Supply Chain Insider
Volume 21, Issue 01,105-131. 27-09-26
Article Received: 01-09-2026
Accepted: 11-10-2026
Available Online: 15-10-2026
ISSN: 2617-7420 (Print), 2617-7420 (Online)
DOI: 10.5281/zenodo.23311160
supplychaininsider.org

Optimization of the Seawater-to-Hydrogen Value Chain: A Safety-Integrated Framework for Hydrogen Production, Storage, and Distribution.

Anudip Das Srijon[1], Athiey Sarker[1], MD. Mehedi Hasan[1], MD. Nayeem Hasan[1], Shahriar Zaman Siam[1]

sarkerathiey3@gmail.com

Abstract

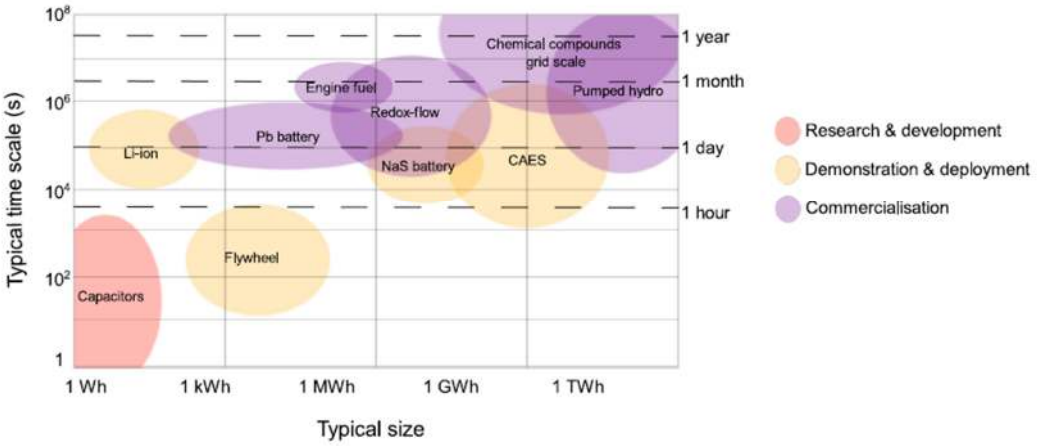
Increasing demand for clean energy to reduce carbon footprint and as well as to reduce fossil fuel consumption has become very important globally. Among all alternatives, hydrogen is the more reliable candidate to replace fossil fuel. seawater electrolysis is increasingly recognized as a promising technology for green hydrogen production. As to production for large scale surface water or ground water will not be enough so for large scale production of Hydrogen from sea water electrolysis is a better choice. This article will provide comprehensive analysis of recent Advancements of water electrolysis and examine an integrated seawater-to-hydrogen supply-chain framework for sustainable hydrogen production in coastal areas. This article also evaluates technical, economic and environmental factors affecting the supply-chain performance, along with solutions how to overcome these problems. And for sea water electrolysis use of renewable energy to reduce the cost of production as well as reduction of pressure on the electricity. Also hydrogen blending with fuels to minimize the dependency on fossil fuels. Particular attention is given to storage the Hydrogen fuel as liquid fuel, or convert the H2 fuel to more stable liquid ammonia or other products, as it can damage pipe lines or storage tanks, and we also give a solutions to overcome this problem. This article also addressed the transportation of hydrogen fuel problems and their solutions. Some ways of transportation are land transportation via trailer and pipeline, overseas shipping and some related commercial data, are reviewed. Nevertheless, brine management, equipment corrosion, high infrastructure investment remain key challenges. This study provides a basis for designing safe and sustainable green-hydrogen supply chains in coastal regions, including how to minimize production costs with the help of other renewable energy sources to split seawater. Moreover, this study also provides solutions to overcome the challenges of safe storage and transportation.

Keywords: green hydrogen, seawater splitting, clean energy, decarbonization.

Introduction:

Because of the rapid growth of population the need for energy is increasing day by day. The global energy sector depends heavily on fossil fuel thus fossil fuel reserves are rapidly depleting. The burning of fossil fuels releases

greenhouse gas(GHG) , which is responsible for global warming. Renewable energy sources including solar, wind, hydro, geothermal, ocean thermal energy conversion (OTEC) and biomass are the leading candidates to replace fossil fuels(Santanu et al., 2023). The global transition towards sustainable energy has necessitated the exploration of alternative fuels to effectively reduce greenhouse gas emissions and mitigate climate change(Mi Tian et al., 2025). Among all alternatives, hydrogen is the cleanest and most environmentally safe fuel with zero carbon footprint, and has strong potential to replace fossil fuels. England, USA, Canada, Australia, Germany, Ireland, Japan, South Korea and China has accounted on hydrogen and invested millions of dollars on establishing the hydrogen economy . Among them, Australia, India, China, Japan, and Korea has completed the formulation of hydrogen policy (Gour Chand et al., 2021). The transportation sector, which emits a growing quantity of GHG emissions, must reduce its GHG emissions by atleast 60% to meet the EU's targets of 80% to 95% reduction in GHG emissions by 2050 (Israt et al., 2025). However, large-scale hydrogen production via water electrolysis faces several difficulties, such as the shortage of freshwater resources, high electricity requirements, and infrastructure limitations. To address these challenges, seawater can be used as an alternative water source for electrolysis. Hydrogen, with one of the highest specific energies (142 MJ/kg), can be an excellent alternative to fossil fuels .Hydrogen can be produced from water electrolysis, using electricity from renewable energy sources that



result in lowest CO_2 foot print worldwide(Sepanta et al., 2023).

Seawater, the most abundant water resource on Earth,covers approximately 71% of the planet's surface and has nearly inexhaustible reserves. The successful industrial application of seawater electrolysis will bring multiple benefits. Firstly, it will significantly reduce pressure on freshwater resources and provide humanity with a clean energy source for sustainable development. Furthermore, seawater electrolysis for hydrogen production can be integrated with offshore wind power, offshore solar power, and other renewable energy sources to create a novel clean energy production system (Yixin et al., 2024).

H_2 was found to reduce component degradation and increase efficiency, allowing for > 80 % renewable energy penetration . H_2 is best suited for long-term seasonal storage but is expensive while batteries are more cost-effective but better for short-term storage. Batteries can be used on a daily basis but are more expensive for long-term energy storage (Ashleigh et al., 2023).

Figure 1.1: Size, scale and maturity level of storage technologies (Ashleigh et al., 2023).

Due to the global inflation of the Ukraine–Russia war and the rise in crude oil prices, many types of diesel and gas-powered power plants are currently closed in the country. The coal reserve is also alarming. A long energy

plan including renewable and hydrogen energy is being emphasized to reduce the dependence on fossil fuels. Incorporation and integration of hydrogen energy into the energy mix of Bangladesh have not been attempted and studied yet (Md Abdus et al., 2023).

Notwithstanding that large chlor-alkali plants utilize this process to produce chlorine gas, the amounts of Cl_2 that would be produced along with the quantities of H_2 required for energy storage at global scales would quickly exceed the demand(Hank Garg et al.,2025).

Chlorine gas not only causes equipment corrosion but also poses toxicity risks, necessitating effective measures to prevent chlorine gas generation and release. some studies have explored adding specific additives to the electrolysis process to inhibit the attack of Cl^- on the anode substrate, thereby improving the stability of seawater electrolysis electrodes(Yixin et al., 2024).

Seawater's complex ionic matrix, rich in chloride (Cl^-), magnesium(Mg^{2+}), calcium (Ca^{2+}), and various organic and microbial constituents, introduces multiple complications during electrolysis. Compared with freshwater electrolysis, Direct seawater electrolysis introduces two coupled difficulties. (i)Electrochemical selectivity, where the chlorine evolution reaction (CER) competes with OER at the anode. This not only compromises the Faradaic efficiency for oxygen production but also generates harmful chlorine gas and corrosive intermediates that can degrade catalysts and membranes . (ii)Chemomechanical durability, where chloride, magnesium, and calcium species accelerate corrosion, passivation, and precipitation, while organics and microorganisms can foul interfaces. These constraints elevate the role of catalyst/electrode architectures that simultaneously modulate electronic structure, interfacial ion distributions, and gas–liquid–solid transport(Pratama & Chan Woo Lee ,2026)

Generally, water electrolysis includes two half reactions, the anodic oxygen evolution reaction (OER) and cathodic hydrogen evolution reaction (HER).Both of these reactions require efficient electrocatalysts to reduce the overpotentials of energy consumption, especially for the OER, which involves a four electron transfer process with a high energy barrier. Owing to the high-concentration(~0.5 M) of chloride anions in seawater, the chloride evolution reaction (CER) will also take place on the anode at a relatively high potential, which will compete with the OER. For the CER in a basic solution, the chlorine will react with OH^- to form hypochlorite with an onset potential of 490 mV higher than that of the OER, thus requiring highly active OER catalysts to drive large current densities at the overpotential below 490 mV to avoid the formation of hypochlorite.(Cheng Wang et al., 2021).

