

From offshore renewable energy to green hydrogen: addressing critical questions

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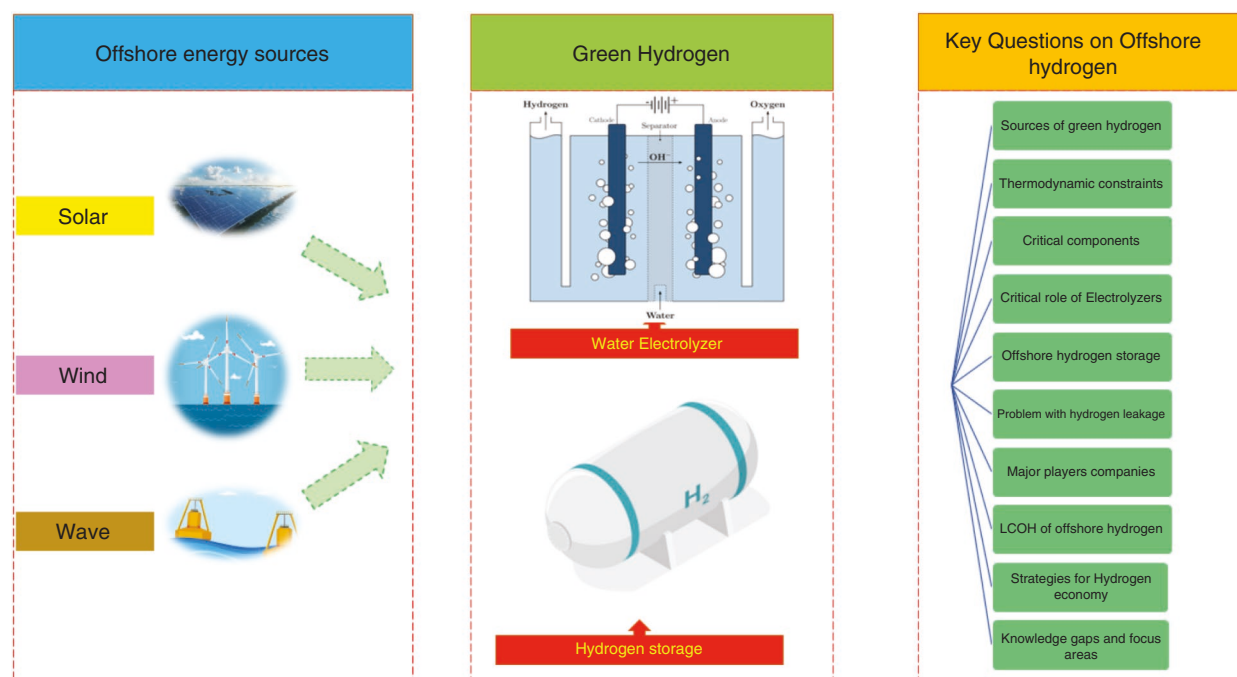
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Abstract

Addressing climate change and navigating the energy transition are more urgent than ever. Several researchers agree that renewable energy adoption and industrial decarbonization are essential pathways forward. As sectors like transportation and heating become increasingly electrified, energy demand is expected to rise, necessitating innovative solutions. Green and blue hydrogen, touted as potential game changers, hold promise in this transition but require advanced electrolysis technologies, sustainable materials, high-pressure storage systems, and optimized system designs for energy efficiency, safety, and scalability to enable large-scale implementation. This study discusses the critical aspects of offshore green hydrogen production, focusing on key findings related to production methods, electrolyzer technologies, and their associated challenges. Key findings highlight that the levelized cost of hydrogen is significantly influenced by the cost of electricity from offshore wind farms, capital expenditure on electrolyzers, and the logistics of offshore platforms, pipelines, and storage. Hydrogen storage advancements, including metal hydrides and chemical carriers, are vital for realizing green hydrogen's potential as an energy vector. Additionally, the industrial-scale production of green hydrogen through electrolysis powered by offshore wind offers promising pathways for decarbonizing energy systems. The study also emphasizes the critical role of collaboration between local and international policy stakeholders, industrial partnerships, and institutional support in shaping a favorable future for hydrogen in the global energy transition.

Graphical abstract



Keywords: green hydrogen; challenges; offshore; cost; storage

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1. Introduction

1.1 Background context

Global energy demand is a critical concern, driven by ongoing industrial growth that remains a central objective for developing and developed nations [1]. The realization of the Paris Agreement's goals relies on significantly decarbonizing the world's energy infrastructure [2]. According to the Intergovernmental Panel on Climate Change (IPCC) scenarios for limiting global warming to 1.5°C, global CO₂ emissions are projected to reach net zero by approximately 2050 [3]. The field of energy technology is undergoing rapid development, with significant progress being made in both generation and storage. Within this context, hydrogen technologies present a range of viable alternatives for addressing future energy needs.

While hydrogen is a crucial input for various industrial processes, including those in chemical plants, fertilizer factories, and oil refineries, its current production is overwhelmingly dependent on natural gas, accounting for approximately 90% of global supply [4]. Given their unique characteristics, island nations have effectively utilized various renewable energy sources (RES), including wind, solar photovoltaic, hydro, biodiesel, and biomass, to meet their energy demands [5]. Commitment and resourcefulness are needed to decarbonize the economy, including industrial facilities and transport [6]. Ambitious national strategies for the deployment of green hydrogen as a key decarbonization measure have been adopted by numerous European countries, Australia, Japan, and the USA [7]. This will necessitate more renewable energy generation, electrification, and deployment of hydrogen technologies to lower the environmental impact and improve energy efficiency [8]. The inherent intermittent nature of RES presents a significant challenge to grid stability. Hydrogen is widely acknowledged as a key solution, offering energy storage capabilities that enable greater integration of these sources without compromising grid reliability [9].

For example, fertilizer production utilizes about 75 million tonnes of hydrogen annually as a chemical [10]. Most of it is produced by fossil fuels, primarily coal and natural gas. This results

in the annual release of 830 million tonnes of carbon dioxide, which amounts to about 2% of the world's coal use and 6% of its natural gas consumption. In the early stages of this shift, there will be an increased source of demand for hydrogen, and green hydrogen is an essential component of that need [3]. Using green energy to produce all of this hydrogen will significantly cut emissions. Figure 1 shows the energy content of various fuel resources [11].

Hydrogen has historically served as a commodity and an intermediary, a substance used in producing products like ammonia, with a few specialized applications [12]. Its adaptability and qualities are now an impetus to reduce carbon emissions through electrification as an energy source, including heavy transportation. There is potential to reuse current resources as offshore RES become more prevalent [12]. Instead of installing new cables to connect wind farms to an already restricted grid, oil and gas infrastructure might transfer energy to the ground using chemicals like hydrogen [13]. Green hydrogen represents a significant opportunity to extend the benefits of renewable energy beyond the power sector [14]. Hydrogen produced from renewable sources (solar, wind, or biogas) is part of the power-to-gas (P2G) concept, where surplus renewable electricity is converted into gaseous fuels for versatile applications [15]. These applications include direct use, storage, industrial processes, and injection into existing natural gas infrastructure, offering multiple pathways to decarbonize the energy sector [16]. Various fossil fuels, including those used in automobiles, low-grade heat, industrial heat, chemical feedstock, electricity, shipping, and aviation, could be replaced by hydrogen in various energy-related applications. Each industry employs multiple technologies and fuels with varying efficiency [17].

