed that the LCOH can be reduced to approximately $2.6/kg in the “fast progress” scenario by 2040, given a rapid scale-up and lower financial costs. The study assumes that PEM technology will continue to dominate hydrogen production from offshore wind. Moreover, Cheng and Hughes (2023) have explored the role of offshore wind in Australia’s renewable hydrogen production via a least-cost optimization model to simulate energy flows and optimize the capacities of offshore wind, solar photovoltaics (PV), battery storage, and electrolyzers. The study has revealed that a hybrid renewable energy system can reduce hydrogen production costs to $2.96-$3.71/kg by 2030.

Hill et al. (2024) have developed a technoeconomic model that incorporates Monte Carlo simulations to account for uncertainties to determine the cost competitiveness of hydrogen produced from offshore wind power and

compared different electrolysis technologies. The results indicate that hydrogen produced through alkaline electrolysis (AEL) is the most cost-effective type of hydrogen, with an LCOH of €7.66/kg in the base case, which is potentially lower under optimized scenarios. In contrast to other studies that prefer PEMEL over AEL, the above paper argues that the modular nature of operating 98 AEL stacks allows the system to adapt to intermittent generation. The weighted average cost of capital (WACC) has a strong influence on the LCOH in all the scenarios. Rogeau et al. (2023) have conducted a resource assessment across Europe, employing a detailed cost modeling approach combined with geospatial analysis. The study estimates that more than 1000 terawatt hours (TWh) of green hydrogen could be produced at a price below $3.3/kg by 2030, making it competitive with gray hydrogen. The above study has highlighted the potential of decentralized offshore electrolysis configurations in maximizing the use of Europe's extensive offshore wind resources.

Lucas et al. (2022) have analyzed the feasibility of producing hydrogen via electricity generated from the WindFloat Atlantic offshore wind farm in Portugal. The study considers PEM electrolyzer systems and evaluates the costs and benefits of hydrogen production under different electricity price conditions. Hydrogen production from offshore wind energy can become profitable at $4.40/kg LCOH with larger wind farm capacities and when hydrogen is produced during periods of low electricity prices. Calado et al. (2024) have assessed the technoeconomic viability of hydrogen production associated with offshore wind farms, taking the Iberian Peninsula as a case study. The study involves the modeling and simulation of the following two hydrogen production systems: one with an offshore electrolyzer and another with an onshore electrolyzer. The onshore electrolyzer system is more economically viable than is the offshore system, mainly because of its ability to purchase electricity from the grid, resulting in a lower LCOH. The LCOH for the onshore system decreases significantly from 2020 to 2030 and then to 2050 as follows: €5.84/kg ($6.15/kg), €3.42/kg ($3.60/kg), and €2.57/kg ($2.71/kg). In the offshore electrolyzer case, the LCOH is €8.98/kg ($9.47/kg), €4.37/kg ($4.61/kg), and €2.68/kg ($2.83/kg).

Guven's (2024) study employs life cycle assessment (LCA) via GREET to assess the environmental impact and economic feasibility of producing green hydrogen via offshore wind power. The paper concludes that while offshore wind-driven green hydrogen production has significant environmental benefits, achieving economic viability requires targeted incentives. The LCOH is estimated at $4.36/kg under the base scenario, which is not profitable under the current corporate tax rate. Akdağ (2023) has focused on the operation of green hydrogen production via offshore wind in Turkey, highlighting the importance of infrastructure investments and supportive policies. The study estimates that the cost per kg of hydrogen could drop from €6.26/kg ($6.60/kg) in 2023 to €1.13/kg ($1.19/kg) by 2050. The analysis also shows that despite initial high costs, green hydrogen can become a viable alternative for fueling stations and the transportation sector with proper policy support and technological advancements.

Farahmand, Günther, and Kristiansen (2024) have explored the potential benefit of hydrogen in terms of the offshore wind utilization rate in the North Sea. The study uses a deterministic optimization model (PowerGIM) to assess the optimal transmission expansion plan and generation expansion plan for the North Sea Offshore Grid, including the integration of a PEM electrolyzer for hydrogen production. Their study finds that coupling hydrogen with offshore wind can reduce wind curtailment and drive the LCOH to €1.4/kg ($1.47/kg) by 2040 when electrolyzer demand is optimized in a market context. Komorowska, Benalcazar, and Kamiński (2023) have focused on assessing the competitiveness and uncertainty of offshore wind-to-hydrogen production systems in Poland and used a Monte-Carlo-based framework to analyze location-based variability and long-term planning uncertainties. By analyzing 23 planned offshore wind farm locations in Poland, the LCOH for offshore wind-to-hydrogen is estimated to be between €3.60 ($3.79/kg) and €3.71/kg ($3.90/kg) in 2030 and between €2.05 ($2.16/kg) and €2.15/kg ($2.26/kg) in 2050. The study finds that electricity prices and electrolyzer utilization rates are the main cost drivers of the LCOH.

Díaz-Motta, Díaz-González, and Villa-Arriet (2023) have evaluated the long-term sustainability and competitiveness of producing renewable ammonia via offshore wind energy, focusing on the production process, technological advancements, and potential cost reductions in the coming decades. The analysis finds that the high production costs of offshore wind-powered ammonia (ranging from $600 to $1,500/t NH_3) currently pose a barrier to its deployment.

The LCOH is highly sensitive to several region-specific factors, such as natural resources, the cost of electricity,

infrastructure, and technological advancements. For Saudi Arabia, understanding the real economics of producing hydrogen from offshore wind is essential for assessing the feasibility of this option as a viable green hydrogen source. Moreover, benchmarking its competitiveness against international figures is important given Saudi Arabia's ambition to become a leader in the energy transition.

As summarized in Table 1, no previous technoeconomic study has specifically assessed the integration of offshore wind into hydrogen production in Saudi Arabia. This study aims to fill this gap by developing a transparent deterministic cost model for the LCOH, focused on the natural resources of Saudi Arabia. Through a detailed case study of a selected wind farm location in the Red Sea, this research will evaluate the cost-effectiveness and efficiency of onshore versus offshore hydrogen electrolysis. By identifying specific cost drivers, this study will inform policymakers and industry stakeholders in focusing on targeted innovations, realistic timelines, and research and development (R&D) investments that have the greatest potential to lower costs.

Table 1. Comparison of offshore wind-based hydrogen production studies.

Reference	Location	Objective	Methodology	Components assessed	Results
Farahmand, Günther, and Kristiansen (2024)	North Sea, Europe	This paper assesses the business case for integrating offshore wind with green hydrogen production in the North Sea while considering the future development of an integrated offshore grid.	This study uses a deterministic optimization model (PowerGIM) to optimize the North Sea offshore grid's expansion plans, integrating a PEM electrolyzer for hydrogen production. The analysis is based on the TYNDP 2020 Global Ambition scenario for 2040.	Fixed wind turbines, PEM electrolyzers, the direct coupling of wind and electrolysis, and the hydrogen pipeline.	Combining a 5-GW PEM electrolyzer with offshore wind farms reduces wind curtailment and boosts electricity market revenue. This study suggests that the LCOH could drop to €1.4/kg H_2, with power costs as the main factor. Sensitivity analysis shows the LCOH ranging between €1.2 and €1.6/kg of hydrogen in 2030 based on electrolyzer CAPEX, lifetime, and efficiency variations.
Calado et al. (2024)	Iberian Peninsula	This study assesses the feasibility and economic potential of integrating hydrogen production with offshore wind farms in the Iberian Peninsula.	This study involves the modeling and simulation of the following two hydrogen production systems: one with an offshore electrolyzer and another with an onshore electrolyzer. An hourly optimization algorithm and neural network forecasts are used to assess day-ahead power production and electricity prices.	Floating wind turbines, HVAC cables, offshore central platform, PEM electrolyzer, desalination unit, compressor, hydrogen pipeline, hydrogen storage, fuel cell, and transmission cables.	The onshore electrolyzer system is more economically viable than is the offshore system due to its ability to purchase electricity from the grid, resulting in a lower LCOH. The LCOH for the onshore system decreases significantly from 2020 to 2030 and then to 2050: €5.84/kg, €3.42/kg, and €2.57/kg. While the offshore electrolyzer case LCOH is €8.98/kg, €4.37/kg, and €2.68/kg.