Additionally, the chemical compounds and contaminants present in seawater progressively diminish the efficiency of the electrodes. Therefore, additional purification steps are required to ensure high purity water feeds, Significantly increasing the overall cost. Consequently, especially in large-scale offshore hydrogen production, bypassing the pre-treatment systems through direct seawater electrolysis offers tremendous potential to enhance economic viability regarding system design, reduced capital costs, minimized maintenance, and smaller physical footprints (Monireh et al., 2025).

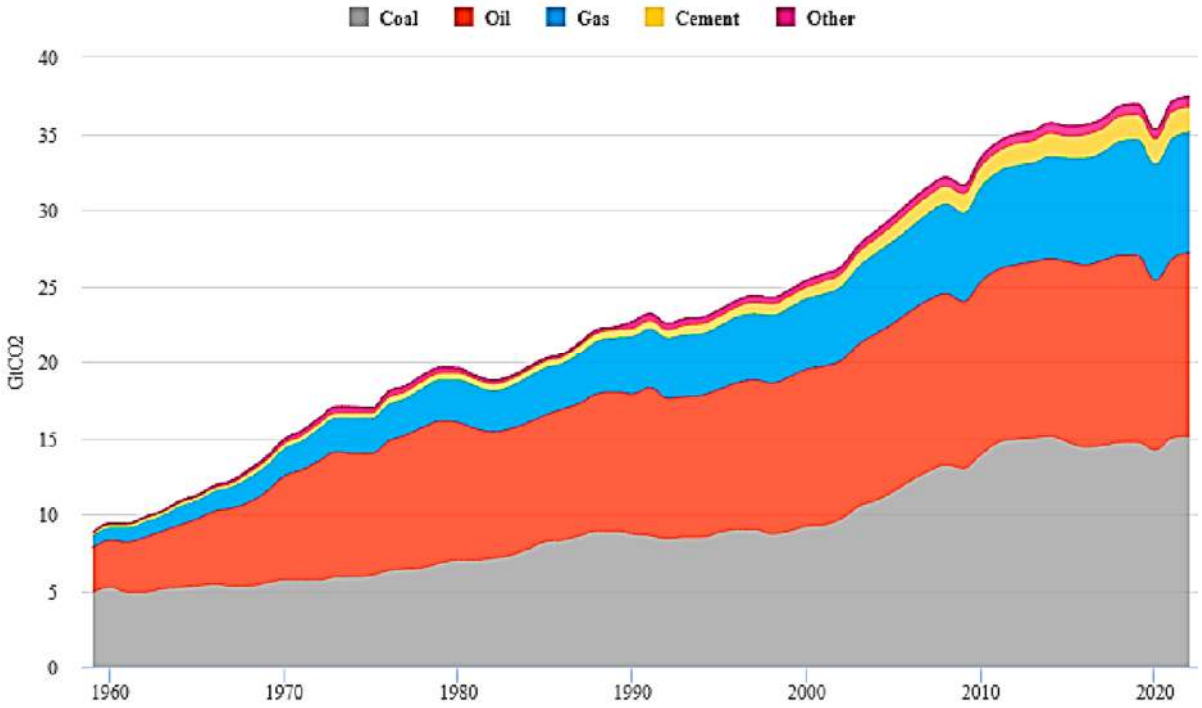


Figure 1.2: Schematic of direct seawater electrolysis and conventional electrolysis coupled with desalination(Monireh et al., 2025).

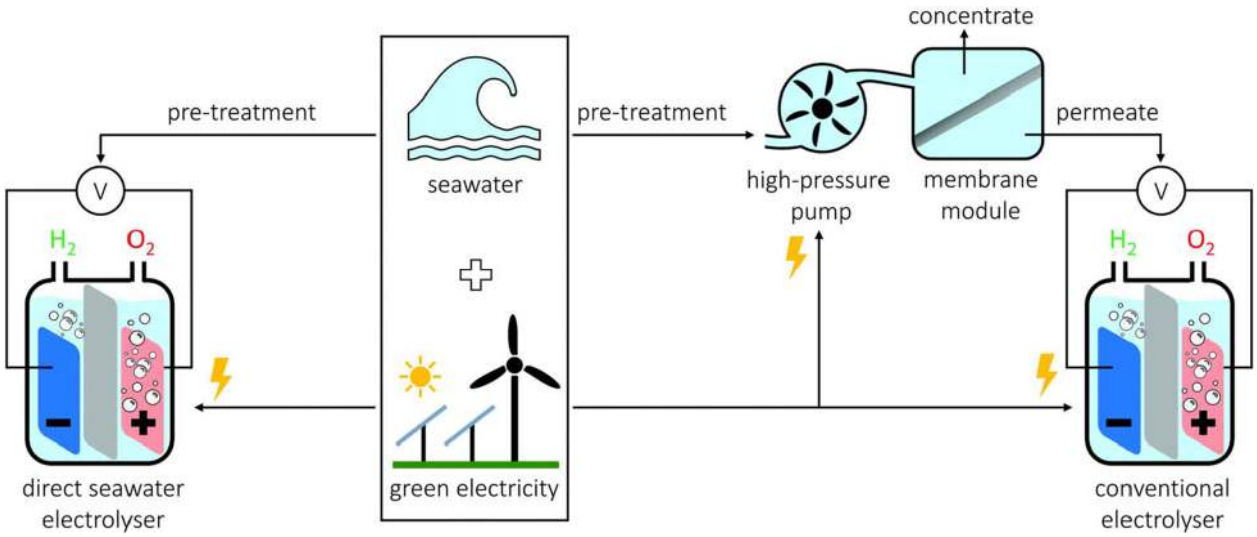


Figure 1.3: Annual CO2 emissions from different types of fuels (Santanu et al.,2023)

Statistically, Bangladesh imports 26% of its natural gas to meet power demand. Bangladesh also imports electricity from India, around 3500 MW, as reported by the Energy and Mineral Resources Division-FY (2022–23) . Still, the demand cannot be fulfilled. Approximately 76% of the population has access to electricity. The situation is worse in rural areas, and it is a bitter truth that 70% of the total population lives in rural areas, whereas 42% have been bestowed with electricity . As fossil fuel-based energy sources affect the environment, and to put

a step towards sustainable energy, Bangladesh started to expand its energy production landscape to renewable energy sources. Approximately 2.87% of total electricity is produced from renewable energy sources in recent times. And to meet both purposes of environmental safety and meeting energy demand, hydrogen can play a vital role in the economy of a country like Bangladesh(Md. Nasirul et al.,2026).

2. Hydrogen Production from Seawater:

2.1 Process Pathways and Design Basis:

Among of the hydrogen production routes, renewable energy-based water electrolysis is particularly relevant to hydrogen production in seaside location. But for this route we have to ensures the renewable electricity production source, cost, balance of plant (BOP) requirements, and finally efficiency of the electrolysis(Dash et al., 2023; Dincer & Acar, 2014). Though sea water provides hydrogen, it does not compete with freshwater. Because seawater contain dissolved salt, suspended solid and many living organisms. Thus, two major pathways are assumed for hydrogel production from sea water. Direct sea water cannot be used in electrolysis due to its high chlorine content, corrosion, scaling capability. So, there needs a pretreating the seawater by screening, desalination, and polishing the water to low conductivity and then a commercial electrolyzer. Since this route removes impurities and hardness ions and particulates, it is the most technically applicable route at this time. During DSE (Direct Seawater Electrolysis) the untreated seawater is directly use in electrochemical device for electrolysis, whereas in ISE (Indirect Seawater Electrolysis) desalination train is required for electrolysis. Its simple block flow and low footprint make it desirable for coastal plants. At the same time, electrodes and membranes need to be resistant to completing corrosion, precipitation and chlorine- chemistry(Zhang et al., 2024). Combining water purification and electrolysis are the third and intermediate concept. Hydrophobic or ion selective membrane allows water while blocking seawater ions and offer a blend of direct and indirect compact design production system. So, the selection of pathways should not only take into consideration; the elimination of desalination equipment but pathway level reliability and hydrogen purity