1.2 The objective of the study

The fundamental differences in the formation of green and blue hydrogen are covered in the current paper. This paper has described the numerous methods for producing green hydrogen offshore and the difficulties facing the hydrogen economy. This study aims to answer multiple research problems in this context.

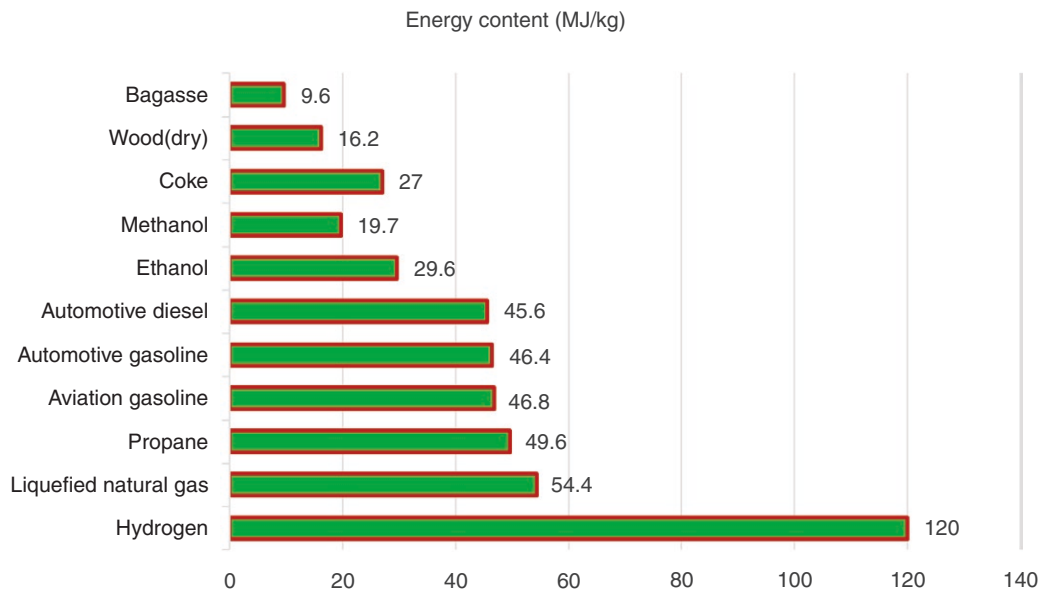


Figure 1. Energy content of various fuels.

1. How to produce, store, and offload clean hydrogen offshore?
2. What are the challenges with green hydrogen for industrial applications?
3. Is the transition to a green hydrogen economy feasible or not?

2. Question 1. What are the sources and applications of green hydrogen?

Different “tags” are applied to hydrogen to reflect various production processes [18]. The designation refers to the source even though the H₂ molecules produced are the same. Additionally, it is crucial to distinguish between the process’s upstream fea-

tures (CO₂ footprint) [19]. If fueled by renewable energy, the electrolyzers separating water into hydrogen and oxygen can produce hydrogen without emitting greenhouse gases (GHGs) [20]. This hydrogen production type is frequently called “green hydrogen” [21]. Green power can be converted into transportation fuel or used as a feedstock in industrial operations where there are currently no climate-neutral alternatives by using green hydrogen as a bridge [22]. Wind energy can serve as a sustainable source for producing green hydrogen and its derivative fuels, such as green ammonia, which have the potential to fuel container ships, significantly reducing carbon emissions in the maritime industry [20]. In this approach, hydrogen can considerably increase the capacity of RES to reduce carbon emissions [23]. Blue hydrogen is produced from natural gas using carbon capture and storage (CCS) technology. This leads to a substantial reduction in carbon emissions [24]. Red hydrogen is produced from nuclear energy through electrolysis. This process is similar to green hydrogen production, but the electricity comes from nuclear power plants [25]. Green hydrogen is produced using energy from renewable sources such as offshore wind and electrolysis to split the water into hydrogen (H₂) and oxygen (O₂) gases. There are just a few sources that offer predictions for the availability of hydrogen worldwide, and they frequently fail to differentiate between the various labels [26]. This is not important in the long run because it is envisaged that “green” will take the place of “gray” as the cost of green hydrogen decreases [27]. Figures 2 and 3 provide the various hydrogen labels and applications.

Hydrogen’s added value as a feedstock for producing synthetic fuels such as methanol, ammonia, and e-fuels lies in its potential to decarbonize sectors, including manufacturing, aviation, shipping, heavy road transport, and heating [28]. These fuels offer a low-carbon alternative for energy-intensive industries, enabling significant emissions reductions where direct electrification is not feasible while supporting the transition to a more sustainable energy system [29].

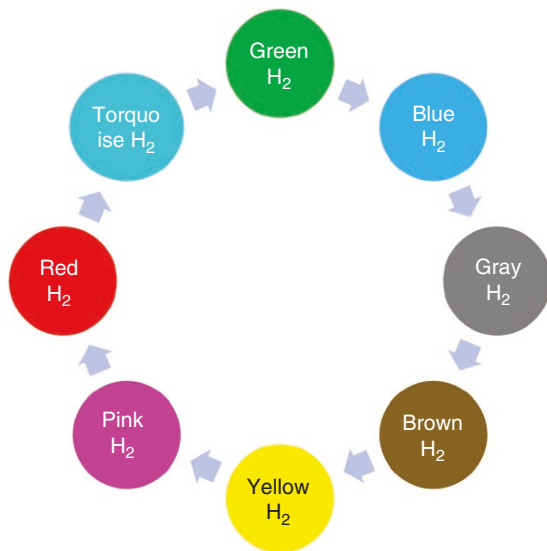


Figure 2. Schematic of various hydrogen colors.

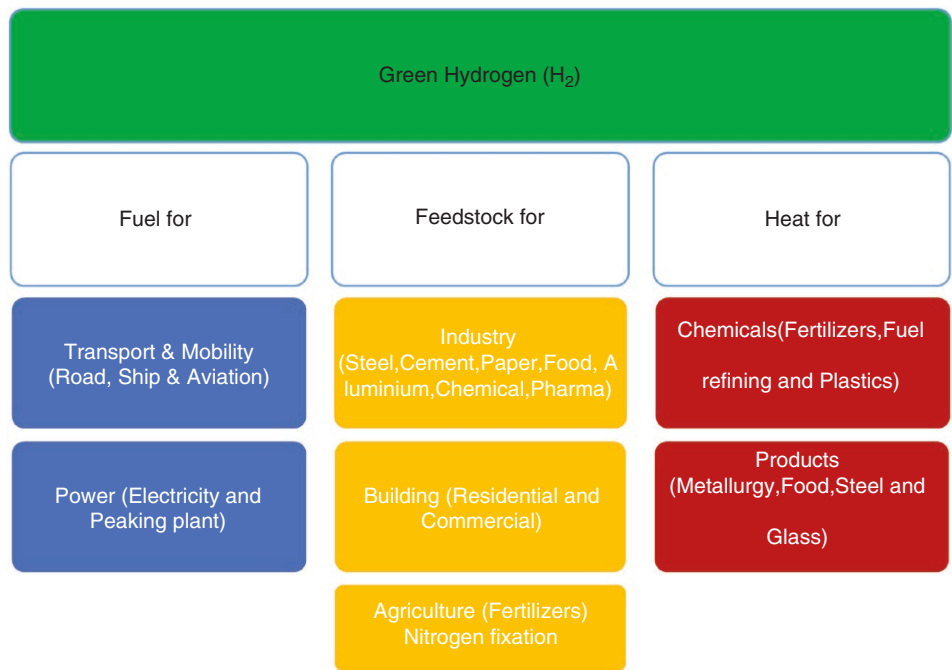


Figure 3. Various applications of green hydrogen.