(*Continued*)

Reference	Location	Objective	Methodology	Components assessed	Results
Bonacina, Bordbar Gaskare, and Valenti (2022)	Mediterranean Sea, Italy	To explore the viability of creating offshore liquefied hydrogen production plants powered by wind energy for the purpose of refueling ships, this work aims to reduce carbon emissions in the naval sector.	This study employs an analytical model combined with an economic prefeasibility analysis. MATLAB simulations are used to assess the performance and economic metrics of different plant configurations, focusing on the optimal sizing of wind farms and hydrogen production capacities.	Fixed wind turbines, floating wind turbines, desalination unit, electrolyzer, liquification plant, hydrogen storage, and ship transport.	The study finds that the LCOH can be below €4/kg for a wide range of plant capacities, and the optimal electrolyzer capacity is between 80% and 90% of the wind farm capacity. The payback time can be reduced to below 11 years if the wind farm capacity is more than 150 MW.
Díaz- Motta, Díaz-González, and Villa-Arrieta (2023)	–	To evaluate the long-term sustainability and competitiveness of producing renewable ammonia using offshore wind energy, this study focuses on the production process, technological advancements, and potential cost reductions in the coming decades.	This study conducts a literature review and quantitative analysis, comparing the production costs, energy consumption, efficiency, and CO_2 emissions of offshore wind-powered ammonia with fossil-based (steam methane reforming) and low-emission ammonia (SMR-carbon capture and storage).	Fixed wind turbines, floating wind turbines, desalination unit, electrolyzer, air separation unit, and ammonia synthesis.	The analysis finds that the high production costs of offshore wind-powered ammonia (ranging from \$600 to \$1,500/t NH_3) currently pose a barrier to its deployment. However, improvements in solid oxide electrolysis (SOEL) technology and reductions in CAPEX could make it competitive in the future.
Komorowska, Benalcazar, and Kamiński (2023)	Baltic Sea, Poland	This work aims to evaluate the competitiveness of green hydrogen production from offshore wind farms in Poland by analyzing the LCOH and exploring uncertainties in the planning and development of these systems.	The study uses a Monte-Carlo-based framework to assess the LCOH for offshore wind-to-hydrogen systems, considering 23 planned offshore wind farm locations in the Baltic Sea. The analysis includes a comparison with onshore wind-to-hydrogen systems for 2030 and 2050.	Fixed wind turbines, PEM electrolyzer, transmission cables, and water prices.	The LCOH for offshore wind-to-hydrogen in Poland is estimated to be between €3.60 and €3.71/kg in 2030 and between €2.05 and €2.15/kg in 2050. This study finds that electricity prices and electrolyzer utilization rates are the main cost drivers for the LCOH.

(*Continued*)

Reference	Location	Objective	Methodology	Components assessed	Results
Lucas et al. (2022)	Atlantic Ocean, Portugal	This study aims to assess the feasibility and economic viability of producing hydrogen from offshore wind energy, specifically using the WindFloat Atlantic offshore wind farm as a case study. This study also evaluates different scenarios for hydrogen production and potential profits from oxygen sales.	The study adopts a technoeconomic analysis, considering the following two scenarios: one with the current 25.2-MW capacity of the WindFloat Atlantic wind farm and another with a future expanded capacity of 150 MW. The study considers PEM electrolyzer systems and evaluates the costs and benefits of hydrogen production under different electricity price conditions.	Floating wind turbines, PEM electrolyzer, water treatment, compressor, hydrogen storage, HVAC cables, and substation.	The study finds that hydrogen production is more economically viable in the long-term scenario with a 150-MW wind farm capacity than in the other scenario. The lowest hydrogen production costs are achieved when hydrogen is produced during both night and afternoon periods, with the potential for profitable operations depending on electricity prices and the inclusion of oxygen sales.
Guven (2024)	Aegean Sea, Turkey	This work assesses the environmental impact and economic feasibility of producing green hydrogen using offshore wind power, with a focus on minimizing greenhouse gas emissions and optimizing the cost-effectiveness of the technology.	This study employs LCA using GREET 2023 and life cycle cost analysis (LCCA) under various economic scenarios, including STEPS, APS, and NZE, to evaluate the environmental and financial performance of the green hydrogen production system. Global climate models (GCMs) are used to predict wind speeds for system sizing.	Fixed wind turbines, PEM electrolyzer, hydrogen storage, transmission cables, and substation.	The global warming potential (GWP) of the system is 0.7 $kgCO_2$-eq./kgH_2 for a 20-year horizon and 0.753 $kgCO_2$-eq./kgH_2 for a 100-year horizon. The LCOH is estimated at \$4.36/kgH_2 under the base scenario. This study finds that the system is not profitable under the current corporate tax rate without incentives, with internal rates of return (IRRs) below the expected cost of equity.

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Reference	Location	Objective	Methodology	Components assessed	Results
Hill et al. (2024)	Offshore, UK	This study aims to determine the cost competitiveness of hydrogen produced from offshore wind power, comparing different electrolysis technologies (alkaline and PEM) and considering the impact of integrating grid electricity and salt-cavern storage for hydrogen production. This study aims to inform strategies for lowering the LCOH to compete with conventional hydrogen production methods.	The study develops a technoeconomic model, incorporating Monte Carlo simulations to account for uncertainties, and evaluates the following three scenarios: AEL, PEMEL, and a grid electricity-backed AEL system. The model considers CAPEX, OPEX, and hydrogen production efficiency under each scenario, alongside sensitivity analyses to identify key cost drivers.	Fixed wind turbines, substations, PEM and AEL electrolyzers, desalination unit, compressor, hydrogen pipe, hydrogen storage, offshore central platform, and transmission cables.	The results indicate that the AEL-driven cost of hydrogen production (€8.38/kgH_2) is only three times that of SMR + CCS-generated hydrogen. PEMEL-driven hydrogen production has a higher cost (€10.49/kgH_2). This study identifies the WACC, wind farm CAPEX, and electrolyzer efficiency as the most significant cost drivers.
Akdağ (2023)	Aegean Sea, Turkey	This study presents a comprehensive model for the installation and operation of a green hydrogen production facility powered by offshore wind and to evaluate its economic viability, particularly in the context of supplying hydrogen fuel stations in Turkey. This study also aims to identify the challenges and potential solutions for the widespread adoption of green hydrogen technology in the transportation sector.	The study uses a technoeconomic analysis approach, incorporating data on wind potential, desalination, and electrolysis technology. This work includes a case study for the Edirne-Enez location in Turkey, where the offshore wind potential and water availability are analyzed to determine the feasibility of setting up a green hydrogen production facility. The analysis also covers the cost of hydrogen production and the associated infrastructure, including storage and transportation to hydrogen fuel stations.	Fixed wind turbines, PEM electrolyzer, hydrogen storage, and truck hydrogen transport.	The results indicate that the cost of producing green hydrogen through offshore wind could decrease significantly by 2050, making it competitive with other forms of hydrogen. This study estimates that the cost per kilogram of hydrogen could drop from €6.26/kg in 2023 to €1.13/kg by 2050. The analysis also shows that despite initial high costs, green hydrogen can become a viable alternative for fueling stations and the transportation sector with proper policy support and technological advancements.

(*Continued*)

Reference	Location	Objective	Methodology	Components assessed	Results
Cheng and Hughes (2023)	Offshore, Australia	This work investigates the role of offshore wind in a hybrid renewable energy system for hydrogen production in Australia, particularly focusing on cost optimization and the integration of offshore wind into other renewable energy sources like solar PV.	The study uses a least-cost optimization model to simulate energy flows and optimize the capacities of offshore wind, solar PV, battery storage, and electrolyzers over a 10-year period. The model evaluates different scenarios, including varying levels of solar PV contribution and cost reductions.	Fixed wind turbines, solar PV, pumped hydrostorage, battery storage, PEM electrolyzer, and HVDC cables.	This study finds that offshore wind plays a significant role in hydrogen production, especially in regions with strong wind resources. The cost of hydrogen can be competitive with solar PV-dominated systems under certain conditions. However, achieving a low-cost hydrogen production system requires further reductions in the costs of offshore wind and electrolyzers.
Giampieri, Ling-Chin, and Roskilly (2024)	North Sea, UK	This study analyzes the economic feasibility of different offshore wind-to-hydrogen production scenarios in the UK, focusing on the LCOH for compressed, liquefied, and chemically bonded hydrogen, and to provide insights into the most cost-effective strategies for future projects.	This study employs a TEA approach, using simulation models to analyze the costs and technical requirements of hydrogen production, storage, and transportation scenarios. Data for capital and operating costs are collected, and scenarios are developed to estimate the LCOH under various conditions.	Fixed wind turbines, substations, PEM electrolyzer, desalination unit, liquification unit, ammonia synthesis, compressor, hydrogen pipe, hydrogen storage, liquid ship tanker, and HVDC cables.	This study finds that compressed hydrogen produced offshore and transported via pipeline is the most cost-effective scenario for projects starting in 2025, with the LCOH potentially reaching £2/kg of hydrogen or lower by 2050. The economic feasibility of each scenario varies significantly based on storage periods and distances to shore.

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Reference	Location	Objective	Methodology	Components assessed	Results
Rogeau et al. (2023)	Offshore, Europe	This work aims to develop a unified cost model that incorporates various configurations (onshore, centralized offshore, and decentralized offshore electrolysis) and to perform a resource assessment at the European scale. This study aims to identify the most economically attractive sites for hydrogen production from offshore wind by 2050.	This study employs a detailed cost modeling approach combined with geospatial analysis to assess the LCOH across different sites in Europe. The analysis includes onshore and offshore electrolysis configurations and considers future projections of turbine and electrolyzer costs.	Fixed wind turbines, PEM electrolyzer, desalination unit, offshore central platform, turbine integrated electrolysis, hydrogen pipe, HVDC cables, and substations.	This study finds that the LCOH could fall from €4.50-€7.50/kg in 2020 to €1.50-€3.00/kg in 2020 to 1.5–3.0 €/kg by 2050 as costs decrease. More than 1,000 TWh of green hydrogen could be produced at a price below €3.0/kg by 2030, making it competitive with gray hydrogen. Offshore electrolysis becomes increasingly relevant closer to shore over time.
Rezaei, Akimov, and Gray (2024)	Offshore, Australia	This study models the cost and efficiency of hydrogen production from offshore wind power using a dynamic system that accounts for real-world factors such as economies of scale, learning by doing, and the variable nature of wind power input. This study aims to determine the LCOH under different scenarios.	This study uses a detailed technoeconomic model that incorporates dynamic electrolyzer efficiency, air density-adjusted wind speeds, and plant-level losses to simulate hydrogen production. The model is applied to various offshore wind sites in Australia to assess the feasibility of achieving a competitive LCOH by 2040.	Fixed wind turbines, PEM electrolyzer, central offshore platform, compressor, and hydrogen storage.	This study finds that the LCOH can be reduced to below AU$3/kg (US$2/kg) in the “fast progress” scenario by 2040, given a rapid scale-up and lower financial costs. Dynamic efficiency and well-planned energy management strategies are crucial in achieving cost-competitive hydrogen production.