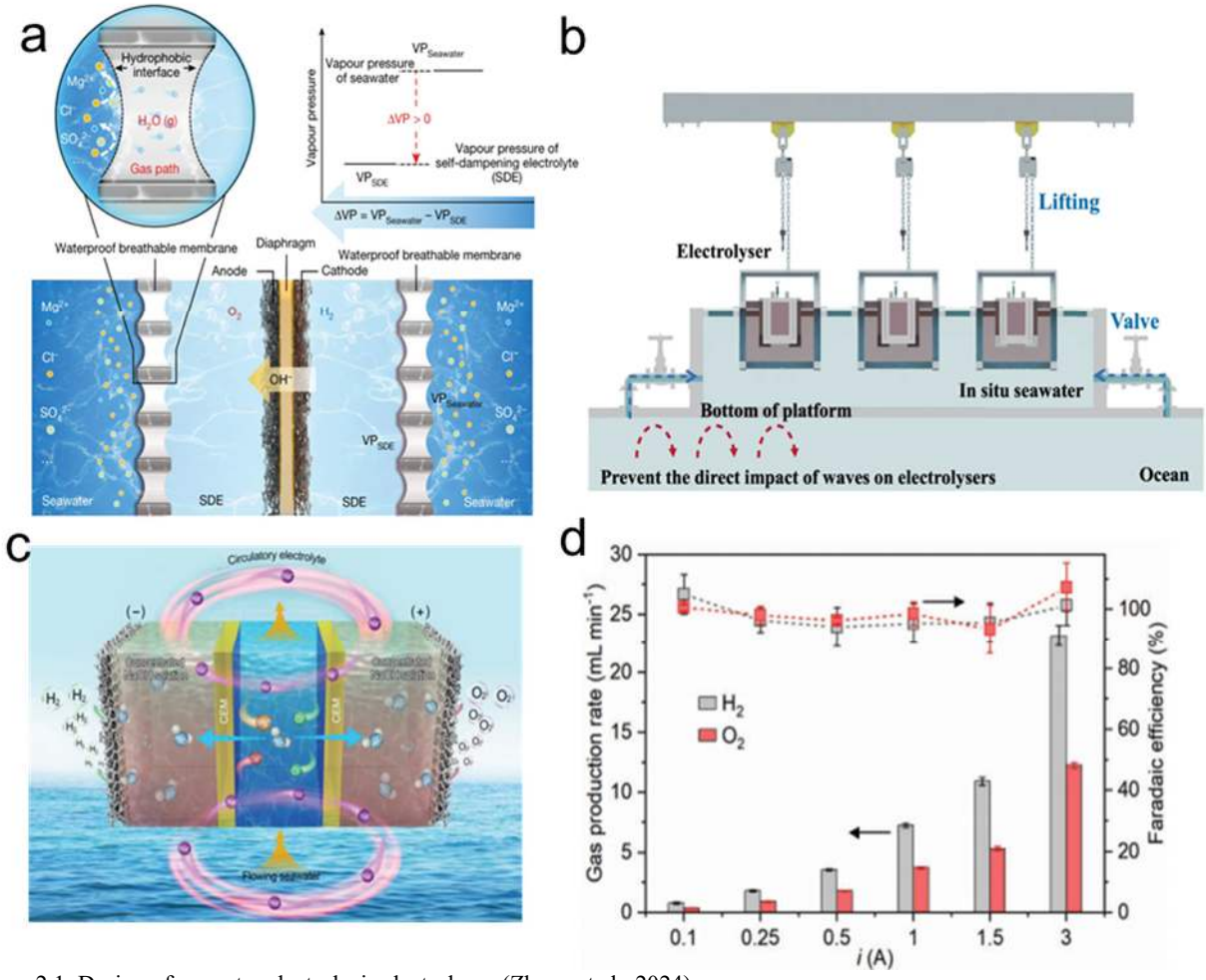


Figure 2.1. Design of seawater electrolysis electrolyzer (Zhang et al., 2024)

2.2 Electrolyzer Configurations:

Proton-exchange membrane electrolysis (PEM), alkaline water electrolysis (AWE) and anion-exchange-membrane (AEM) electrolysis are most relevant configurations. In AWE, generally alkaline solution is used as an electrolyte (typically KOH). This configuration has a level of commercial maturity due to comparatively low capital, low specific energy requirement for application, in addition to the use of inexpensive nickel-based materials. But traditional alkaline arrangement is complicated, response is slow enough, and handling of electrolyte has to be carefully managed. In contrast, PEM provides high current density and high purity pressurized hydrogel production due to its solid polymer membrane. Again, it is an ideal solution for wind and solar electricity for its fast response, but this process is costly due to acetic operation noble metal catalyst and corrosion resistance stack parts. Stated by (Henry et al., 2023) in commercial-unit comparison, at a H_2 production efficiency of 70.78%, the specific electricity demand of an alkaline system was 58.94 kWh kg^{-1}, and for PEM, H_2 production efficiency at 68.96%, the specific electricity demand was 62.44 kWh kg^{-1}. Though this result is scenario dependent, it shown the importance of equipment selection. AEM electrolysis uses less-expensive transition-metal catalysts. Nowadays the main problem of AEM is chemical durability, industrial lifetime, and membrane conductivity(Dash et al., 2023). During stable baseload conditions and for short term seawater project RO-AWE is suitable for its lower cost. In contrast, direct RO–PEM is suitable when the scales are smaller and

when renewable intermittency is more significant. However, these techniques are still upgrade, which would need long-term validation

Fig. 2.2. Principal electrolyzer configuration(Dokhani et al., 2023)

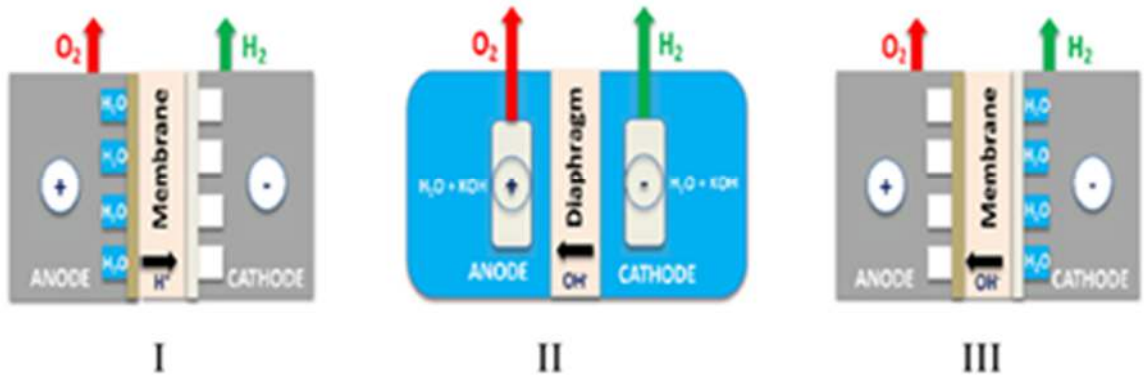


Table 2.1. Comparative assessment of electrolyzer configurations

Feature	AWE	PEM	AEM
Electrolyte/ion	Liquid alkaline electrolyte (OH^-)	Solid acidic membrane (H^+)	Solid anion membrane (OH^-)
Strength	Low-cost catalyst, large scale output	High purity H2 production, rapid response	Potential use of non-noble catalyst with compact membrane assembly
Key limitation	Large validation, caustic handling and gas separation control	High cost for noble metal catalyst and corrosion resistant component	Chemical stability, lifetime, and scale-up
Best renewable duty	Stable	Highly variable wind/solar	Emerging option
Electricity use	58.94 KWh Kg^{-1}	62.44 KWh Kg^{-1}	Not established

(Dash et al., 2023; Henry et al., 2023)

2.3 Chloride Competition, Anode Corrosion, and Catalyst Selectivity:

During Direct Seawater Electrolysis (DSE), the main challenge is that the undesired chlorine evolution reaction (a two-electron pathway) is kinetically preferred rather than the desired four-electron pathway for oxygen evolution reaction (OER). As seawater contain large amount of chloride ion, it can absorb at the anode and react to form metal–chloride intermediates, which can penetrate passive layer, initiate corrosion and reduce the sensitivity of catalyst or the current collector. Chlorine and hypochlorite can create toxic, and contaminated products. Four complementary design strategies can be employed: i) Use highly active OER catalyst that enhances

OER at lower potential range rather than CER, ii) develop a layer that block chlorine at the electrode-electrolyte interface, iii) ensures the desired oxidation reaction is more favorable on the anode side rather than chlorine formation, and iv) consume chlorine species or remove chlorine species rapidly (Zhang et al., 2024). Protective treatment at anode like, sulfidation, phosphidation, selenization, and layered double hydroxide coating, helps to change surface chemistry and protect from chloride ions. Catalyst screening needs to now consider OER selectivity in real seawater, chlorine formation, corrosion rate and faradaic efficiency at industrial current densities.