2.1 Cement and steel industries

Indigenous green hydrogen is badly needed to replace gray hydrogen in cement, steel, and other industries to reduce pollution, an issue affecting survival [30]. To make synthetic fuels, often known as “e-fuels,” that can replace fossil fuels, renewable hydrogen can be mixed with carbon dioxide from industrial operations that would otherwise be released into the environment or via direct air capture [31].

2.2 Mobility and transport

While battery-powered vehicles have range restrictions, hydrogen-powered electric cars present a sustainable long-distance driving option [32]. Compared to ships powered by batteries, fuel cells can propel ships over significantly longer distances while also providing the additional energy requirements of larger vessels [9]. Aviation and shipping can both be decarbonized using renewable hydrogen.

Hydrogen-powered aircraft could be the best way for the air travel industry to meet its bold pledge to achieve net-zero carbon emissions by 2050. For that to happen, hydrogen must be stored safely on these next-generation aircraft. The potential pathway forward for aviation [sustainable aviation fuel (SAF), battery electric, H_2 combustion, or H_2 fuel cell] with the least possible environmental hazard has to be addressed [9]. This is particularly true if the plan is to upscale these technologies to aviation's current fossil fuel combustion level. There is also the rapid development of hypersonic aircraft for potential commercial use and growth in commercial rocket propulsion and space tourism. Each of these has potential environmental and climate impacts that should be carefully assessed [33].

2.3 Methanol/ammonia

Green hydrogen can be utilized as a feedstock to produce methanol and ammonia, with ammonia for fertilizer offering a more sustainable approach to agriculture [34]. Three hydrogen atoms enclose one nitrogen atom to form the common chemical ammonia. For global transportation, hydrogen can be transformed into ammonia liquid and back again [30]. Direct Methanol (CH_3OH) gets much attention as the choice of zero-carbon fuel for fuel cells [35]. Methanol or ammonia derived from hydrogen can be utilized for transportation in maritime vehicles [36]. With the energy industry beginning to deliver zero-carbon fuels, Power-to-X aims to produce renewable fuels for existing industrial markets [7].

2.4 Carbon capture and storage

Green hydrogen + captured CO_2 offers a unique advantage in producing fuel, including green methanol [37]. Real green H_2 is produced by microbes utilizing mosses and algae as biomass feedstock, leading to the generation of biodiesel, ethanol, methane (CH_4), hydrogen (H_2), and high-nitrite/nitrate fertilizers, all while sequentially sequestering carbon dioxide (CO_2) [17]. When the green hydrogen production and carbon capture processes are integrated into a circular system, there is no “waste”; every step generates a valuable product, leading to a sustainable and pollution-free cycle [38].

2.5 Rotary engine

Hydrogen rotary engine technology, which has been modified to use hydrogen as its fuel, delivers excellent environmental performance while emitting no CO_2 [39]. A dual-fuel system enables the car to run on gasoline or hydrogen; the rotary engine only

needs a few design modifications to allow it to do so [40]. The automobile is convenient since it can go far distances to locations without hydrogen stations, so the driver does not have to worry about running out of hydrogen. Mazda was able to produce hydrogen-powered rotary engine cars at a reasonable price.

3. Question 2. What are the primary thermodynamic constraints of green hydrogen as a fuel?

Hydrogen is a pure, reactive chemical energy carrier [41]. The fundamental thermodynamic and physical properties of hydrogen are highlighted in Table 1. Hydrogen can be used to cut high-energy density emissions, but it must be handled carefully. Hydrogen is an energy-intensive, reactive gas with a high burning velocity. It makes hydrogen very likely to ignite and combust if gas leakage occurs. The reactivity combines a flammable range of 4%–75% oxygen and low ignition energy [42].

The fundamental electrolysis reaction involves the electrochemical decomposition of water. The overall reaction can be written as:



This endothermic reaction requires energy. The change in enthalpy (H), representing the total energy change of the system, can be expressed in the form of

$$H = G + TS \quad (2)$$

where H (J/mol) denotes the change in enthalpy measured in Joules per mole, G (J/mol) represents the minimum electrical energy required for the reaction to occur under constant temperature and pressure, and TS (J/mol) denotes the process temperature and the entropy change, which indicates the minimum thermal energy requirement. A temperature change can reduce the demand for electric energy, and G can balance the thermal energy demand. Theoretically, it takes 39.699 kWh or 142.1 MJ of green energy to make 1 kg of green H_2 [43]. When comparing the specific energy demand in kilowatt-hours per kilogram (kWh/kg) to the thermodynamic minimum, the overall process efficiency refers to the higher heating value of 39.405 kWh/kg. Low-temperature

Table 1. Properties of hydrogen [42, 43].

Property	Value
Mass (1 kg)	11.1 Nm ³
Heating value	LHV: 33.3 kWh HHV: 39.4 kWh
Energy density	1 kg H_2 = 3.77 L gasoline 1 Nm ³ H_2 = 0.34 L gasoline
Water electrolysis (1 MW) (~5 kWh/Nm ³ H_2)	200 Nm ³ /h H_2 ±18 kg/h H_2
Energy (1 kg H_2)	±55 kWh of electricity 11.1 Nm ³ ±10 L of demineralized water
Power (PEM fuel cell) 1 kg H_2	(±50% efficiency) 16 kWh
Boiling point	−253°C
Density at 0°C, atm	0.90 kg/m ³
Flammable range in air	4%–75%
Minimum ignition energy	0.017 mJ

LHV (Lower Heating Value) and HHV (Higher Heating Value) are measures of the energy content of fuels (with LHV excludes the latent heat of vaporization, while HHV includes it).

electrolysis requires around 175 MJ/kg of energy to produce hydrogen at 350 bar under steady-state conditions [41].

4. Question 3. What are the critical components of offshore wind-to-green hydrogen systems?

Offshore wind-powered hydrogen production can be implemented using either fixed-bottom foundations in shallow waters (up to 60 m depth) or floating platforms in deeper waters [44]. The systems use specialized electrolyzers adapted for seawater desalination and electrolysis to produce hydrogen [45]. This versatile approach can be deployed across various offshore locations worldwide, with the choice between fixed or floating structures depending on water depth, seabed conditions, and local marine environment [46]. When developing offshore hydrogen solutions, careful consideration of design elements, including foundation type, platform stability, electrolysis systems, and hydrogen transport infrastructure, is essential. While floating offshore wind is a promising development area, fixed-bottom turbines are currently the dominant technology in the offshore wind industry. A schematic of the various components is presented in Fig. 4.

4.1 Offshore wind turbines

The facility includes wind turbine rotors, a nacelle (housing the generator, gearbox, etc.), and a tower to generate green electricity. The floating foundations for the wind turbines are either single-spar or semi-submersible [48]. Offshore wind is desirable for producing power since it has faster and more reliable wind speeds.

4.2 Desalination

Since very pure water is needed for hydrogen synthesis, seawater must first be desalinated before it can be used.

4.3 Water electrolysis

The electrolyzer stacks the water treatment unit for demineralized water production. It is powered by renewable wind energy to split the hydrogen from desalinated seawater [48]. This increases the plant's capacity to meet the wind farm's maximum power

production [1]. The electrolyzer can be located either onshore (with hydrogen transported via pipeline) or offshore, directly on the platform or on a nearby dedicated platform. Offshore electrolysis minimizes hydrogen transport costs but introduces maintenance and seawater management challenges.