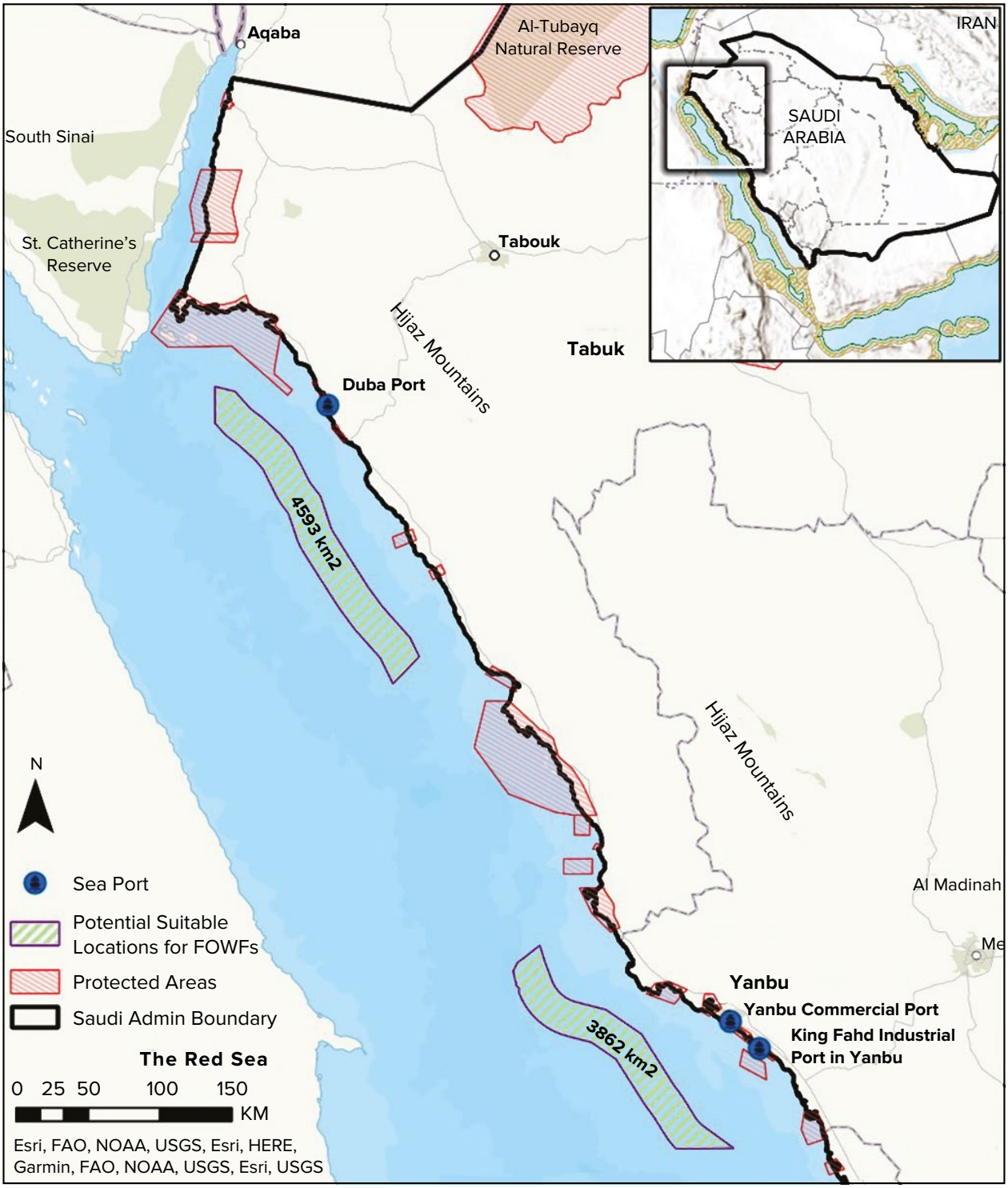
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Reference	Location	Objective	Methodology	Components assessed	Results
Kang, Gbadago, and Hwang (2024)	Offshore, Republic of Korea	This work aims to determine the LCOH for both gaseous and liquid hydrogen produced using floating offshore wind turbines and to assess the economic viability of different transportation methods for hydrogen in Korea.	The study uses Aspen Plus and Custom Modeler to model PEMEL and hydrogen liquefaction processes, includes a sensitivity analysis of transportation methods and costs, and considers real-time wind data for modeling power generation.	Floating wind turbines, PEM electrolyzer, water treatment, compressor, hydrogen pipe, liquification unit, and truck H_2 transport.	This study finds that liquid hydrogen is more cost-effective at scales up to 250 MW, with an LCOH of $11.04/kg H_2. However, gaseous hydrogen becomes less expensive as production scales exceed 500 MW due to its greater sensitivity to production volume.
Groenemans et al. (2022)	Atlantic Ocean, U.S.	This study evaluates the economic viability and efficiency of producing hydrogen directly at offshore wind sites using PEMEL, comparing it to traditional methods where electricity is transmitted to shore for hydrogen production.	This study uses a TEA approach, modeling the hydrogen production process using real wind data and comparing costs across methods. The assumptions include a 14-MW GE turbine and a pipeline length of 60 km.	Fixed wind turbines, transmission cables, and PEM electrolyzer.	The results show that the LCOH from direct offshore wind electrolysis could be as low as $2.09/kg H_2, compared to $3.86/kg H_2 from traditional electrolysis using transmitted electricity.
This work	Red Sea, Saudi Arabia	This work aims to evaluate the LCOH of green hydrogen production from offshore wind in Saudi Arabia, with a focus on assessing the feasibility of this option as a viable green hydrogen source.	This study uses a deterministic technoeconomic assessment of green hydrogen production from offshore wind in Saudi Arabia, comparing centralized onshore and offshore electrolysis approaches. This study analyzes the LCOH for both scenarios, identifies the key cost drivers, and assesses the competitiveness of each approach for large-scale hydrogen production.	Floating wind turbines, substations, PEM electrolyzer, desalination unit, compressor, hydrogen pipe, offshore central platform, and HVAC cables.	This study aims to provide a transparent deterministic cost model for the LCOH from floating offshore wind power in the context of Saudi Arabia.

3. Technoeconomic Assessment of Hydrogen Production from Offshore Wind in Saudi Arabia

In this study, the following two cases will be compared: onshore electrolysis and centralized offshore electrolysis. Decentralized hydrogen production will be discussed qualitatively. The analysis will begin with the selection of a suitable offshore wind farm location. Locating offshore wind farms is based on a prior study, and turbines will be located 35-km offshore at water depths of approximately 720 m, opposite Duba port in the Red Sea. The wind farm's capacity will be set to 1,000 MW, chosen to represent a GW-scale project, which is reasonable for offshore wind development and provides a reference point for scaling costs up or down for various project sizes. The capital expenditure (CAPEX) estimates will be derived from BVG Associates' guidelines for FOWF costs (BVGA 2023). While the cost estimates and projections from BVGA will provide a valuable reference for understanding the potential cost structure of floating offshore wind, these figures are based primarily on conditions and markets in Europe, where floating wind technology and supply chains are more mature. In the context of Saudi Arabia, unique local factors, such as site-specific conditions, infrastructure readiness, and supply chain maturity, may lead to cost variances. Nonetheless, BVGA's guidelines will offer a solid foundation for the technical assumption and provide insights into how costs may evolve as the industry matures globally, which can inform preliminary assessments for Saudi offshore wind projects. CAPEX encompasses development and project management, wind turbines, the balance of plants, and installation costs.

Figure 2. Potential areas for floating offshore wind project development.



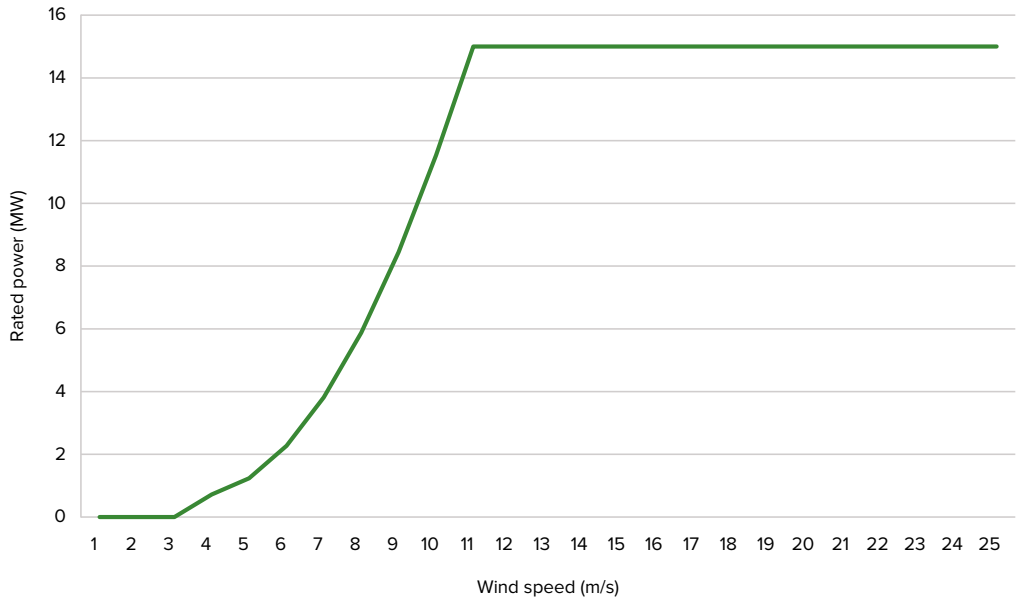
Source: Albalawi et al. 2024.