2.4 Cathodic Precipitation and Fouling Control

At cathode, hydrogen evolution generates hydroxide ion which causes to increase PH. Due to the precipitation of magnesium species and calcium species, reagent resistance increase that inhibit mass transfer, and reduce current density. Magnesium hydroxide forms at a lower pH than calcium hydroxide, so even the macro level "OK" electrolyte can experience extreme fouling at the micro scale at the cathod(Zhang et al., 2024). Hydrodynamic and interfacial controls are much more desirable than purely periodic chemical cleaning. Forced circulation of electrolyte/seawater reduces Concentration and PH gradient and again three-dimensional porous electrodes help to remove the bubbles and self-cleaning cathode eliminate unwanted deposit by the help of hydrogel bubbles. Hardness ions may be blocked from reaching a nucleation site by means of an ion-rejecting surface layer and/or through local pH regulation via the use of "proton sponge" materials. Via an ion-rejecting surface layer and proton sponge materials, hardness ion may be blocked from reaching a nucleation site through local PH regulation. During balance-of-plant design, the range and frequency of filtration, periodic polarity-reversible washdown and clean-in-place operations should be considered.

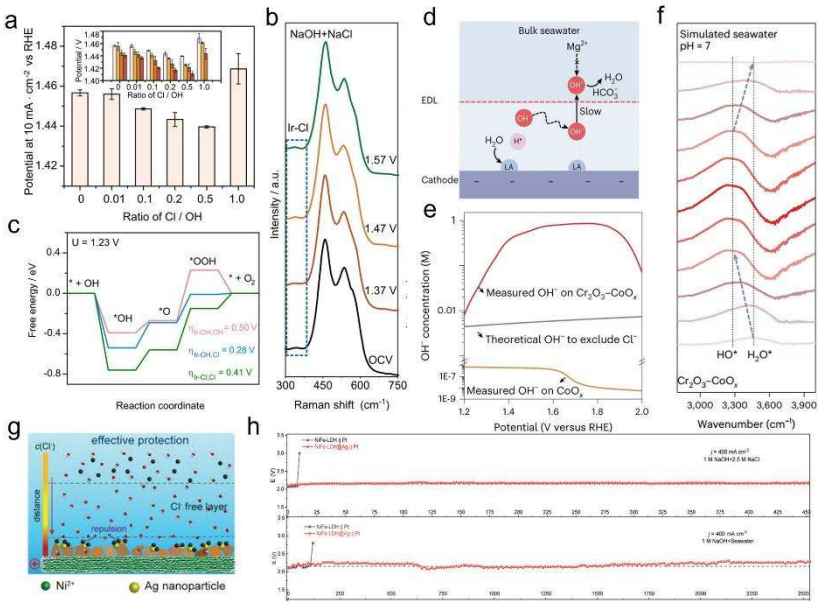


Fig 2.3. Cathodic precipitation, self-cleaning strategies in sea water electrolysis (Zhang et al., 2024)

2.5 Desalination Coupling and Energy-Efficiency Optimization

The key process for hydrogen production from seawater include water intake and screening, RO desalination, deionization/polishing, a buffer tank, electrolysis, gas–liquid separation, hydrogen drying and purification, compression, and oxygen handling and/or venting. Pretreatment increase equipment cost and consumes additional energy, though the energy and cost penalties are relatively low. (Dokhani et al., 2023) have estimated that pretreatment(desalination) requires almost ~ 1% of the total process energy and ~ 1% of the total hydrogen cost under their case for desalination of seawater, which results the total cost of hydrogen is ~ US$3.51 kg^{-1} under

the given grid and infrastructure conditions. However, energy, water, and financing cost can vary by location, those numbers are not representative for all locations. Electricity consumption in the electrolyzer remains the largest energy and cost component. So, system optimization should be minimized total specific energy consumption while maintaining the stack lifetime. The required variables during optimization are current density, cell voltage, operating temperature, pressure, water recovery, electrolyzer turndown, storage support and renewable power source. Oversized electrolyzer can utilize peak renewable power, but it reduces the utilization, whereas the undersized one can maintain a high utilization, but reduces the available power. Alkaline type equipment can be used to generate hydrogen at lower cost in large continuous output, while PEM is expected to have improved dynamic operation(Henry et al., 2023). Measured profiles of renewable resources should be used to identify locations for wind-solar hydrogen systems (WSHS) for coastal Bangladesh. The seawater salinity, carbon intensity, cyclone exposure and infrastructure availability should also be considered. In particular, it is important for projects around the Bay of Bengal (Salam et al., 2023). Experimental trial prove that electrolysis equipment manufactured in Bangladesh can be integrated with solar and wind resources. However, its reported hydrogen purity, conversion efficiency, and production rate also highlight modes of further improvement and scalability validation prior to commercialization (Chand Mazumder et al., 2023).



Figure 2.4. Recommended indirect seawater to hydrogen process (Created by author)

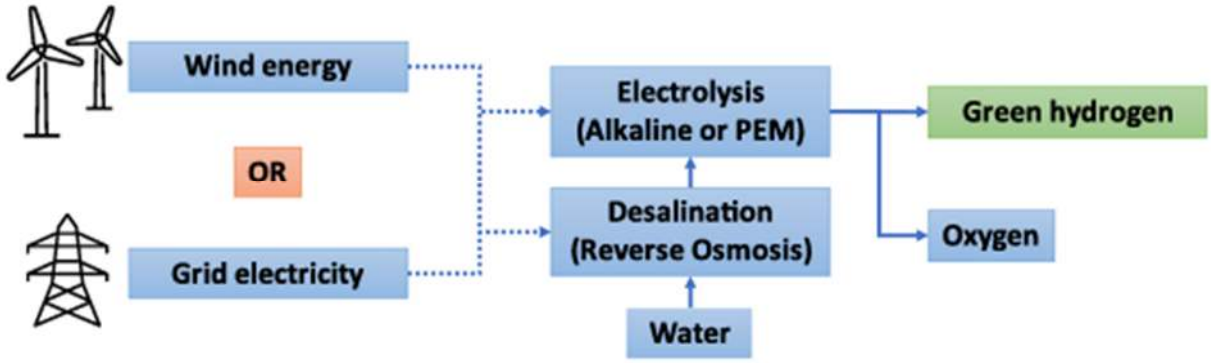


Fig.2.5. Schematic diagram for H2 production system using either wind or grid-delivered electricity(Henry et al., 2023).

2.6 Production Safety Barriers and Recommended Configuration:

Hydrogen and oxygen can form flammable mixture due to membrane damage, pressure imbalance, low-load operation, or blocked outlets. So, they must be kept physically separate each other with proper orientation. The production train should incorporate independent hydrogen and oxygen separators, purity analyzers, differential-pressure control to maintain gas separation safely. Again, automatic shutdown, non-return valves, flame arresters where applicable, ventilation should also be incorporate. Hydrogen and chlorine detectors, hazardous-area electrical classification pressure-relief devices, and corrosion-resistant wetted materials are essential for H_2 production. Since seawater contain a large amount of chlorine, chlorine detection is essential for any direct-seawater concept, where a positive signal should isolate the stack and divert off-gas to treatment again. Moreover, different operating procedure and interlocks are required for caustic exposure, high DC voltage, oxygen enrichment, and high-pressure hydrogen.

For current situation, the recommended configuration is- Screened seawater → Reverse Osmosis and polishing → Alkaline electrolysis or PEM, selected based on renewable variability and scale. In this structure, sea-water is first purified and removes all suspended solid, and ions from it before electrolysis through

commercial electrolyzer. This separation helps to maintain water quality, gas purity, and ensure safer operation. Direct and in situ desalination electrolysis should be advanced through modular pilots only after demonstrating sustained chlorine-free operation, deposit control, membrane integrity, and stable energy consumption under real seasonal seawater conditions. This design is cost effective and balances efficiency, operability, and process safety across the seawater-to-hydrogen value chain.

Downstream storage selection must also be treated as part of production safety. Compressed, liquid, cryo-compressed, and hydride-based systems impose different pressure, temperature, materials-compatibility, footprint, and lifecycle requirements(Barthelemy et al., 2017).

2.7 Supply-Chain Competitiveness, Research Gaps, and Strategic Direction

A competitive sea-water to supply chain must be optimized as a connected system rater than only an isolated electrolyzer. Stack utilization and maintenance requirements depend on coastal site selection, renewable-resource quality, intake design, pretreatment, and brine management.