4.4 Offshore platform

Serving as a central hub, an offshore platform houses the electrolyzers and desalination plant, harnessing wind, wave, and solar energy for hydrogen production and managing resources efficiently, minimizing reliance on external support. All system components should be able to resist variable wind turbine power and repeat start-stop cycles without experiencing undue wear or delay [4]. Mooring systems anchor the floating platform to the seabed and must be designed to withstand harsh offshore conditions.

4.5 Hydrogen storage and transport

A facility for the liquefaction and distribution of hydrogen to ships is crucial for marine transport. Hydrogen gas is compressed to 700 bars to optimize storage density using an ionic compressor and reducing the storage volume compared to atmospheric pressure. At this pressure, hydrogen achieves a density of approximately 42 kg/m³, requiring about 9500 m³ of storage volume for 400 tonnes of hydrogen, accounting for standard safety factors and vessel design. Large-scale facilities can potentially store up to hundreds of tonnes of hydrogen, provided sufficient infrastructure and space are available. Furthermore, carrying energy as molecules (such as hydrogen through a pipeline) instead of electrons allows for significantly cheaper energy transportation at more enormous volumes (electricity through a cable) [49]. The high-pressure hydrogen gas is kept in a tank system made of modules. Tanks made of lightweight composite material are less expensive and weigh less. The green hydrogen is moved offshore to the onshore locations using a hydrogen pipeline. The hydrogen that has been extracted is compressed and stored in preparation for tanker delivery to the shoreline. At first, installing an undersea transmission line to deliver electricity to land could seem much more expensive than carrying hydrogen from offshore rigs by

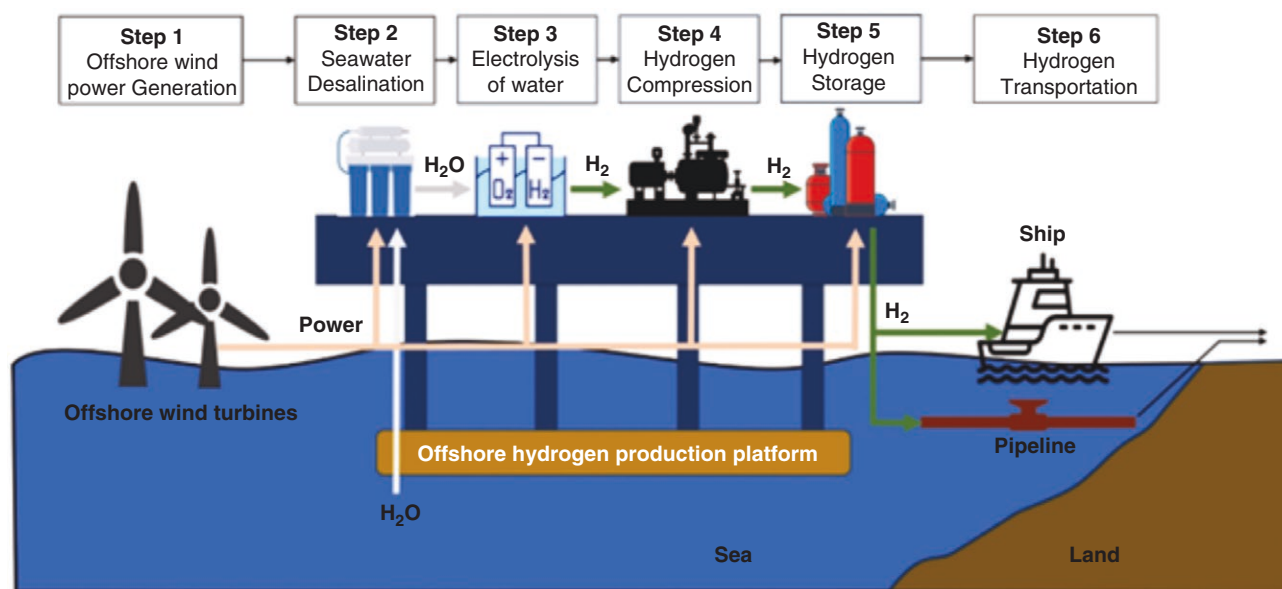


Figure 4. Schematic of offshore hydrogen production from wind. Reproduced from Chen et al. [47] with permission from Elsevier.

Table 2. Comparison of electrolyzer technologies for offshore application.

Feature	PEM	Alkaline	SOEC
Operating temperature	50–80°C	60–80°C	700–900°C
Operating pressure	Atmospheric up to 40 bar (g)	Atmospheric up to 30 bar (g)	Pressurized at 20 to 50 bar (g)
	52–57 kWh/kg H ₂	50–70 kWh/kg H ₂	37–45 kWh/kg H ₂
Efficiency	Medium	Lower	Highest
Water purity	Ultra-pure required	<20 µS/cm	<5 µS/cm
Footprint	Small	Larger	Medium
Cost	Higher	Lower	High (but potentially decreasing)
Response time	Fast	Slower	Slow
Lifetime	Up to 60 000 hours	Up to 80 000 hours	Not fully known
Offshore suitability	Suitable (with proper protection) for platform-based Subsea-based (modified PEM electrolyzer)	Challenging (due to size and motion) Suitable for floating system	Less practical (due to high-temperature requirements)

pipeline. A semi-submersible floating turbine with onboard electrolyzers was the most affordable option for all ranges 50, 100, and 250 km from the shore. The cost of high-voltage cables back to shore diverges beyond 100 km [50]. The approach, however, has lower power density and higher maintenance needs [51].

4.6 Onshore facilities

Power runs back to onshore electrolyzers. Green hydrogen produced from renewable sources can be easily stored in pipelines, salt caverns, or depleted gas fields to mitigate the disadvantages of intermittent renewable energy [44].

4.7 Backup source

If wind power is unavailable, a battery and fuel cell backup system work together to supply the energy required to keep crucial equipment running. As a result, wind energy can be stored and utilized, ensuring a continuous power supply [6]. As an alternative, wave power can be used for electrolysis, H₂ compression, and desalination because it is a more reliable energy source than wind. Furthermore, wave and tidal energy technologies may face less public resistance due to their lower visual impact than wind turbines, potentially leading to more significant deployment and utilization.

5. Question 4. What is the critical role of electrolyzers in offshore green hydrogen production?

A relatively underappreciated technology known as an electrolyzer plays a crucial role in environmentally friendly hydrogen production by using electricity to separate water into hydrogen and oxygen [52]. More than 200 years ago, scientists first discovered the electrolysis process, leading to the introduction of commercial electrolyzers in the 1920s. Unlike wind turbines and solar cells, which are relatively straightforward, electrolyzers can be more complex to understand. Smaller, modular versions consist of clusters of electronics and machinery housed in containers the size of shipping boxes or refrigerators, while larger electrolyzers typically present a more intricate arrangement of tubes and pipes. Notably, when powered by renewable sources such as solar, wind, or nuclear energy, the electrolysis process produces no greenhouse gas emissions. While other hydrogen production methods generate emissions requiring capture and storage, electrolyzers produce carbon-free hydrogen [12]. Water electrolysis is a promising technology for hydrogen production,

with three main types: proton exchange membrane (PEM), alkaline electrolyzer (AEL), and solid oxide electrolyzer cell (SOEC) (Table 2). PEM electrolyzers stacked in multiple layers separate water into high-purity hydrogen and oxygen. Compact and adaptable PEM electrolysis can react instantly to intermittent power supplies. Each type has unique characteristics and challenges, particularly in offshore applications. Integration with RES, especially offshore wind, presents opportunities for sustainable hydrogen production but faces challenges related to remote locations and fluctuating power [53]. Critical components for green hydrogen production include offshore renewable energy, water electrolysis, and transportation infrastructure, with three main design approaches: onshore electrolyzer, offshore central electrolyzer, and integrated electrolyzer at each wind turbine.