3.1 Hydrogen Production from Onshore Electrolysis

In the case of transmitting generated electricity to shore, HVAC transmission is assumed because of the relatively short distance involved. Offshore and onshore substations are employed to optimize power conversion and ensure efficient transmission. Our model shows that the CAPEX of the wind farm, including the export cables for the onshore electrolysis case, is $4,993/kW. Additionally, the operation and maintenance (O&M) costs are assumed to be 2% of the total CAPEX per year. Decommission costs are estimated at 4% of CAPEX (BVGA 2023).

To estimate the wind farm's annual energy production, we start by calculating the capacity factor (CF). This is done via a methodology similar to that outlined in Chandler and Whitlock (2005), which involves analyzing hourly wind speed data against the turbine power curve. Wind speed data are obtained from NASA's power tool for the period from 2021 to 2023. We choose a three-year average to account for annual and seasonal variations in wind speed. The wind speed data are then adjusted to a hub height of 136 m, which corresponds to the NREL annual technology baseline turbine used in our analysis (NREL 2021). Wind speed is adjusted via Gipe's power law, and a surface roughness exponent of 0.1 is used for open water (Gipe 1999). Next, we employ the specified power curve of the 15-MW NREL model turbine to correlate the adjusted wind speeds with the estimated power output.

Figure 3. NREL ATB reference 15-MW turbine power curve.



Source: NREL 2021.

The CF is then calculated by dividing the total annual estimated power output by the theoretical maximum energy that can be produced, which is the product of the turbine's rated capacity and the total number of hours in a year:

$$Capacity\ factor = \frac{Energy\ production}{Wind\ farm\ capacity * \ Hours\ per\ year}$$

Our analysis yields a CF of 38.51%. Table 1 outlines the specific characteristics of the wind farm.

Using the above inputs, we calculate the levelized cost of electricity (LCOE) for the wind farm over the project life cycle using a discount rate (r) of 5% as follows:

$$LCOE = \frac{\sum \frac{CapEx + OpEx + Decommissionning}{(1+r)^t}}{\sum \frac{Energy\ production}{(1+r)^t}}$$

Equation 1

The resulting LCOE for the 1,000-MW offshore wind farm is calculated to be approximately 1$124.19/MWh, including the export cables used to transmit the power to shore.

To estimate the LCOH, the characteristics of the PEM electrolyzers are assumed, as shown in Table 2.

Table 2. Characteristics of the offshore wind farm.

Characteristics	Value	Reference
Site latitude	27.49	Selected site
Site longitude	35.05	Selected site
Distance from shore (km)	35	Selected site
Water depth (m)	720	Selected site
Wind farm capacity (MW)	1000	Assumed
Turbine rated power (MW)	15	NREL 2021
Turbine rotor diameter (m)	240	NREL 2021
Inter-array cable length (m)	100,500	Hill et al. 2024
Annual average wind speed at hub height (m/s)	7.04	NASA 2024
CF (%)	38.51	Model result
Discount rate (%)	5	Assumed
CAPEX ($/kW)	4,993.39	Total CAPEX
Development and project management ($/kW)	191.45	BVGA 2023
Wind turbine ($/kW)	1,755.4	BVGA 2023; DNV 2023
Balance of plant ($/kW)	2,884.29	BVGA 2023; DNV 2023
OPEX (% of CAPEX)	2	BVGA 2023; DNV 2023
Project life (years)	30	NREL 2021
Decommissioning (% of CAPEX)	4	BVGA 2023

Table 3. Characteristics of the PEM onshore electrolyzers.

Characteristics	Value	Reference
Capacity of stack (MW)	20	Alhadhrami et al. 2024
Number of electrolyzer stacks	27	Model result
CAPEX ($/kW)	1450	Alhadhrami et al. 2024
OPEX (% of CAPEX)	2.5	Alhadhrami et al. 2024
Water consumption (L/kg)	9	Alhadhrami et al. 2024
Efficiency (%)	80	Alhadhrami et al. 2024
Energy input for 1 kg of hydrogen produced (kWh/kg)	50	Model result
Discount rate (%)	5	Assumed

The LCOH is a key metric used to determine the cost-effectiveness of hydrogen production over the lifetime of a project and is calculated via the following formula:

$$LCOH = \frac{\sum \frac{CapEx + OpEx + Decommissionning}{(1+r)^t}}{\sum \frac{Hydrogen\ production}{(1+r)^t}}$$

Equation 2

Here, CAPEX includes the initial investment in wind turbines, electrolysis systems, desalination units, platforms, and pipelines (as applicable). Operational expenditure (OPEX) covers ongoing maintenance, operational costs, energy input for electrolysis, and any other recurring expenses.

After performing the cost analysis over the expected project lifetime, the LCOH is found to be $6.47/kg, reflecting the weak cost-effectiveness of producing hydrogen via offshore wind under the given assumption. To put this finding into perspective, a previous KAPSARC analysis showed that the LCOH using solar PV power is approximately $3/kg (Alhadhrami et al. 2024). Clearly, a significant reduction in the cost of FOWF technology is needed before it can be competitive with onshore renewable energy.

Onshore electrolysis using offshore wind energy benefits from established onshore infrastructure and reduces the need for complex offshore platforms and equipment, making its O&M easier. However, despite these advantages, the LCOH for onshore electrolysis using FOWFs is notably greater than is that for onshore electrolysis using solar PV. Currently, the LCOH for offshore floating-wind-based hydrogen production is significantly higher than is that of solar PV-based systems in Saudi Arabia. This significant cost disparity presents a challenge for the economic competitiveness of hydrogen production from offshore wind in the current market.

3.2 Hydrogen Production from Central Offshore Electrolysis

Central offshore hydrogen production presents a compelling approach to harnessing offshore wind energy by centralizing the electrolysis process on an offshore platform. For offshore hydrogen production, the wind farm CAPEX is adjusted to exclude the costs of export cables and substations, as no electrical energy needs to be transmitted onshore. The 30 wind turbines are connected via inner-array cables to an offshore platform where the electrolyzers are centrally located. Additional costs in this setup include the offshore platform, desalination unit, compressors, and gas pipeline used to transport the generated hydrogen to shore. The cost of a new dedicated hydrogen pipeline, which factors in the

pipeline and compressor, is approximately $3.11 million/km (Kotek, Takácsné Tóth, and Selei 2023).

The desalination system is sized to be 80% of the electrolyzer capacity to account for a buffer in the desalination system capacity (Rogeau et al. 2023). The cost of the desalination system is estimated via CAPEX to be approximately $0.022/kg of hydrogen produced (Singlitico, Østergaard, and Chatzivasileiadis 2021; Donkers 2020). This simplified assumption allows for direct cost estimation on the basis of hydrogen output.

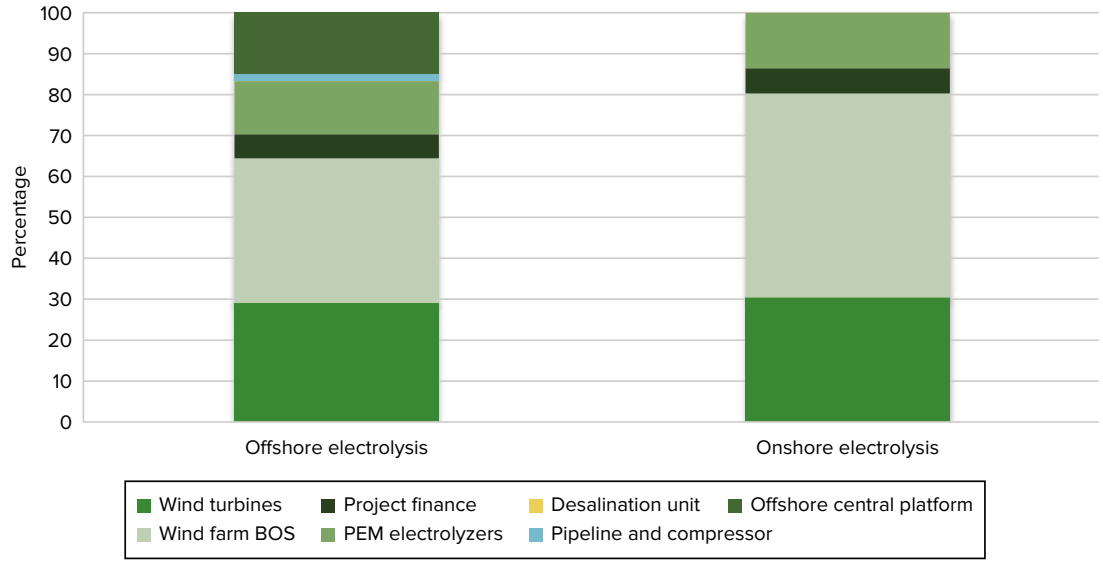
The cost of floating offshore platforms for centralized hydrogen production in waters deeper than 150 m, where floating foundations are needed, is not explicitly provided in the available data. However, this cost is generally recognized as being high due to engineering complexities and installation challenges at such depths (Rogeau et al. 2023; Singlitico, Østergaard, and Chatzivasileiadis 2021). Floating platforms, while offering flexibility in deep waters, are associated with higher maintenance costs and risks due to factors such as movement from wind and waves and vulnerability to external damage (Gerrits 2017).