Midstream performance depends on electrolyzer efficiency, durability, gas purity, dynamic operation, and availability of replacement components. Downstream competitiveness depends on drying, compression, storage, transport distance, end-user demand, and the value or disposal route for oxygen and brine. Therefore, low initial stack cost doesn't always mean a low hydrogen production. Rapid degradation, low utilization, expensive storage and frequent shutdowns can increase the final production cost (Barthelemy et al., 2017; Henry et al., 2023).

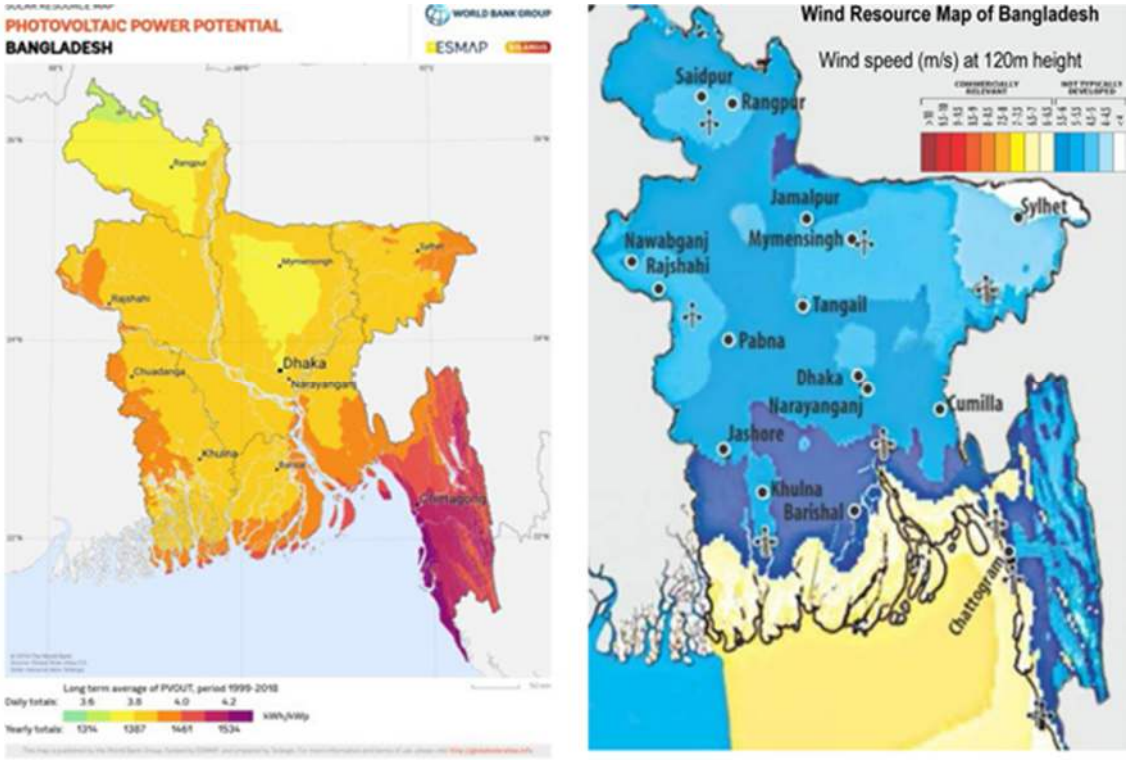


Fig 2.6.Solar Potential and wind-resource map in Bangladesh (Salam et al., 2023)

The evidence also exposes important research gaps. First of all, many direct-seawater studies have considered only initial overpotential, and short-term selectivity. There is less work on long-term stability at an industrial

current density in seawater. Secondly, catalyst studies rarely integrate chlorine monitoring, corrosion rates, scale formation, membrane ageing, and gas purity. Third, techno-economic result varies due to electricity price, capacity factor, financing, stack replacement, and infrastructure assumption. So, results result can differ for different location (Dokhani et al., 2023; Zhang et al., 2024). Fourth, some researches in Bangladesh demonstrate renewable-hydrogen potential. But unable to provide coastal supply-chain model incorporating cyclone resilience, seawater pretreatment, port logistics, demand aggregation, storage, and delivered cost (Chand Mazumder et al., 2023; Salam et al., 2023).

The strongest competition strategy is therefore a phased, evidence-led deployment. In Phase-1 seawater is screened, RO polishing, and a commercial PEM or alkaline stack, with technology selected against the measured power profile and required output. Phase 2 should localize balance-of-plant fabrication, establish preventive maintenance and spare-parts capability, and link production to dependable industrial or mobility demand. Phase-3 may introduce direct seawater modules, confirms chlorine-free operation, deposit control, durable membranes, acceptable degradation, and delivered-hydrogen. This approach converts seawateravailability into a reliable supply-chain advantage without transferring unresolved electrochemical risks into commercial operations.

Table-2.2. Decision framework for a competitive seawater-to-hydrogen supply chain

Supply Chain stage	Primary value driver	Main Risk	Competition Priority
Resource	Renewable capacity factor	Weak infrastructure, cyclone	Design properly to endure cyclone and use measured wind/solar data
Water preparation	Stable feed quality and stack protection	Brine Impact, fouling	Optimize screening, RO, monitoring as one train
Electrolysis	Low electricity use, utilization & protection	Degradation, membrane dependence	Select AWE/PEM based on situation
Storage	Deliver pressure & buffer capacity	Leakage, and material ageing	Select storage capacity against demand, distance
Market & logistic	Demand & deliver H_2 price	Transportation cost & demand uncertainly	Locate plant near the demand, Make oxygen feasible

Source: (Chand Mazumder et al., 2023; Dokhani et al., 2023; Henry et al., 2023; Salam et al., 2023; Zhang et al., 2024)

3. Safe, Efficient, and Cost-Optimized Hydrogen Storage

Now there is a need to store hydrogen produced by seawater electrolysis or any other method that works with a production rate that varies over time and a demand that is moved, distributed and used at various times and locations (Moran et al., 2024). So storage is not a separate step but it is related to the production step in Section 2 and the transportation and distribution step in Section 4. The type of storage selected at the production site influences directly the way hydrogen can be transported, while the pressure, temperature and purity requirements of the chosen transport route limit the types of storage that can be employed. The main hydrogen storage technologies are discussed in this section, along with their performance, costs and suitability for purpose. It also

addresses safety hazards to be controlled at all levels such as leakage, high pressure, flammability, exposure to cryogenic temperatures, and material compatibility.

3.1 The Role and Classification of Storage in the Hydrogen Supply Chain

In the supply chain, the amount of hydrogen that needs to be stored ranges from a few grammes in a lab to hundreds of thousands of tonnes underground. Mehr et al. (2024) divide these needs into four groups: small/laboratory (up to 10 kg, 0.33 Wh–33 kWh); medium/vehicle (10 kg to several tonnes, 33 kWh–33 MWh); large (up to 100 t, 33 MWh–3.3 GWh); and huge/geological. For small-scale storage in a lab, metal hydrides and physical adsorbents work best. For medium- to large-scale storage, like in vehicles, petrol stations and factories, liquid organic carriers and compressed, liquefied and cryo-compressed hydrogen work best. For huge, seasonal storage volumes, underground geological formations are the only technically and economically viable option.

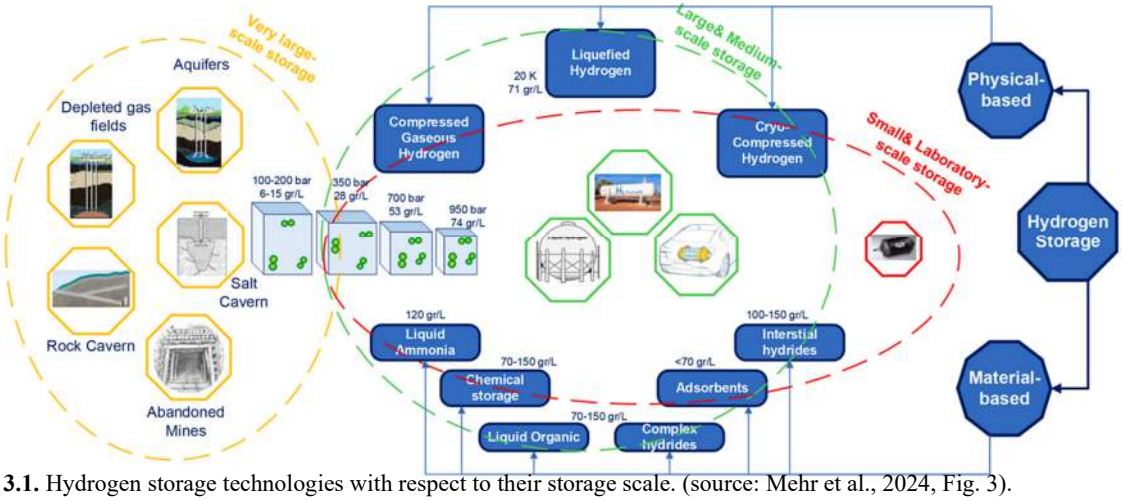


Fig. 3.1. Hydrogen storage technologies with respect to their storage scale. (source: Mehr et al., 2024, Fig. 3).