Figure 5 shows a comparison of the various electrolysis production and consumption techniques [14].

1. Onshore hydrogen production: To absorb some of the fluctuating power from offshore wind energy, the hydrogen production station employs water electrolysis to make hydrogen, and the remaining stable power transmission network successfully reduces the effects of offshore wind energy oscillations on the grid system [15].
2. Offshore partial hydrogen generation: The electrolytic water hydrogen production device is directly incorporated from the fan's direct current (DC) bus bar.
3. Off-grid hydrogen production: To achieve off-grid operation, the hydrogen and pure oxygen are carried onshore once the power is generated onsite. Alternative current/direct current (AC/DC) inverters, wind turbine transformers, and other devices are eliminated, along with undersea cables, sea booster stations, and transformers.

6. Question 5. How do we store green hydrogen in offshore geological sites? What are the knowledge gaps in offshore and onshore hydrogen storage?

Our annual changes in energy demand are relatively small. However, the inherent unpredictability of marine RES, such as solar, wind, and wave power, presents significant challenges to achieving a consistent energy supply [54]. For instance, periods of low wind can hinder energy production, leading to potential shortfalls in meeting demand. Consequently, achieving a fully

renewable energy system necessitates integrating energy storage solutions, such as hydrogen electrolysis, which utilizes excess electricity generated during peak production times [55]. Offshore green hydrogen storage systems employ multiple methods depending on site conditions and capacity requirements. For larger volumes, the idea is to store significant amounts of energy by pumping extra hydrogen into various deep geological storage sites, providing a scalable solution. However, this depends on suitable geological formations available at the offshore sites (Fig. 6) [13]. This storage can occur in subsea salt caverns, offshore aquifers, and subsea-depleted hydrocarbon resources (gas reservoirs) [42]. Subsea-depleted oil and gas reservoirs offer large storage capacities and existing infrastructure. They also require careful assessment for hydrogen compatibility in the marine environment (e.g. seawater intrusion, corrosion). Subsea salt caverns can be created by solution mining in offshore salt domes. They offer high injection and withdrawal rates but are geographically limited and require careful environmental assessment. Offshore aquifers are water-bearing rock formations beneath the seabed. They offer sizeable potential storage volumes but require exten-

sive geological characterization and prudent management to prevent hydrogen leakage into the marine environment. Until it is needed, the hydrogen might remain there for days, weeks, or even months. This stored hydrogen can subsequently be pumped, stored, and converted back into electricity when energy production is minimal, facilitating a continuous and reliable energy supply throughout the year [56]. This stored hydrogen can subsequently be pumped, stored, and converted back into electricity when energy production is minimal, facilitating a continuous and reliable energy supply throughout the year [57].

6.1 Current advancement/broader perspective/knowledge gaps

Hydrogen, a tiny particle, might permeate the rock. This can eventually result in hydrogen loss while being stored [13]. Experimental testing under the appropriate pressure and temperature conditions is required to determine the potential for diffusion and general subsurface movement. Large-scale modeling studies can also take advantage of the findings [55]. Hydrogen may chemically react with nearby rocks and minerals as it comes into touch with them. Reduced gas purity and hydrogen loss may be the outcome [53]. Understanding the size and speed of hydrogen reactions in storage environments is crucial. Certain bacteria that consume hydrogen are often found in underground storage sites, and more research is needed on how hydrogen storage affects these microorganisms, their growth patterns, and possible inhibiting factors. Additionally, hydrogen's interaction with underground gases and water needs further investigation [54]. Mixing hydrogen with other gases, such as methane or CO₂, and water or brine, could have unknown effects on hydrogen purity and potential losses. Furthermore, the best geological locations for hydrogen storage remain unclear, highlighting the need for targeted geological mapping [54]. Due to hydrogen's unique properties and behavior in geological formations, experiments must be conducted under high pressures, temperatures, or salinities.

7. Question 6. What are the main problems with hydrogen leakage?

Hydrogen is attractive as a potential means of maintaining current energy consumption levels without reliance on fossil fuels.

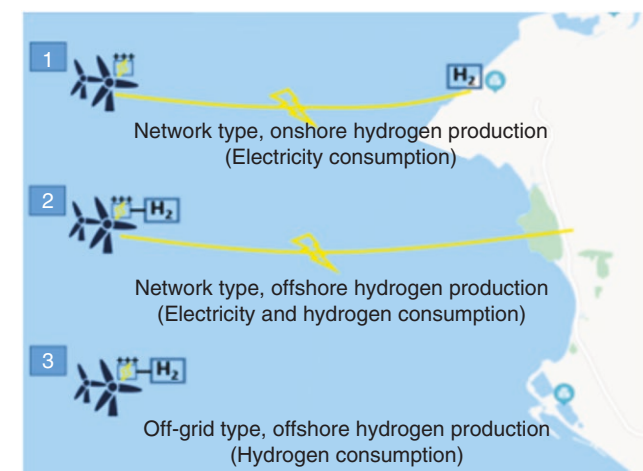


Figure 5. Different methods of electrolysis production and consumption [14].

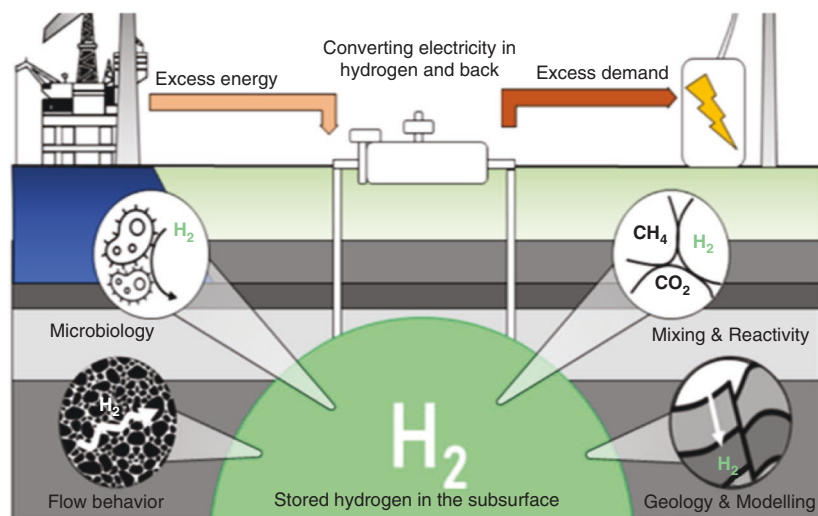
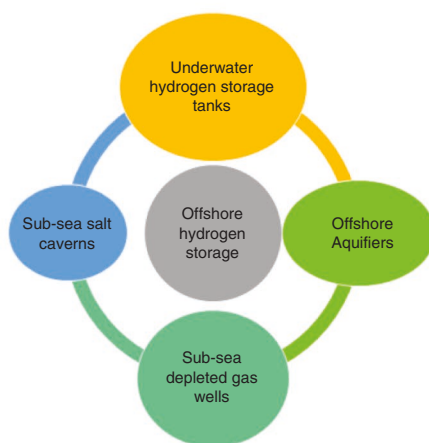


Figure 6. Schematic of underground and offshore hydrogen storage. Source: Illustration courtesy of Dr Nicole Dopffel, Norwegian Research Centre (NORCE), Norway.