The CAPEX assumptions for these balance-of-plant components are detailed in Table 3. The resulting LCOH is calculated to be $8.01/kg, which is higher than that in the case where the electrolyzers are placed onshore.

Table 4. Costs of the offshore hydrogen balance-of-system (BOS) components.

Characteristics	Value	Reference
Desalination CAPEX ($/kg hydrogen)	0.022	Singlitico et al. 2021; Donkers 2020; Hill et al. 2024; Scottish Government 2020
Pipeline and compressor CAPEX ($/m)	3,110	Kotek et al. 2023; Hill et al. 2024; Scottish Government 2020
Offshore platform CAPEX ($/MW)	1,668,300	Hill et al. 2024; Scottish Government 2020

Figure 4. CAPEX shares of the main components for the two scenarios.



Source: Authors.

The high LCOH for the onshore electrolysis case stems primarily from the higher CAPEX associated with FOWFs than with other types of wind farms. The installation and maintenance costs of offshore turbines, the need for high-voltage transmission infrastructure to bring electricity onshore, and the inherent logistical challenges of operating in harsh marine environments increase the overall cost of hydrogen production.

For onshore electrolysis using offshore wind to become economically competitive with solar PV, substantial reductions in the cost of FOWFs are necessary. Advances in technology, economies of scale, and improved deployment techniques are essential to reduce the costs of floating wind turbines and reduce the LCOH for hydrogen production. As floating wind technology matures, the potential for cost reductions can make offshore wind a more attractive option for hydrogen production in the future. The case for offshore wind in hydrogen production may also become stronger as land availability constraints for solar PV become stricter, especially in densely populated regions or areas with limited suitable land for solar development.

The CAPEX share of wind farm BOS decreases to $4,245/kW for the offshore electrolysis case, as no electrical transmission to shore is needed. Although the share of PEM electrolyzers is slightly lower than that of onshore electrolyzers, the overall cost increases because of the additional expenses associated with offshore installation and infrastructure. However, the costs related to the central offshore platform, which hosts the electrolyzers, are significant. This platform introduces substantial cost uncertainty, and its high CAPEX share complicates accurate project feasibility assessments. Furthermore, this uncertainty makes it challenging to estimate the potential large-scale benefits of offshore hydrogen production. Theoretically, aggregating power outputs from several wind farms and transporting the energy to shore as hydrogen via a single pipeline appears advantageous. In contrast, the electrical transmission of wind power to shore requires each project to incur the same high costs for substations and transmission lines. While the concept of aggregating multiple wind farms seems promising, current figures do not clearly indicate at what scale this approach becomes economically favorable, further complicating the assessment of its long-term feasibility.

Sensitivity analysis is conducted on the LCOH model for the offshore electrolysis case to determine the primary cost drivers for each scenario. In this analysis, the input parameters are adjusted to their respective limits for each scenario, with only one parameter altered at a time from the baseline scenario to observe its impact on the LCOH. The reduction range of 30% is based on a study by Catapult (2021), which reveals that FOWF costs could decrease by 30%-50% by 2030, driven primarily by scaling turbine sizes, economies of scale, and technological advancements. A similar cost reduction is projected for electrolyzers, with Fraunhofer (2021) estimating an ~30% decline in electrolyzer costs by 2030 due to advancements in stack components and manufacturing processes. The outcomes of the sensitivity analysis are presented in Table 5. An additional sensitivity analysis combining cost reductions in the three main components simultaneously is considered for both the onshore and offshore electrolysis cases to estimate an optimistic lower bound for the LCOH. The resulting range is between $4.57 and $6.07/kg.

Table 5. Sensitivity results for the offshore electrolysis case.

Input variable	Base scenario	Sensitivity analysis	New LCOH ($/kg)	Change %
Baseline LCOH			8.01	
Turbine foundation	Floating	Fixed	6.52	–19
Wind farm CAPEX	Business as usual (BAU)	30% reduction	6.73	–16
Electrolyzer CAPEX	BAU	30% reduction	7.6	–5
Central offshore platform CAPEX	BAU	30% reduction	7.67	–4
Wind farm, electrolyzer, and central offshore platform CAPEX	BAU	30% reduction	6.07	–24
Discount rate	5%	3%	6.96	–13

4. Discussion

Onshore electrolysis using offshore wind energy benefits from established onshore infrastructure and reduces the need for complex offshore platforms and equipment, making O&M easier. However, despite these advantages, the LCOH for onshore electrolysis using FOWFs is notably greater than is that for onshore electrolysis using solar PV. Currently, on the basis of our results, the LCOH for offshore floating-wind-based hydrogen production is approximately three times greater than is that of solar PV-based systems in Saudi Arabia. This significant cost disparity presents a challenge for the economic competitiveness of hydrogen production from offshore wind in the current market. Nonetheless, ongoing advancements in technology, supply chain maturity, and key component cost reductions are expected to significantly lower these costs in the near future. In regions with limited land availability, these improvements could make offshore wind a viable alternative for hydrogen production.

The high LCOH for offshore wind stems primarily from the higher CAPEX associated with FOWFs. The installation and maintenance costs of offshore turbines, the need for high-voltage transmission infrastructure to bring electricity onshore, and the inherent logistical challenges of operating in harsh marine environments increase the overall cost of hydrogen production. In comparison, solar PV has significantly lower CAPEX because of its simpler installation processes, minimal maintenance requirements, and the rapidly declining costs of solar panels over the past decade.

For onshore electrolysis using offshore wind to become economically competitive with solar PV, substantial reductions in the cost of FOWFs are necessary. Advances in technology, economies of scale, and improved deployment techniques are essential to reduce the costs of floating wind turbines and reduce the LCOH for hydrogen production. As floating wind technology matures, the potential for cost reductions could make offshore wind a more attractive option for hydrogen production in the future. As mentioned above, the case for offshore wind in hydrogen production may also become stronger as land availability constraints for solar PV become stricter, especially in densely populated regions or areas with limited suitable land for solar development.

The central offshore hydrogen production model offers scalability benefits. In large-scale aggregated offshore wind projects, such as those reaching 10 GW, each project typically requires separate high-voltage cables to transmit electricity onshore. In contrast, a single, well-sized and strategically planned hydrogen pipeline can carry the hydrogen output from multiple projects, significantly reducing overall infrastructure costs as the project scale increases (Derelle 2023). This situation reduces the operational complexity and capital costs associated with the installation of multiple platforms. With a central offshore platform, hydrogen production can be efficiently managed, with shared infrastructure such as desalination, compression, and transport systems, making it a promising solution for large-scale offshore wind farms.

The results show that while central offshore hydrogen production involves high CAPEX, especially for the platform, the potential for cost reductions exists as

projects scale up. In this model, hydrogen is produced offshore and transported to shore through pipelines, which is the most commonly used method for shorter to moderate distances, where large volumes of hydrogen can be efficiently carried to onshore storage or distribution hubs. However, this approach is not the only option available for hydrogen transport. Other options, such as using ships to transport liquefied hydrogen or hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs), offer alternative pathways, especially for projects located further from shore or in deeper waters, where pipeline infrastructure may become prohibitively expensive. Ship transport allows for the flexibility of scaling up transport as demand grows without the need for fixed infrastructure, and the technology for liquefying hydrogen is continuously improving. Although liquefaction requires significant energy input, advances in efficiency may reduce these costs in the future.

Moreover, hydrogen carriers such as ammonia or LOHCs provide additional flexibility. These carriers allow for easier storage and transport over long distances, as they are more stable and can be integrated into existing global shipping networks. Ammonia, for example, can be easily converted back to hydrogen or used directly as a fuel, adding another layer of utility. Importantly, the conversion of hydrogen into ammonia at offshore facilities can be performed at a relatively low cost, further increasing its feasibility for export. However, these methods come with their own sets of technical and economic challenges.