The technologies are divided into two families. Hydrogen is stored in its elemental form through compression (CGH_2), cooling below its boiling point (LH_2), or combining both (CCH_2). Material-based storage binds hydrogen to a carrier material or converts it into liquid organic hydrogen carriers (LOHC), metal hydrides, or "power fuels" like ammonia and methanol, which can be recovered. Hydrogen is an elemental gas, but underground geological storage uses natural rock formations instead of engineered vessels.

3.2 Physical-Based Storage: Compressed, Liquid and Cryo-Compressed Hydrogen

3.2.1 Compressed Gaseous Hydrogen (CGH_2)

No phase change or chemical bonding is involved in mechanically compressing hydrogen gas into a pressure vessel to store it. The process is fully reversible and requires no additional energy to reverse it. Table 3.1 lists four commercial vessel types. Type I vessels, fully metallic (steel or aluminium) cylinders rated to 15–30 MPa, have the lowest cost and gravimetric density (1.7 wt%) and are used for stationary industrial gas storage. Type II vessels, used for cascade storage at hydrogen refuelling stations, have a hoop-wrapped fibre composite over a metal liner and can withstand pressures up to 95–100 MPa. The preferred choice for tube trailers and on-board

vehicle tanks is Type III and Type IV vessels, which are fully wrapped with composite fibre over a thin metal or polymer liner and have gravimetric densities of 4.2 wt% and 5.7 wt%, respectively. They cost five to ten times as much as Type I/II vessels.

Vessel Type	Construction	Typical Pressure	Gravimetric Density	Indicative Cost	Main Application
Type I	Fully metallic (steel/Al)	15–30 MPa	1.7 wt%	~€77.5/kg H_2 (tank + gas)	Stationary industrial-gas storage
Type II	Metal liner, hoop-wrapped composite	up to 95–100 MPa	2.1 wt%	~€80/kg H_2	HRS cascade / stationary storage
Type III	Thin metal liner, fully wrapped composite	30–70 MPa	4.2 wt%	~€248–530/kg H_2	Tube trailers, on-board storage
Type IV	Polymer liner, fully wrapped composite	30–70 MPa	5.7 wt%	~€633/kg H_2	Lightest on-board/tube-trailer storage

Table 3.1. Pressure-vessel types used for compressed gaseous hydrogen storage (Mehr et al., 2024, and Yang et al., 2023).

CGH2 storage requires 1 to 3.3 kWh per kg of hydrogen to compress, depending on target pressure, with a negligible energy penalty upon release (Yang et al., 2023).

3.2.2 Liquid Hydrogen (LH_2)

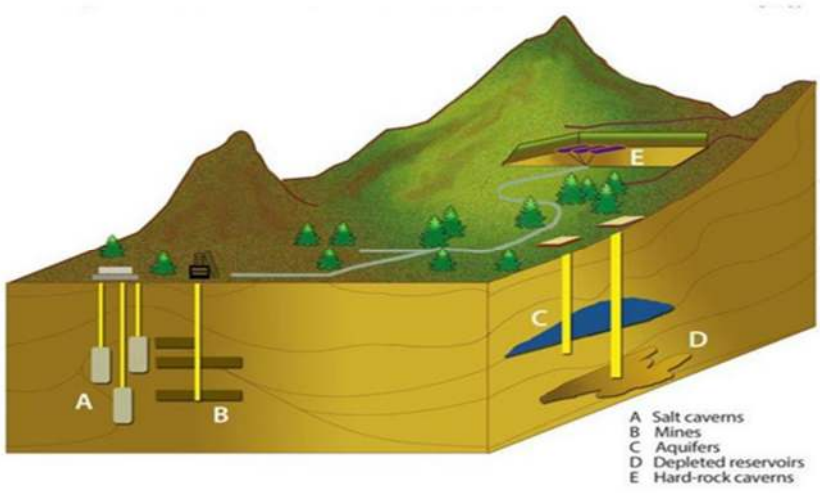
Liquid hydrogen storage cools hydrogen below its boiling point of 20.28 K, typically using a Claude-cycle liquefaction plant with liquid-nitrogen pre-cooling, and holds the cryogenic liquid in double-walled, vacuum- or multilayer-insulated tanks (Yang et al., 2023). Because hydrogen must also be converted from its ortho- to its more stable para-form during cooling, liquefaction is far more energy-intensive than compression, consuming approximately 6–10 kWh per kilogram of hydrogen (Yang et al., 2023). In return, LH_2 reaches a volumetric density of roughly 71 kg/m³, several times higher than CGH_2 at moderate pressure, which allows a single trailer or ship to deliver a far larger payload of hydrogen. The unavoidable drawback of cryogenic storage is boil-off: heat leaking into the tank continuously evaporates a small fraction of the stored liquid, at a rate of roughly 0.01–5% per day depending on the quality of insulation, and this vapour must eventually be vented, recompressed or productively used unless advanced multilayer-vacuum insulation or integrated refrigeration systems are installed (Yang et al., 2023).

3.2.3 Cryo-Compressed Hydrogen (CcH_2)

In a vacuum-insulated (Type-III-class) pressure vessel, cryo-compressed hydrogen is cooled above 20 K and compressed to 70 MPa. According to Yang et al. (2023),this method mitigate the boil-off problem of pure LH2 with a higher density than CGH2 at the same temperature. While CcH_2 is compatible with gaseous and liquid dispensing on automotive platforms, but is still in lower technology readiness than CGH_2 or LH_2 and requires a more complex, costly vessel that can withstand high-pressure and cryogenic failure modes (Yang et al., 2023).

3.3 Very-Large-Scale Underground (Geological) Storage

For seasonal or strategic buffering of hydrogen above roughly 100 tonnes, only underground geological formations offer sufficient volume at an acceptable cost. Compressed hydrogen (100–250 bar) is injected into a



salt cavern, the pore space of a saline aquifer, a depleted gas/oil reservoir, a lined hard-rock cavity or an abandoned mine and withdrawn on demand. Some 'cushion gas' must remain to maintain the working pressure. Salt caverns are ideal for hydrogen storage due to their 99% impermeability, low cushion-gas fraction (around 30%), and near-pure hydrogen delivery at a levelized cost of 0.25-1.58 €/kg H_2. Aquifers have large, widely available storage volumes but require a higher cushion-gas fraction (70–80%) and risk hydrogen loss through microbial consumption and lateral migration; depleted gas and oil fields fall between these two extremes. These two extremes reuse existing, well-characterised infrastructure at the cost of possible purity loss from residual hydrocarbons (Mehr et al., 2024). Because suitable salt, aquifer or reservoir geology is not available everywhere, the choice of geological storage option is ultimately site-specific, and it is this very large-scale storage layer that would need to absorb seasonal mismatches in a coastal hydrogen supply chain of the kind discussed in Section 2, where hydrogen production tracks a variable renewable-electricity resource.

Fig. 3.2. Underground hydrogen storage options: salt caverns, mines, aquifers, depleted gas/oil reservoirs, and hard-rock caverns (Mehr et al., 2024, Fig. 6).

3.4 Material-Based Storage: Chemical Carriers

3.4.1 Liquid Organic Hydrogen Carriers (LOHC)

Toluene/methylcyclohexane and dibenzyltoluene/perhydro-dibenzyltoluene systems chemically bind hydrogen through catalytic hydrogenation of an unsaturated "lean" carrier, forming a hydrogen-"rich" liquid that can be stored and transported at ambient temperature and pressure. Catalytic dehydrogenation regenerates the lean carrier for reuse. Dehydrogenation is strongly endothermic and requires 9 kWh of heat per kilogramme of hydrogen released (Yang et al., 2023). Hydrogenation is exothermic. LOHCs are liquid at ambient conditions, allowing for use of existing hydrocarbon fuel infrastructure and avoiding boil-off losses. They are ideal for medium-scale storage and long-distance transport, provided a source of waste or renewable heat is available for energy-intensive dehydrogenation and shipping costs are acceptable.