However, stringent safety protocols and robust infrastructure are essential for widespread hydrogen adoption. Robust safety protocols and rigorous standards are necessary for safely handling and using hydrogen. Due to its colorless and odorless properties and its classification as a highly flammable gas, hydrogen production, transportation, and storage process presents a certain level of associated risk, potentially caused by uncontrolled events [58]. Therefore, achieving high levels of safety across the entire green hydrogen infrastructure value chain will be crucial, starting with design and engineering and ending with operation and maintenance (O&M) [58]. In addition, hydrogen combustion can produce nitrogen oxide (Nox) compounds, recognized as indirect GHGs due to their role in ozone formation and the breakdown of methane in the atmosphere.

Furthermore, the byproduct of hydrogen fuel cells, water vapor, is a naturally occurring greenhouse gas. The release of water vapor into the atmosphere by hydrogen fuel cell aircraft could influence climate change, particularly at high altitudes, where it contributes to contrail formation and impacts the radiative budget [35]. Secondary reactions of NO and NO₂ with acidic aerosols can result in the formation of N₂O. NOx is controlled in gas turbines at about 10 ppm, and selective catalytic reduction (SCR) has a 90% control efficiency. Formed N₂O in ambient should be in parts per trillion (ppt) ranges since NOx dilutes to parts per billion (ppb) ranges, so it is not even close to CO₂ or methane. Atmospheric deposition of nitrogen compounds to land or water can also result in a reaction that gives rise to N₂O under appropriate conditions. Most combustions cause NOx pollution, which is toxic even in parts per million (ppm) concentration, so combustion and leakage of hydrogen is not a good option [26]. However, the atmospheric residence time of N₂O is 120 years, and the greenhouse warming potential is 300 times that of CO₂. Water vapor emissions do not affect the amount of water vapor in the atmosphere. Hydrogen emissions interfere with the degradation of methane and other GHGs, making them last longer, so their effective global warming potential (GWP) rises [59]. There is no way to monitor or repair leaks in buried underground pipes. The leakage rate may be more significant, and the GWP of H₂ is similar to methane [60]. Currently, technologies to reduce leakages are nonexistent. Proper research needs to accurately assess the impact of switching from fossil fuel burning to hydrogen combustion or using open-loop hydrogen fuel cells in aviation and other applications.

8. Question 7. Who are the major players in chasing the islanded green hydrogen?

Several companies are looking at offshore hydrogen production, including RWE, Siemens, TotalEnergies, and ENGIE Group. The various companies involved in the offshore hydrogen project are listed in Table 3.

9. Question 8. What are the opportunities, strengths, and key drivers of the system's levelized cost of hydrogen?

Locating hydrogen production offshore streamlines ship refueling operations and eliminates the need for onshore space allocation. The facility to generate liquified green hydrogen might be housed on platforms once used by the oil and gas sector [47]. Additionally, from an economic standpoint, the anticipated drop in the investment costs of wind turbines and electrolyzers may be an additional benefit. The naval industry can be decarbonized with the

help of new infrastructure to generate and refuel liquid green hydrogen directly offered on the sea. The pipeline infrastructure can bring hydrogen to shore at a low cost and high pressure [61]. Hydrogen shipping to shore, electrolysis equipment, and wind farms are the main cost factors. The primary requirements for the project's financial feasibility are the electrolysis units and the wind park, which are anticipated to experience significant cost reductions. Table 4 highlights the key drivers of offshore hydrogen projects, including decarbonization goals, abundant offshore energy resources, synergies with other industries, declining costs, financial incentives, and the growing need to address global climate concerns and energy demands.

A levelized cost of hydrogen (LCOH) model was developed to understand the key variables affecting the cost of manufacturing green hydrogen from offshore wind [4]. The LCOH is a metric used to characterize the costs of hydrogen generation across the lifetime of the assets, much like the levelized cost of electricity, which is often used in the renewable energy sector [62]. The LCOH represents the average cost per unit of hydrogen produced over a project's lifetime, considering capital expenditures (CAPEX), operational expenditures (OPEX), and other expenses. The net present value (NPV) of hydrogen generation can be expressed as the sum of the NPV of CAPEX, OPEX, and transport costs. The detailed expression is as follows:

NPV Hydrogen generation

$$= \text{NPV CAPEX} + \text{NPV OPEX} + \text{NPV TRANSPORT COSTS} \quad (3)$$

The expense of producing green hydrogen is now the most significant barrier to development [7]. Because the electrolyzers—the technology used to make green hydrogen—are still too expensive, hydrogen is three times more costly than natural gas and far more expensive than gray or blue hydrogen [7]. The production cost of gray hydrogen can be as low as roughly 1 USD/kg H₂ for regions with low gas/coal prices, such as the Middle East, Russia, and North America. At the same time, it remains well below 2 USD/kg H₂ for other regions, including Europe [63]. Price estimates for green hydrogen now range from USD 2.5 to USD 6 per kilogram of H₂. This shows that, in most cases, green hydrogen is more expensive than gray and blue hydrogen, but at the lower end of the range, it is cost-competitive with blue hydrogen [64]. The lowest LCOH was calculated to be 2.4 €/kg for offshore electrolysis and hydrogen-driven operation mode, which is competitive with the price of gray and blue hydrogen at the time [64]. Table 5 presents a comparative analysis of the costs associated with offshore green hydrogen production relative to other energy carriers, highlighting the economic considerations and competitiveness within the energy sector.

In 2018, according to the hydrogen trajectory report from KPMG, the LCOH of gray hydrogen rose from \$1.2 to \$2.8 per kilogram, the price of blue hydrogen rose from \$1.5 to \$4 per kilogram, and the price of green hydrogen ranged from \$3 to \$6 per kilogram, which makes investments still not affordable, especially in some geographical locations [24]. Meanwhile, there is a global strategy to reduce the prices of electrolyzers. Green hydrogen is expected to become economically competitive from 2030, heading to 2050, when the production cost will reach the market price of \$2 to \$3 per kilogram [65].

The cost of electricity from offshore wind farms, capital investment in electrolyzers, expenses related to constructing and maintaining offshore platforms, pipelines, and storage facilities, along with operational and maintenance costs, desalination, hydrogen purification, storage, and transportation to end-users, all contribute significantly to the overall cost of offshore green hydrogen production. Key cost drivers include capital costs, electrolyzer efficiency, and wind farm capacity factors [43].

Table 3. Companies involved in offshore hydrogen projects (planned and operational projects).

Company	Country	Project details	Technologies used	Source
Ørsted	Denmark	SeaH ₂ Land: deliver green hydrogen to industrial clusters near the Netherlands and Belgium.	Offshore electrolysis Integration with wind farm	http://seah2land.nl/
Siemens Energy	Germany	HySynGas: syngas production combines hydrogen from offshore sources with CO ₂ to produce synthetic fuels.	Offshore hydrogen electrolysis Advanced gasification and syngas technologies	https://www.siemens-energy.com/global/en/home/
Neptune Energy	The Netherlands	H ₂ opZee: conversion of oil platform into hydrogen production station	Pump hydrogen ashore to the Netherlands Existing infrastructure of natural gas pipelines	https://www.rwe.com/en/research-and-development/hydrogen-projects/h2opzee/
Engie & Equinor	Belgium	H ₂ BE project: technical and economic suitability of a potential location in the Ghent area	Natural gas using ATR technology combined with CCS	https://www.h2be.eu/
RWE	Germany	AquaVentus: large-scale green hydrogen from offshore wind GET H ₂ Nukleus: first hydrogen pipeline network in Germany	Offshore wind-based hydrogen production Hydrogen storage and pipeline infrastructure	https://www.rwe.com/en/research-and-development/hydrogen-projects/
TotalEnergies	Spain and France	H2Med project: hydrogen corridor between Spain and France	Offshore hydrogen production is linked to RES	https://h2medproject.com/the-h2med-project/
Engie	North Sea, Belgium	PosHYdon: feasibility study for an offshore green hydrogen production concept	Existing gas infrastructure	https://poshydon.com/en/home-en/
Lhyfe & Chantiers de l'Atlantique	France	Sealhyfe: first offshore green hydrogen production in the Atlantic Ocean	SEM-REV offshore testing Hydrogen production under harsh conditions	https://www.ir.pluginpower.com/press-releases/

Centrale Nantes, SEM-REV, is the first site for multi-technology offshore testing that is connected to the grid. ATR, autothermal reforming.