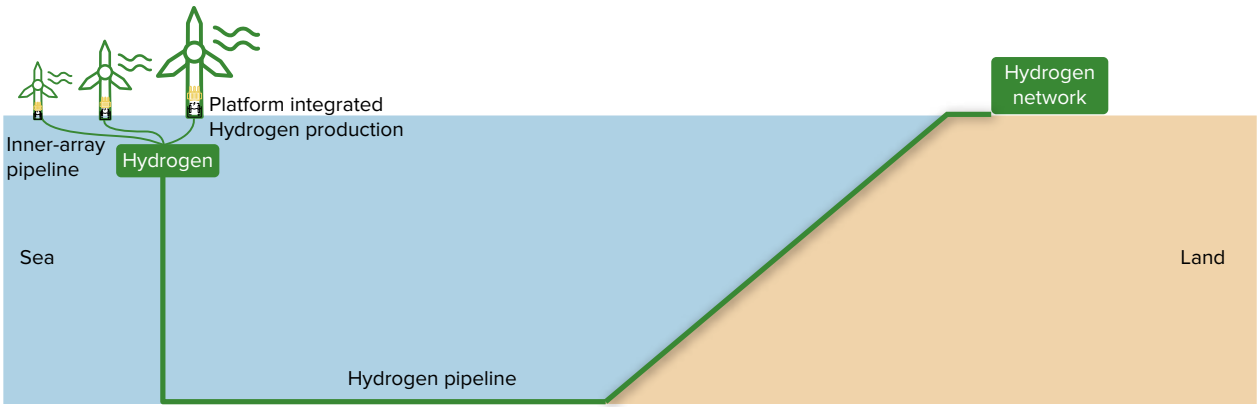
In our analysis, central offshore hydrogen production and pipeline-based transport are selected because of their lower energy consumption and feasibility for hydrogen transport over moderate distances. While our study focuses primarily on the domestic production of hydrogen, its export potential should also be considered. As Saudi Arabia aims to become a leader in the global hydrogen market, a key question is whether producing hydrogen onshore or offshore for export is more cost effective. Although export-related costs are not central to our analysis, future studies should explore the potential of shared offshore infrastructure among countries, as seen in the North Sea, to reduce costs and improve competitiveness. Nonetheless, as the scale of offshore hydrogen production grows and projects move further from shore, alternative transport methods such as ships or carriers may become more cost competitive, with estimates for shipping hydrogen from Saudi to Northwest Europe in the form of ammonia being approximately $1/kg (Alhadhrami et al. 2024). The incorporation of these options into the global landscape of the hydrogen economy and potential exports across continents could provide a more comprehensive view of the potential benefits of these options.

4.1 Hydrogen Production from Decentralized Offshore Electrolysis

Decentralized hydrogen production (i.e., the deployment of electrolysis systems at individual wind turbines) offers a novel approach to leveraging offshore wind energy. By placing electrolyzers directly at the source of generation, this method bypasses the need for complex and expensive electricity transmission infrastructure, such as high-voltage cables, and allows hydrogen to be produced and transported as a fuel directly from the wind turbine. The promise of decentralized hydrogen production lies in its potential to reduce grid congestion, lower transmission losses, and provide a flexible solution for hydrogen storage and distribution. However, despite these theoretical advantages, there are significant challenges that need to be addressed before decentralized hydrogen production can be widely adopted.

Conversely, one of the primary hurdles impeding the development of decentralized offshore electrolyzers is the lack of large-scale pilot projects that demonstrate the technical and economic viability of decentralized electrolysis. The concept remains largely in the experimental phase, with only one notable demonstration project underway in the UK (Venugopalan, Garcia Navarro, and Buijs 2024). Without comprehensive operational data, performing a detailed quantitative analysis or accurately assessing the LCOH for decentralized systems is difficult. This uncertainty limits the ability to predict the scalability of decentralized electrolysis and makes it challenging to determine how it compares to centralized or onshore alternatives in terms of cost effectiveness and overall performance.

Figure 5. Decentralized offshore electrolysis.



Source: Authors.

The technical complexity of integrating electrolyzers into individual turbines introduces additional layers of uncertainty. While decentralized electrolysis reduces the need for offshore platforms and pipelines, it requires each wind turbine to have its own electrolyzer, desalination unit, and potentially compression and storage system. This modular approach complicates maintenance and operational logistics, as each unit needs to be monitored and serviced separately. Moreover, placing desalination units at every turbine to purify seawater for electrolysis is both resource and energy intensive, further increasing costs and operational challenges. It will take time for pilot projects to demonstrate and evaluate whether such systems can function efficiently at scale.

From an economic standpoint, decentralized electrolysis carries the risk of higher CAPEX due to the need for individual components at each turbine. The lack of economies of scale, which centralized systems can exploit by aggregating resources and infrastructure, also poses a barrier to reducing costs. Nevertheless, the potential for decentralized electrolysis to unlock hydrogen production in remote or deep-water offshore wind farms, where traditional electrical grid connections are not feasible, is an exciting opportunity. As FOWFs become more viable, decentralized hydrogen production could allow developers to build wind farms far from shore without the need for expensive electrical infrastructure. In these scenarios, producing hydrogen at the source and transporting it via ships or pipelines could offer a cost-effective solution, especially if future technological developments reduce the costs of decentralized systems.

4.2 Challenges, Risks, and Barriers Ahead

While both onshore and offshore electrolysis present unique advantages, it is essential to consider the common barriers that can influence the feasibility of both approaches.

1. **Offshore hydrogen production involves considerable CAPEX, posing significant financing challenges.**

   Offshore hydrogen production faces significant challenges, including high capital costs, economic uncertainties, and technological integration issues. Substantial upfront investments are required for infrastructure, including the installation of wind turbines, electrolysis systems, pipelines, and supporting facilities. Furthermore, uncertainties surrounding the future market price of hydrogen complicate the economic viability of these ventures. The integration of offshore wind technology with large-scale offshore hydrogen production is still in its early stages of development.

2. **Offshore production and technology integration increase regulatory and permitting complexities.**

   The regulatory and permitting complexities of offshore hydrogen production are major barriers. The regulatory

landscape for hydrogen is still emerging, and obtaining permits for large-scale projects can be time consuming. Streamlining regulatory processes and creating standardized regulations for hydrogen production, transport, and storage are essential for accelerating project development. Furthermore, integration with hydrogen transport and storage systems presents significant technical challenges, particularly with respect to reliability, efficiency, and safety.

3. **Managing too many stages and steps presents operational challenges.**

   Grid integration and infrastructure development pose significant challenges, including the development and operation of hydrogen pipelines, storage infrastructure, subsea piping systems, and intermediate storage solutions for hydrogen. The installation and maintenance of subsea pipelines present technical challenges and operational risks, adding complexity to infrastructure planning and development.

4. **Offshore hydrogen production is hindered by intermittent wind power.**

   Electrolyzers, which are used to produce hydrogen, need to operate continuously to maximize efficiency and cost-effectiveness. However, the variability of wind energy can lead to interruptions, necessitating the use of backup systems or energy storage solutions such as batteries, which would further increase costs. Thus, it is essential to develop systems that can manage this intermittent supply without compromising hydrogen output to ensure the feasibility of offshore hydrogen projects.

5. **Safety and environmental issues will require careful management.**

   Environmental concerns are crucial in hydrogen production via electrolysis, which requires significant fresh water and energy-intensive desalination processes, impacting marine life. The safety risks associated with hydrogen storage and transport in offshore environments require careful management. It is crucial to establish technological standards and ensure long-term operational stability for the success of offshore hydrogen production.

6. **International offshore wind and hydrogen projects will require effective cooperation.**

   Finally, regional cooperation is challenging for international offshore wind and hydrogen projects because of differing regulations and national interests. Effective cooperation is vital to optimize resource use and develop cross-border hydrogen infrastructure, thus requiring careful negotiation and collaboration.

5. Conclusions and Ways Forward

Despite the challenges, offshore wind-to-hydrogen systems offer an opportunity for decarbonization and energy security, particularly in sectors that are hard to electrify, such as heavy industry, aviation, and shipping. Hydrogen produced from renewable offshore wind energy provides a zero-emission alternative to fossil fuels, positioning it as a key solution in the transition to cleaner energy. The development of the offshore wind-to-hydrogen industry also presents sizable potential for economic growth and job creation. As the industry expands, opportunities will emerge across the entire value chain, from the manufacturing of wind turbines and electrolyzers to the construction, operation, and maintenance of both offshore wind farms and hydrogen production facilities. This growth can drive local economies, particularly in coastal regions where offshore wind farms are located, creating long-term, high-skilled jobs in the renewable energy and hydrogen sectors. Governments can leverage this opportunity to stimulate industrial growth and strengthen domestic supply chains, fostering a robust green economy.

Additionally, countries that develop strong offshore wind-to-hydrogen industries have substantial export potential. As the global demand for green hydrogen continues to rise, nations with abundant offshore wind resources can position themselves as key exporters. International collaboration in terms of infrastructure, technology development, and regulatory frameworks will be essential in accelerating this growth and opening new markets. Collaborative efforts will enhance technological advancements and standardization, driving down costs and increasing efficiency for global hydrogen markets, further boosting the competitiveness of offshore wind-to-hydrogen systems.

However, from the Saudi perspective, the economics of offshore wind-to-hydrogen production, particularly in the Red Sea, where much of the resource potential lies in deeper areas suitable for FOWFs, make it less competitive for green hydrogen production. Compared with similar projects in Europe, this technology does not provide a competitive advantage in exporting green hydrogen, which has greater potential for FOWFs and is further developed in terms of technological deployment and cost efficiency. Moreover, in terms of offshore wind hydrogen production, Saudi Arabia will struggle to compete with domestic onshore hydrogen production from solar PV, which benefits from the country's vast solar resources and much lower production costs.

As a result, the development of Saudi Arabia's offshore wind-to-hydrogen sector will likely be a medium- to long-term target, driven by the need for further cost reductions in offshore wind technology. In addition, incentives for green hydrogen will be essential for making offshore wind hydrogen production financially viable. While the current focus may remain on leveraging Saudi Arabia's more

cost-effective solar and onshore wind resources, offshore wind could play a more prominent role in the future as the technology matures.

One of the primary economic advantages of offshore hydrogen production is that transporting hydrogen is less expensive than is transmitting electricity over long distances. Hydrogen produced from several offshore wind farms can be transported via a single pipeline, dramatically reducing material requirements, installation costs, and the space needed on the seabed. Offshore electrolysis becomes particularly attractive for projects located far from shore, where the cost of hydrogen pipelines is considerably lower than is that of installing electrical cables. For large-scale projects, a hydrogen pipeline can cost up to three times less than can an electrical cable to transmit the same amount of energy, providing a strong case for further investment in offshore electrolysis infrastructure.