3.4.2 Metal Hydrides

Metal hydrides store hydrogen in solid lattices by chemical bonding, e.g [$Mg + H_2 \rightleftharpoons MgH_2$], and release it by heating (Mehr et al., 2024). This solid-state storage method provides the highest volumetric hydrogen density and is safer than compressed or cryogenic storage as it doesn't involves high pressure or cryogenic temperature. The theoretical capacity of MgH_2 is 7.6 wt%, but the practical gravimetric capacities is still low (1.4–2 wt%) and the desorption temperatures are high (300–900°C) with slow reaction kinetics. Currently metal hydrides are limited to small-to-medium-scale or specialised applications where compactness and intrinsic safety outweigh the costs and speed of hydrogen release (Mehr et al., 2024).

3.4.3 Ammonia and Methanol as Hydrogen Carriers

The reviewed literature calls ammonia and methanol "power fuels" that can act as indirect hydrogen carriers. Hydrogen is produced from methanol by steam reforming of methanol (which is made by hydrogenating carbon dioxide), and ammonia can be cracked back to hydrogen and nitrogen by the Haber–Bosch process (Yang et al., 2023 Ammonia liquefies at -33°C at atmospheric pressure or 20°C under 7.5 bar and both carriers have large, mature global shipping and handling infrastructure, shipping 17.5 million tonnes of ammonia annually. Ammonia is 17.7% hydrogen by weight. Ammonia synthesis and cracking back to hydrogen consumes 8.2–13.3 kWh/kg, and methanol synthesis and steam reforming consume 6.7 kWh/kg to release hydrogen (Yang et al., 2023). Thus, ammonia is most attractive when it can be used directly as a fuel or chemical feedstock, avoiding cracking, or when its shipping infrastructure is used to transport hydrogen long distances.

3.5 Storage Efficiency, Energy Requirements, Cost and Sizing

The storage technologies examined previously vary significantly in the energy required to achieve and subsequently revert the storage state, as outlined in Table 3.2. Compressed gaseous hydrogen

Storage Form	Energy to Establish Storage Condition (kWh/kg H_2)	Energy to Release H_2 (kWh/kg H_2)	Notes
CGH_2, 35 MPa	1–2.8	0	Compression only; no phase change
CGH_2, 70 MPa	1–3.3	0	Higher pressure raises compression duty
LH_2	6–10	0	Includes ortho-to-para conversion; boil-off adds further loss over time
Ammonia (NH_3)	8.2–13.3	~6.3	Haber–Bosch synthesis; cracking recovers H_2
Methanol (CH_3OH)	~2.3 (heat released)	~6.7	CO_2 hydrogenation is exothermic; steam reforming releases H_2
LOHC	~9 (heat released)	~9	Hydrogenation exothermic; dehydrogenation strongly endothermic
Metal hydride (MgH_2)	Exothermic (heat released on charging)	~10.3	A high desorption temperature limits practical use

Table 3.2. Indicative energy requirements to establish and later reverse the storage condition for different hydrogen storage forms (compiled from Yang et al., 2023, Table 6).

necessitates the minimal energy expenditure overall, as it solely relies on mechanical compression, with no energy required for gas release. In contrast, liquefaction and chemical-carrier methods (ammonia, LOHC, and methanol) each deplete a significant portion of hydrogen's intrinsic energy, both for establishing storage conditions and, in the case of chemical carriers, for extracting pure hydrogen at the utilisation site (Yang et al., 2023).

Cost is scale-dependent and follows a similar pattern. Salt-cavern storage is the most cost-effective option for large geological storage, with levelized costs ranging from 0.25 to 1.58 €/kg H_2. Aquifers and depleted fields require more cushion gas, resulting in higher costs (Mehr et al., 2024). After tank costs, medium-scale physical storage in pressure vessels costs €77.5/kg for heavy Type I cylinders and over €600/kg for the lightest Type IV composite tanks (Mehr et al., 2024). Figure 3.2 shows these costs across several representative storage options.

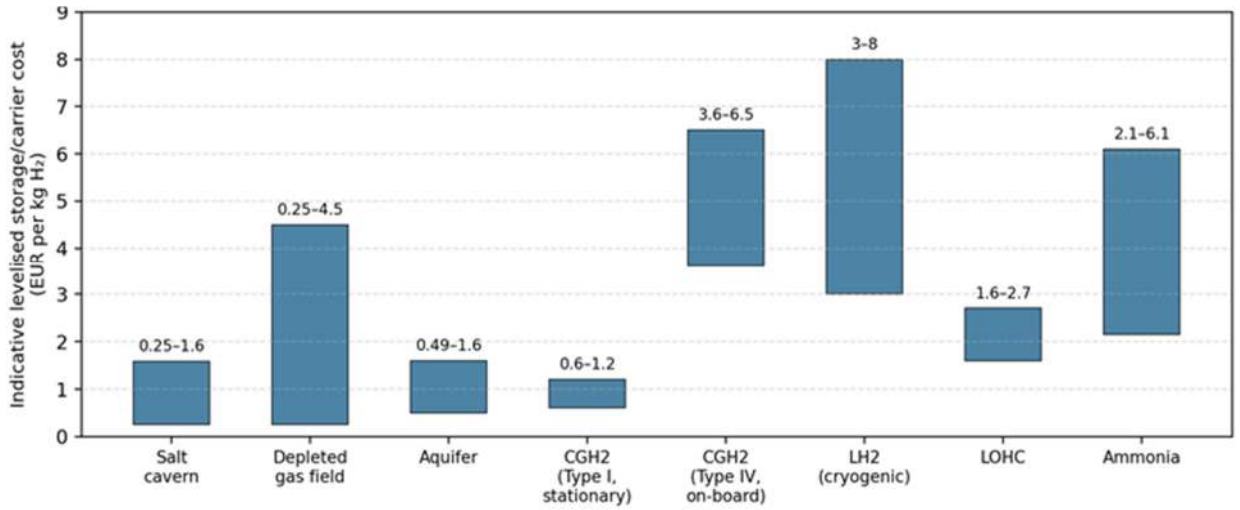


Figure 3.2. Representative levelised cost ranges are reported for large-scale geological storage and for medium-scale physical and material-based storage options (compiled from Mehr et al., 2024, and Yang et al., 2023).

Several system-level studies show that storage buffer size affects supply-chain cost, not just technology. After accounting for storage costs, Moran et al. (2024) find that increasing hydrogen storage capacity reduces the production-only levelised cost of hydrogen by 8–35% across wind-, solar-, and grid-based electrolysis scenarios by allowing the electrolyser to take advantage of cheap or abundant renewable electricity. However, this benefit only applies to low-cost storage media like salt caverns. At the plant level, Gorre et al. (2020) found that correctly balancing hydrogen-storage and methanation capacities, rather than oversizing either, reduced production costs by up to 17% in a power-to-gas system with an interim hydrogen buffer that decouples the electrolyser from a downstream methanation reactor. The optimal balance depended on whether the plant was powered by wind, solar, or grid In a hydrogen-storage-based microgrid with photovoltaics, a battery, an electrolyser, and a fuel cell, Phan-Van et al. (2023) show that an optimally sized hydrogen tank (1.6–2 tonnes in their case study) complements shorter-duration battery storage, supporting the idea that hydrogen storage is best for long-duration buffering and batteries are cheaper for daily cycling. These studies suggest that storage capacity should be an explicit design variable, optimised alongside production and conversion equipment, rather than sized independently of the supply chain.

3.6 Hydrogen Storage Safety

Hydrogen storage presents unique safety challenges compared to traditional fuels due to the extreme conditions of operation required to store hydrogen at high density, the interaction of hydrogen with structural materials, and the properties of chemical carriers. The main risk with compressed gas is failure of a high-pressure vessel by rupture or leakage due to manufacturing defects, fatigue or impact. This risk is why pressure vessels are standardised by type and fitted with safety devices such as pressure-relief valves and burst discs. Leakage is also important in underground storage where the high mobility of hydrogen can lead to migration along faults or poorly sealed wellheads. Salt caverns are therefore preferred to aquifers because of their low permeability. Cryogenic

Hazards: Liquid hydrogen storage presents cryogenic hazards; contact with LH_2 or cryogenically cooled surfaces may cause severe cold burns, and unsuitable materials may become brittle and fail. The need to minimise losses and risk drives the use of advanced insulation and integral refrigeration. Inevitable boil-off must be safely vented or captured to avoid over-pressurisation and the build-up of flammable gas.

Hydrogen embrittlement degrades mechanical properties in pipelines, pressure vessels, and well infrastructure. Steel alloys and low oxygen content can improve pipelines, but cryo-compressed containers have difficulty with hydrogen exposure and cold temperatures . In geological storage, hydrogen must be dehydrated before injection and extraction to prevent corrosion, and aquifers or exhausted fields may experience microbial hydrogen transformation into methane or hydrogen sulphide, reducing recoverable volume and purity. Salt caverns are recommended when available. Some storage methods have other disadvantages besides flammability and ignition concerns: ammonia borane generates catalyst-inhibiting borazine, regeneration requires a highly toxic substance, and ammonia is corrosive and toxic with the potential for NOx emissions on combustion. Additionally, liquid organic hydrogen carriers pose health and aquatic ecosystem threats, requiring careful management.