Table 4. Some key drivers of offshore hydrogen projects.

Description
Decarbonization goals of energy-intensive industries
The ocean covers two-thirds of the earth's surface
The positive impact of the Marine Renewable Energy project
Increasing global climate concerns and energy prices
Availability of redundant offshore natural gas pipelines
Fast-developing Asian market and geographical expansion
Declining cost and energy innovations
International competitiveness of hydrogen, financial incentive, and market leadership
Electrical transmission issues the grid's resilience with a single source
Specific challenges of island communities and the oil/gas industry
Abundant offshore energy resources and production capacity
Synergies with other industries

As of 2024, based on literature, LCOH cost targets and estimates for offshore green hydrogen varied widely due to the nascent state of the technology and site-specific factors [66].

Near-term (2025–30): \$4–8/kg H₂
 Mid-term (2030–40): \$2–5/kg H₂
 Long-term (2040+): \$1.5–3/kg H₂

These projections assumed continued cost reductions in both offshore wind and electrolyzer technologies. The economic feasibility of offshore green hydrogen projects depends on achieving a competitive LCOH [63].

10. Question 9. Why is the global community studying offshore green hydrogen hubs, and what are the strategies for achieving a green hydrogen economy?

Hydrogen and fuel cell technology development has been characterized by periods of high expectations, often followed by the realization of significant practical and economic barriers. A real hydrogen economy will be necessary, involving markets, infrastructure, pricing, carbon trading, and risk management [54]. Because it will empower participants from various value chain segments to drive innovation, such an ecosystem will be transformative [67]. Hydrogen offers a cleaner-burning alternative to fossil fuels in applications such as factories, power plants, and jet aircraft, as its combustion primarily produces water vapor (and some NO_x under certain conditions) [68]. Hydrogen can also be made from fossil fuels like coal and natural gas, though these methods have a higher carbon footprint. Existing natural gas pipelines can be repurposed to transport hydrogen, though some modifications may be necessary to ensure compatibility and prevent leaks [9]. Unlike previous attempts, recent advancements—driven by lower renewable energy and fuel cell costs,

stricter climate regulations, and substantial engagement from China—offer a more realistic pathway for hydrogen to play a key role in the energy transition [43]. Japan, Australia, China, and South Korea are currently the leading nations in the Asia-Pacific (APAC) area regarding hydrogen technology innovation [69]. The Netherlands and Germany are two of the most active European countries regarding pilot project implementation and hydrogen technology innovation [70]. Transmitting energy from areas of abundant, inexpensive resources to higher-demand markets is a long-established paradigm [71]. In the past, it was thought that renewable electricity would be brought from northern Africa to Europe. Although numerous complex non-technical barriers to this development must be overcome, some technical issues must be resolved, such as the prohibitive cost of creating power transmission lines from Africa to Europe [69]. However, hydrogen can be used as an energy vector to travel long distances in pipelines, ships, or trucks for a lower price than power transmission cables, whether gaseous, liquified, or stored in various forms [72]. There are multiple obstacles to overcome for the hydrogen economy to replace fossil fuels [64]. These difficulties include producing hydrogen from clean sources, dealing with hydrogen storage, producing pure hydrogen for fuel cells, building the infrastructure for making and using hydrogen, and dealing with safety and environmental issues [73]. Continuous research, commercial interest, investment, and government regulations supporting hydrogen fuel use can all help overcome these adoption barriers [74]. However, coordinating cross-sectoral investments necessary for hydrogen value chains can be complicated and increase risk, particularly for new network infrastructure [75]. To achieve the required advancements in hydrogen utilization, governments, energy providers, and hydrogen advocates must prioritize three critical activities:

- ✓ Increasing the adoption of low-carbon hydrogen in existing industrial applications [76].
- ✓ Expanding the range of applications for hydrogen [14].

Table 5. Cost of offshore green hydrogen compared to other energy carriers [64].

Unit measure	H ₂ offshore	Gasoline	Natural gas
kWh/kg	33.3	12.00	14.7
£/kg	6.5	1.49	0.26
£/kwh	0.18	0.124	0.018

- ✓ Addressing the hydrogen's lifecycle management issue to optimize its longevity and effectiveness [25].

As governments, energy providers, and the general public accept hydrogen fuel more frequently, it can be used in several crucial sectors, as indicated in the following sections [8]. Figure 7 highlights the major factor influencing the green hydrogen economy [77].

The following key steps are needed to create a viable hydrogen economy [78].

10.1 Strategy

To plan investments, governments, stakeholders, and manufacturers need to have a comprehensive understanding of long-term hydrogen supply and demand [74].

10.2 Policy

Governments must develop enticing regulations and subsidiaries to promote the use of hydrogen fuel in a way that benefits manufacturers, suppliers, distributors, and consumers [21].

10.3 Green hydrogen infrastructure

The development of large-scale manufacturing, storage, transportation, and distribution infrastructure is required for the hydrogen economy [44].

10.4 Research and development

To lower costs and increase performance, more work must be done on the hydrogen economy's complete supply chain, notably regarding electrolyzers, fuel cells, membrane and storage systems, etc. [15].

10.5 Summary of strategies towards green hydrogen economy

Expanding renewable energy capacity forms the backbone of green hydrogen production. Advanced electrolyzer technologies supported by government incentives and industry investments are essential to reduce costs and scale production. Infrastructure development, from hydrogen pipelines to refueling stations, is critical to ensure efficient distribution and accessibility. Carbon pricing and market mechanisms must be implemented to create an economically viable green hydrogen market. These policies will close the cost gap between green hydrogen and fossil fuels. Simultaneously, international cooperation and standardization will enable the continuous trade of hydrogen across borders. Education and workforce development are equally important,

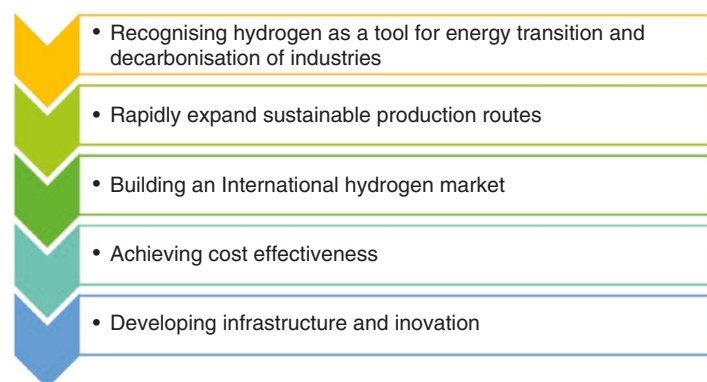


Figure 7. Significant factors influencing the green hydrogen economy.

ensuring that a skilled workforce is ready to meet the demands of this emerging industry. Demonstration projects showcasing the use of hydrogen in real-world applications can inspire confidence and encourage adoption across sectors. Governments must provide stable, long-term policies and funding for research and development to accelerate innovation. This holistic approach will position green hydrogen as a cornerstone of the sustainable energy transition, driving economic growth while mitigating climate change.