To ensure the successful development of offshore wind-to-hydrogen systems, developing a hydrogen strategy that integrates offshore wind deployment is crucial. Such a strategy will offer a clear direction to businesses and industries, thus supporting investment decisions and providing a long-term roadmap. Additionally, this strategy will involve linking the siting of offshore wind farms with the proximity of hydrogen end-use sectors or industrial bases. Offshore wind locations should be strategically chosen to minimize the cost and complexity of hydrogen transport and ensure efficient delivery to demand centers or export facilities. Setting capacity targets will help establish a pipeline of projects, giving stakeholders visibility into future opportunities, whereas cost targets will encourage innovation and cost reduction across the supply chain. A well-structured strategy can align offshore wind capacity with hydrogen production goals, supporting the growth of both domestic and international hydrogen markets.

Investment in R&D will be vital in advancing those key technologies required for the offshore hydrogen economy. Funding for R&D is necessary to accelerate progress in areas such as advanced electrolyzers, more efficient hydrogen storage solutions, and cost-effective pipeline infrastructure. Identifying and supporting demonstrator projects, particularly those targeting the first GW of hydrogen production capacity, will be critical in kick starting the supply chain and attracting investment. Additionally, encouraging diverse business models will foster innovation and competition, thus driving down costs and improving the scalability of offshore hydrogen production.

Finally, international collaboration will play a crucial role in advancing offshore hydrogen systems, especially in regions with shared sea boundaries that offer opportunities for cross-border projects. Collaboration on technology sharing, regulatory harmonization, and infrastructure development can help reduce costs and improve the efficiency of hydrogen production and transport. Aligning regulatory standards across borders will further streamline the development of transnational hydrogen pipelines and facilitate the movement of green hydrogen among nations.

Endnote

[1] The FPSO concept involves generating hydrogen on the same floating platform as the wind turbine and storing it onboard. The stored hydrogen can then be offloaded for transport by ships, offering greater flexibility compared to pipeline-based systems, especially in deep-water locations.

References

Akdağ, Ozan. 2023. "The Operation and Applicability to Hydrogen Fuel Technology of Green Hydrogen Production by Water Electrolysis Using Offshore Wind Power." *Journal of Cleaner Production* 425: 138863. https://doi.org/10.1016/j.jclepro.2023.138863.

Albalawi, Ahmed A., Nora Nezamuddin, Frank A. Felder, Abdelrahman Muhsen, and Amro M. Elshurafa. 2024. "Assessment of the Potential of Floating Offshore Wind Turbines in the Red Sea." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://www.kapsarc.org/research/publications/assessment-of-the-potential-of-floating-offshore-wind-turbines-in-the-red-sea.

Alhadhrami, Khalid, Ahmed Albalawi, Shahid Hasan, and Amro M. Elshurafa. 2024. "Modeling Green Hydrogen Production Using Power-to-X: Saudi and German Contexts." *International Journal of Hydrogen Energy* 64: 1040–1051. https://doi.org/10.1016/j.ijhydene.2024.03.161.

AquaVentus. 2024. "AquaVentus." https://aquaventus.org/en.

Barrow Green Hydrogen. 2024. "Producing 100% Green Hydrogen." https://www.barrowgreenhydrogen.co.uk/theproject.

Bødal, Espen Flo, Sigmund Eggen Holm, Avinash Subramanian, Goran Durakovic, Dimitri Pinel, Lars Hellemo, Miguel Muñoz Ortiz, Brage Rugstad Knudsen, and Julian Straus. 2024. "Hydrogen for Harvesting the Potential of Offshore Wind: A North Sea Case Study." *Applied Energy* 357. https://doi.org/10.1016/j.apenergy.2023.122484.

Bonacina, Camilla Nicol, Nima Bordbar Gaskare, and Gianluca Valenti. 2022. "Assessment of Offshore Liquid Hydrogen Production from Wind Power for Ship Refueling." *International Journal of Hydrogen Energy* 47 (2): 1279–1291. https://doi.org/10.1016/j.ijhydene.2021.10.043.

BVG Associated (BVGA). 2023. "Guide to a Floating Offshore Wind Farm." BVG Associates Limited. Published on behalf of the Offshore Renewable Energy Catapult, The Crown Estate, and Crown Estate Scotland, 16 October. https://bvgassociates.com/comprehensive-guide-to-a-floating-offshore-wind-farm-launched-to-support-industry-learning.

Calado, Goncalo, Rui Castro, A. J. Pires, and Miguel J. Marques. 2024. "Assessment of Hydrogen-Based Solutions Associated to Offshore Wind Farms: The Case of the Iberian Peninsula." *Renewable and Sustainable Energy Reviews* 192 (March): 114268. https://doi.org/10.1016/j.rser.2023.114268.

Catapult. 2021. *The Floating Offshore Wind: Cost Reduction Pathways to Subsidy Free*. Offshore Renewable Energy (ORE) Catapult. https://cms.ore.catapult.org.uk/wp-content/uploads/2021/01/FOW-Cost-Reduction-Pathways-to-Subsidy-Free-report-.pdf.

Chandler, William S., Charles H. Whitlock. 2005. "Determining Wind Resources as a Function of Surface Roughness and Height from NASA Global Assimilation Analysis." Proceedings of the International Solar Energy Society 2005 Solar World Congress, Orlando, Florida, August 6–12.

Cheng, Cheng, and Llewelyn Hughes. 2023. "The Role for Offshore Wind Power in Renewable Hydrogen Production in Australia." *Journal of Cleaner Production* 391 (March 10): 136223. https://doi.org/10.1016/j.jclepro.2023.136223.

Danish Energy Agency (DEA). 2024. "Energy Island in the North Sea." Danish Energy Agency. https://ens.dk/en/our-responsibilities/offshore-wind-power/energy-island-north-sea.

Department for Energy Security and Net Zero (DESNZ). 2024. "Contracts for Difference Allocation Round 6 Results." Gov.UK, September 3. https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-6-results.

Derelle, Shane, Heffernan Manon. 2023. "An Overview of the UK Hydrogen Market." *Bringa*. https://www.youtube.com/watch?v=EpK2-8DKIQ8.

Det Norske Veritas (DNV). 2023. *Cost and Performance Data for Offshore Hydrogen Production.* DNV Denmark A/S (2900 Hellerup, Denmark). https://ens.dk/sites/ens.dk/files/Energioer/cost_performance_data_offshore_hydrogen_production.pdf.

Díaz-Motta, Armando, Francisco Díaz-González, and Manuel Villa-Arrieta. 2023. "Energy Sustainability Assessment of Offshore Wind-Powered Ammonia." *Journal of Cleaner Production* 420 (September 25): 138419. https://doi.org/10.1016/j.jclepro.2023.138419.

Dolphyn Hydrogen. 2024. "Our Hydrogen Production Trials." https://www.dolphynhydrogen.com/production-trials.

Donkers, Koen. 2020. "Hydrogen Production on Offshore Platforms: A Techno-Economic Analysis." Master's thesis, Master Energy Science, Utrecht University. https://studenttheses.uu.nl/bitstream/handle/20.500.12932/37491/Thesis%20research%20Koen%20Donkers%20-%20%20Final%20version.pdf?sequence=1.

East Coast Hydrogen. 2023. *East Coast Hydrogen Delivery Plan.* https://www.eastcoasthydrogen.co.uk/east-coast-hydrogen-delivery-plan.

Enerdata. 2024. "Enerdata Key Energy Intelligence." https://www.enerdata.net/publications/reports-presentations/world-energy-trends.html.

European Commission. 2020. "An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future." https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666.

Farahmand, Hossein, Sander Holt Günther, and Martin Kristiansen. 2024. "Evaluating the Offshore Wind Business Case and Green Hydrogen Production: A Case Study of a Future North Sea Offshore Grid." *Electric Power Systems Research* 234 (September): 110814. https://doi.org/10.1016/j.epsr.2024.110814.

Fraunhofer. 2021. *Cost Forecast For Low-Temperature Electrolysis – Technology Driven Bottom-Up Prognosis For Pem And Alkaline Water Electrolysis Systems.* Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 279110 Freiburg, Germany. https://www.ise.fraunhofer.de/en/publications/studies/catf.html.

Gerrits, Stefan. 2017. "Feasibility Study of the Hub and Spoke Concept in the North Sea Developing a Site Selection Model to Determine the Optimal Location." Master thesis. Department of Hydraulic Engineering, Delft University of Technology. https://repository.tudelft.nl/record/uuid:9de1680b-7c16-4c93-bf3e-2af5e198eee0.

Giampieri, Alessandro, Janie Ling-Chin, and Anthony Paul Roskilly. 2024. "Techno-Economic Assessment of Offshore Wind-to-Hydrogen Scenarios: A UK Case Study." *International Journal of Hydrogen Energy* 52 (Part B, January 2): 589–617. https://doi.org/10.1016/j.ijhydene.2023.01.346.

Gipe, Paul. 1999. *Wind Energy Basics*. Chelsea Green Publishing.

Glaum, Philipp, Fabian Neumann, and Tom Brown. 2024. "Offshore Power and Hydrogen Networks for Europe's North Sea." *Applied Energy* 369 (September 1): 123530. https://doi.org/10.1016/j.apenergy.2024.123530.

Groenemans, Hugo, Genevieve Saur, Cortney Mittelsteadt, Judith Lattimer, and Hui Xu. 2022. "Techno-Economic Analysis of Offshore Wind PEM Water Electrolysis for H2 Production." *Current Opinion in Chemical Engineering* 37 (September): 100828. https://doi.org/10.1016/j.coche.2022.100828.

Guven, Denizhan. 2024. "Offshore Wind-Driven Green Hydrogen: Bridging Environmental Sustainability and Economic Viability." *International Journal of Hydrogen Energy* 72 (June 27): 661–676. https://doi.org/10.1016/j.ijhydene.2024.05.335.

Havinga, Hylke C., H. Z. Adriaan van der Loos, and Markus Steen. 2024. "Collaboration or Competition? Interactions between Floating and Fixed-Bottom Offshore Wind in Norway." *Environmental Innovation and Societal Transitions* 52 (September): 100872. https://doi.org/10.1016/j.eist.2024.100872.

Hill, Samuel James Peter, Olusola Bamisile, Luke Hatton, Iain Staffell, and Malte Jansen. 2024. "The Cost of Clean Hydrogen from Offshore Wind and Electrolysis." *Journal of Cleaner Production* 445 (March 15): 141162. https://doi.org/10.1016/j.jclepro.2024.141162.

Ibrahim, Omar S., Alessandro Singlitico, Roberts Proskovics, Shane McDonagh, Cian Desmond, and Jerry D. Murphy. 2022. “Dedicated Large-Scale Floating Offshore Wind to Hydrogen: Assessing Design Variables in Proposed Typologies.” *Renewable and Sustainable Energy Reviews* 160 (May): 112310. https://doi.org/10.1016/j.rser.2022.112310.

Jansen, Malte, Philipp Beiter, Iegor Riepin, Felix Müsgens, Victor Juarez Guajardo-Fajardo, Iain Staffell, Bernard Bulder, and Lena Kitzing. 2022. “Policy Choices and Outcomes for Offshore Wind Auctions Globally.” *Energy Policy* 167 (August): 113000. https://doi.org/10.1016/j.enpol.2022.113000.

Kang, Taehyung, Dela Quarme Gbadago, and Sungwon Hwang. 2024. “Techno-Economic Analysis and Comparison of Hydrogen Supply Using Offshore Wind Power Sources on the Coast of the Korean Peninsula.” *International Journal of Hydrogen Energy* 71 (June 19): 1201–1213. https://doi.org/10.1016/j.ijhydene.2024.05.188.

Komorowska, Aleksandra, Pablo Benalcazar, and Jacek Kamiński. 2023. “Evaluating the Competitiveness and Uncertainty of Offshore Wind-to-Hydrogen Production: A Case Study of Poland.” *International Journal of Hydrogen Energy* 48 (Issue 39, May 5): 14577–14590. https://doi.org/10.1016/j.ijhydene.2023.01.015.

Kotek, Peter, Borbála Takácsné Tóth, and Adrienn Selei. 2023. “Designing a Future-Proof Gas and Hydrogen Infrastructure for Europe – A Modelling-Based Approach.” *Energy Policy* 180 (September): 113641. https://doi.org/10.1016/j.enpol.2023.113641.

Lucas, Tiago R., Ana F. Ferreira, R. B. Santos Pereira, and Marco Alves. 2022. “Hydrogen Production from the WindFloat Atlantic Offshore Wind Farm: A Techno-Economic Analysis.” *Applied Energy* 310 (March 15): 118481. https://doi.org/10.1016/j.apenergy.2021.118481.

Luo, Zhibin, Xiaobo Wang, Heng Wen, and Aiguo Pei. 2022. “Hydrogen Production from Offshore Wind Power in South China.” *International Journal of Hydrogen Energy* 47 (Issue 58, July 8): 24558–24568. https://doi.org/10.1016/j.ijhydene.2022.03.162.

Lüth, Alexandra, Paul E. Seifert, Ruud Egging-Bratseth, and Jens Weibezahn. 2023. “How to Connect Energy Islands: Trade-Offs Between Hydrogen and Electricity Infrastructure.” *Applied Energy* 341 (July 1): 121045. https://doi.org/10.1016/j.apenergy.2023.121045.

Lüth, Alexandra, Yannick Werner, Ruud Egging-Bratseth, and Jalal Kazempour. 2024. “Electrolysis as a Flexibility Resource on Energy Islands: The Case of the North Sea.” *Energy Policy* 185 (February): 113921. https://doi.org/10.1016/j.enpol.2023.113921.

NASA. 2024. “NASA Prediction of Worldwide Energy Resources (POWER).” https://power.larc.nasa.gov.

National Renewable Energy Laboratory (NREL). 2021. “NREL Annual Technology Baseline: Offshore Wind.” National Renewable Energy Laboratory. https://atb.nrel.gov/electricity/2021/offshore_wind.

NorthH_2. 2024. “NorthH_2 Project.” https://www.north2.eu.

National Renewable Energy Laboratory (NREL). 2021. “NREL Annual Technology Baseline: Offshore Wind.” https://atb.nrel.gov/electricity/2021/offshore_wind.

Net Zero Technology Centre (NZTC). 2023. “Hydrogen Backbone Link: Connecting Scotland and Europe.” Aberdeen, Scotland: Net Zero Technology Centre. https://www.netzerotc.com/reports/hydrogen-backbone-link-report.

Ørsted. 2021. “Ørsted Breaks Ground on First Renewable Hydrogen Project.” https://orsted.com/en/media/news/2021/05/953942245693267.

Pérez-Vigueras, Malinalli, Rogelio Sotelo-Boyá, Rosa de Guadalupe González-Huerta, and Francisco Bañuelos-Ruedas. 2023. “Feasibility Analysis of Green Hydrogen Production from Oceanic Energy.” *Heliyon* 9 (9): e20046. https://doi.org/10.1016/j.heliyon.2023.e20046.

PosHYdon. 2024. “PosHYdon Project.” https://poshydon.com/en/home-en/process.

Ramakrishnan, Shanmugam, Mostafa Delpisheh, Caillean Convery, Daniel Niblett, Mohanraj Vinothkannan, and Mohamed Mamlouk. 2024. “Offshore Green Hydrogen Production from Wind Energy: Critical Review and Perspective.” *Renewable and Sustainable Energy Reviews* 195. https://doi.org/10.1016/j.rser.2024.114320.

Rezaei, Mostafa, Alexandr Akimov, and Evan Mac A. Gray. 2024. “Techno-Economics of Offshore Wind-Based Dynamic Hydrogen Production.” *Applied Energy* 374. https://doi.org/10.1016/j.apenergy.2024.124030.

Rogeau, Antoine, Julien Vieubled, Matthieu de Coatpont, Pedro Affonso Nobrega, Guillaume Erbs, and Robin Girard. 2023. "Techno-Economic Evaluation and Resource Assessment of Hydrogen Production through Offshore Wind Farms: A European Perspective." *Renewable and Sustainable Energy Reviews* 187. https://doi.org/10.1016/j.rser.2023.113699.

Rostock EnergyPort Coorperation. 2024. "HyTechHafen Rostock – Green Hydrogen for Energy Transition." https://energyport-rostock.de/en/.

RWE. 2024. "Hydrogen Production in the North Sea: AquaVentus." *RWE*. https://www.rwe.com/en/research-and-development/hydrogen-projects/aquaventus.

Scottish Government. 2020. *Scottish Offshore Wind to Green Hydrogen Opportunity Assessment.* The Scottish Government, St Andrew's House, Edinburgh EH1 3DG. https://www.gov.scot/publications/scottish-offshore-wind-green-hydrogen-opportunity-assessment.

Shell. 2022. "Shell to Start Building Europe's Largest Renewable Hydrogen Plant." https://www.shell.com/news-and-insights/newsroom/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html.

Singlitico, Alessandro, Jacob Østergaard, and Spyros Chatzivasileiadis. 2021. "Onshore, Offshore or In-Turbine Electrolysis? Techno-Economic Overview of Alternative Integration Designs for Green Hydrogen Production into Offshore Wind Power Hubs." *Renewable and Sustainable Energy Transition* 1: 100005. https://doi.org/10.1016/j.rset.2021.100005.

Venugopalan, Suriya, Julio Garcia Navarro, and Lennert Buijs. 2024. *State of Art in Offshore Hydrogen Production. Utrecht: TKI Offshore Energy.* https://energycentral.com/system/files/ece/nodes/688785/state_of_art_in_offshore_hydrogen_production.pdf.

Wang, Zhiwen, Hu Wang, Tonio Sant, Zecheng Zhao, Rupp Carriveau, David S. K. Ting, Peng Li, Tielei Zhang, and Wei Xiong. 2024. "Subsea Energy Storage as an Enabler for Floating Offshore Wind–Hydrogen Production: Review and Perspective." *International Journal of Hydrogen Energy* 71: 1266–1282. https://doi.org/10.1016/j.ijhydene.2024.05.329.

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About the Project

This paper is part of the project “Innovations in electricity markets, network regulations, low-carbon investments and technologies” under KAPSARC’s Energy Transitions and Electric Power Program. This project aims to provide insights into the transformation of the Saudi electricity sector. This transformation is characterized by a willingness to increase the share of renewables and replace liquid fuels with natural gas. This transformation must also ensure fiscal balance, expand electricity exports, produce green hydrogen and diversify the Saudi economy through localization. This project provides insights into this transition by discussing and learning from electricity markets worldwide.



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