11. Question 10. What are the scientific challenges, knowledge gaps, and focus areas on offshore hydrogen production?

The practical difficulties in commercializing green hydrogen are in the four phases of production, storage, transportation distribution, and use [79]. Based on current infrastructure and capacities, the strategy designates ammonia and pipelines as the primary means of long-distance hydrogen transport. A growing role for liquid hydrogen or liquid organic hydrogen carriers (LOHCs) is also possible. These technologies are, however, less developed than the earlier ones [73]. Although offshore hydrogen production holds significant promise, there are still numerous hurdles to overcome. These challenges encompass political, economic, technical, and environmental implications. Table 6 provides an overview of the technical challenges associated with the production, storage, transportation, and utilization of offshore green hydrogen, emphasizing critical areas requiring further research and development.

While green hydrogen currently represents only about 1% of manufactured hydrogen globally, offshore production is emerging through pilot projects and demonstrations, with several large-scale developments planned or under construction. The offshore green hydrogen sector is in its early stages but showing promising growth with multiple projects in development worldwide. The optimal offshore energy system must be chosen in technical and economic terms. The offshore hydrogen hub is mainly impacted by the wind turbine capacity factor [81]. The offshore green hydrogen production and storage module should be

built following international norms and standards, particularly those governing the specifications and layouts of loss prevention and safety systems [6, 78].

Additionally, these facilities would act as a catalyst for research on floating structures for ocean energy consumption, supporting the growth and diversification of the shipbuilding sector in the regions where they would be used [82]. Large-scale green hydrogen production may offer additional possible business prospects as an energy hub. Extra costs might be necessary for other processes and infrastructure installations [83]. Higher O&M expenses and shorter electrolyzer models and systems lifespan could result from the hub's operations using an offshore wind farm with high, unpredictable wind speeds [25]. Five significant obstacles include a sizeable initial expenditure, complex planning and design, a lack of fast modeling technology, a lack of technical standards, and an undeveloped business model that are considered critical barriers of offshore wind-to-hydrogen projects (OWHPs) and should therefore be given more focus and effort [84]. The transportation of hydrogen to the onshore and new technology requirements are two additional difficulties associated with offshore hydrogen production [49]. The production of electricity and hydrogen, the amount of hydrogen, market demand, the price of hydrogen and electricity, and other factors all affect the technical and economic elements in general [6]. The amount of electrolysis capacity that may be mounted on the platform is constrained by weight and space [80]. Due to high finance costs and the industry's high-risk status, along with significant issues with offshore construction and operation, technology is still in its infancy [61]. Table 7 lists some critical areas where businesses in the green hydrogen sector can develop, industrialize, and compete with companies worldwide.

12. Concluding remarks

The decarbonization of numerous sectors, including transportation, electricity production, and industry, is primarily supported by green hydrogen. The essential elements of offshore hydrogen generation and storage have been reviewed in this study through questions and answers. The information presented in this work

Table 6. Technical challenges in production to end-use of green hydrogen [80].

Green hydrogen production	Green hydrogen storage	Transport and distribution	End-use
Improved onsite compressors and overall energy efficiency are required.	Due to its low specific gravity, compressed hydrogen storage requires a lot of energy.	The infrastructure for hydrogen transport is insufficient to satisfy anticipated demand.	Vehicles and fuel cell stacks require compressed hydrogen gas tanks that are as light, large, and inexpensive as possible.
A low lifetime of electrolyzers	Requires temperature and pressure while storing hydrogen in solid form.	Because of embrittlement, existing natural gas pipelines cannot be used to transport hydrogen directly.	The fuel cell needs to be improved in terms of efficiency, degrading problems, durability, resiliency, size, power, and current densities.
High complexity and scaling of the process	Aspects of design, legal difficulties, societal challenges, and high cost	The flow of hydrogen at refueling stations is not precisely controlled.	There are no systems to keep track of the system's health and performance.
	Safety problems are raised by the materials' low storage durability (fiber, metals, polymers, etc.) and probable chemical reactions.	Temperature variations during quick transfers of compressed hydrogen	High fuel cell system complexity, particularly in heat and water management, purification, and humidification
	Hydrogen may become contaminated during bulk storage at geographical characteristics, necessitating additional purification before use.	It is necessary to expand the network of hydrogen refueling stations.	Fuel cell runtime for portable electronic gadgets must be increased without growing larger.

Table 7. Key focus areas [85].

Type	Remarks
Industrialization and innovation	It is possible to industrialize the production of turbines and foundations, but this will require even more part standardization.
New integrated design	Better integrated designs allow for more effective offshore installation, significantly lowering costs.
Digital maintenance	Remote digital structural health and condition monitoring of OWE facilities is crucial to cut maintenance costs. AI-based technology and autonomous process control of the plant.
Self-healing materials	Over the wind farm's lifetime, using self-healing materials in the blades can significantly save maintenance and repair expenses.
Optimized wind farm control	It is currently unclear how large-scale aerodynamic interactions occur within wind farms. Using simulations and physical models to comprehend these interactions better is vital.
Larger turbines	Manufacturers are making larger and larger turbines, and 20 MW variants are already in the works.

OWE, offshore wind energy.

provides several insights into the project's potential for investment by developers. From the literature review, it can be concluded that:

- Most (96%) of hydrogen produced today uses carbon-intensive processes (from gas, oil, and coal). However, developing a robust global supply chain, supported by diverse offshore hydrogen production pathways, is essential for realizing a sustainable hydrogen economy.
- The ongoing expansion and engagement of local and international policy players, industrial partnerships, and economic coalitions support an optimistic outlook for hydrogen in the global energy system. Future large-scale deployment and integration of renewable energy globally will be based on green hydrogen islands.
- Renewable hydrogen can reduce carbon emissions in a wide variety of applications. Offshore wind, Power-to-X, and green energy systems provide new exciting opportunities for the world and thus can contribute to significant economic growth and job creation.
- The entire hydrogen value chain must be aligned with sustainability goals to realize hydrogen's full decarbonization potential. A sufficiently high carbon price on gray hydrogen production could make offshore hydrogen production more economically attractive.
- Before sites are decommissioned, it is crucial to map the prospective locations for offshore hydrogen production where the current oil and gas infrastructure meets existing offshore wind farms.
- Building electrolyzers alongside RES may become a low-cost hydrogen supply option as solar PV and wind energy costs continue to fall, even after accounting for transmitting and distributing hydrogen from far-flung areas to end consumers.
- Although supply chain optimization and technological advancement can reduce overall CAPEX, the cost of fuel (OPEX) is determined by the availability of a low-carbon electricity source, which is now a limiting constraint.

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Author contributions

K Sudhakar (Conceptualization [equal], Investigation [equal], Writing—original draft [equal]), S. Shanmuga Priya (Project administration [equal], Resources [equal], Software [equal], Visualization [equal], Writing—review & editing [equal]), and Mohd Fairusham Ghazali (Project administration [equal], Supervision [equal], Validation [equal], Visualization [equal], Writing—review & editing [equal])

Conflict of interest statement

None declared.

Data availability

No new data were generated or analyzed in support of this research.

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