The storage type severely limits transport options and spreads safety and efficiency issues through the value chain. Tube trailers and pipelines use compressed hydrogen and require constant high pressure integrity and embrittlement management. Liquid hydrogen storage system is connected to cryogenic trailers and ships . A cryogenic temperature is maintained by continuous boil-off and partial emptying of the tank . Material-based storage (ammonia or liquid organic carriers) is compatible with bulk-liquid logistics but has toxicity and environmental risks. Distance and mode Storage conditions, losses and hazards determine safe and feasible transport modes. affect optimal storage technology, capacity and siting; storage and transportation need to be designed as a coupled system rather than optimised in isolation.

4. Transportation

Depending on the quantity, phases of hydrogen, delivery distances and local surroundings hydrogen can be transported from production site to the final consumer in many ways. The mode of transportation mainly can be divided into three main categories based on the current existing transportation systems. From the Fig. 4 , the three ways are road transportation, pipeline transportation and seaway transportation (Yang et al., 2023). While selecting the most cost-effective method of transportation of hydrogen, it is important to consider not only the investment cost, quantity and transport distance but also the cost related to integrating the overall supply chain (Lu et al., 2025).

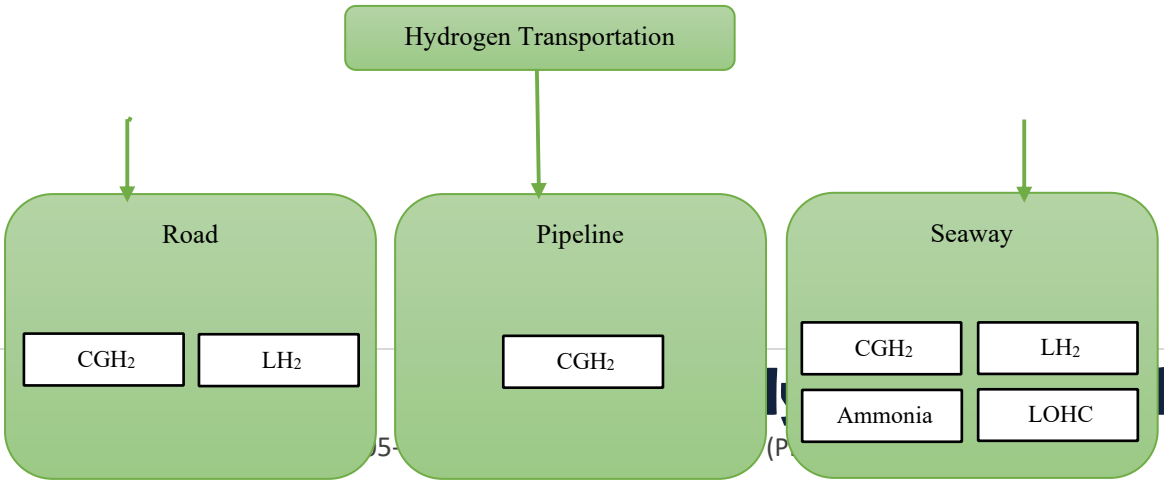


Fig. 4.1: Mode of transportation of hydrogen.

4.1 Road transportation

Hydrogen can be transported in the form of liquid or compressed gas via trucks/trailers in the case of road transportation (Yang et al., 2023). This way is used for small or medium demand. If the demand increases the number of trucks have to be increased which is not beneficiary (Lu et al., 2025). Transport distance is another major factor. Cost will increase with the increasing transport distance. Considering cost and safety, hydrogen is generally transported at pressure of 20-50 MPa so one truck can carry 200-1000 kg of hydrogen. As LH_2 has a comparatively higher volumetric storage density than CGH_2, one LH_2 trailer can carry significantly more hydrogen than a CGH_2 trailer. But an issue that is boil-off raises in case of transportation of LH_2 (Yang et al., 2023). Boil-off loss will be higher with the longer transport distance and storage that will also increase the transportation cost (Lu et al., 2025). It should be noted that the whole quantity of the transported CGH_2 and LH_2 can not be delivered to the customer. The residual amount of hydrogen in CGH_2 trailer depends on the pressure level of the supply chain. Approximately 10% of the LH_2 have to be kept in the tank to maintain cryogenic temperature (Yang et al., 2023).

4.2 Pipeline transportation

This mode of transportation is used for large and continuous demand of hydrogen. This is the most lucrative way to transport hydrogen to mitigate large demands in densely populated and industrialized area. It is a fact that establishing a completely new pipeline system would require high investment and a long construction time (Yang et al., 2023). The cost of pipeline is mostly depends on the diameter, gas velocity, average pressure and terrain (Lu et al., 2025). To address this problem, existing natural gas pipelines would be preferable solution. Due to the high compressibility of hydrogen, the pressure drop in pipelines over a long distance is lower than natural gas. However, the lower heating value of hydrogen makes it less energy-efficient than natural gas (Yang et al., 2023). Pipelines are evaluated as the alternative transportation of trucks/trailers transportation for high demand scenario. Pipeline also helps to reduce carbon emission as it does not use direct fuel like trucks or trailers do (Lu et al., 2025).

4.3 Seaway transportation

Seaway transportation is an alternative way of transporting hydrogen with carriers for large scale demand and it is cost-effective. Hydrogen is carried under high pressure or low temperature with various carriers such as LH_2, NH_3, CH_3 and LOHC. Factors that determines the cost of ship transportation are carrier cost, travel cost, port management cost, passage cost. The total number of shipment and total number of ships are mainly relied on the capacity of ship (Lu et al., 2025). As gas compression is energy-efficient shipping hydrogen in gaseous state is an easiest way. Again, due to the higher volumetric storage density of liquid hydrogen, shipping hydrogen in liquid state is another attractive way if boil-off issues can be eliminated. Compared with the requirements of tanks to hold high pressure for CGH_2 shipping and maintain cryogenic temperature for LH_2 shipping, transporting

hydrogen in the form of ammonia is much more easier and convenient. Ammonia shipping can be carried out at 1 atm and -33°C or at 25°C and 10 bar. This method has been used for more than 100 years. Approximately 17.5 million tons of ammonia are being transported worldwide every year. However, the synthesis and cracking process of ammonia is more energy-consuming than the liquification of hydrogen. So, ammonia-based hydrogen transportation is not so effective at present. Another option of shipping hydrogen in the form of LOHC. By hydrogenation, LOHC transport hydrogen then release it by dehydrogenation. LOHCs are much more easier and safer to transport via shipping than LH_2 and have higher hydrogen density than CGH_2. As a result, LOHCs shipping has several advantages such as no boil-off losses, safer storage and high payload that are favorable for hydrogen supply chain. The main disadvantages of LOHC shipping are additional fuel requirement of ship, the return transport of dehydrogenated LOHC and the high initial cost. Despite having these drawbacks, LOHC is the best choice to transport hydrogen for large scale over very long distance from the economic point of view. Technological improvement is needed to minimize the energy requirements of dehydrogenation and increase catalyst stability (Yang et al., 2023).

5. Discussion

5.1 Comparison of Seawater-to-Hydrogen Production Pathways

Three main approaches for seawater-based hydrogen production are:

Direct Seawater Electrolysis (DSE), **Indirect Seawater Electrolysis (ISE)**, and **Hybrid/Selective-Membrane Systems**. However, untreated seawater introduces chloride-related reactions, electrode corrosion, and calcium/magnesium precipitation. These effects can reduce long-term stability and make direct operation challenging at industrial current densities. However, Hybrid systems(developing) is introduced to overcome these limitations by selectively restricting seawater ions and keeping a compact configuration.

A more reliable alternative is provided by ISE. In this method, seawater is first screened, then desalinated by RO, polished and supplied to a commercial electrolyzer. Although pretreatment introduces additional equipment and energy consumption. but the evidence reviewed suggests the impact could be relatively small in comparison to the total electrolysis requirement. Therefore, the additional treatment stage can be justified by improved feed-water quality, hydrogen purity, and protection of the electrolyzer.

Thus, with the current technological maturity, ISE is the most appropriate pathway for near-term implementation, while DSE and hybrid systems should be further developed through pilot scale testing.

5.2 Electrolyzer Selection and Renewable Energy Integration

The choice of the electrolyser technology should be connected to the renewable electricity profile and the desired production scale. AWE can provide relatively low electricity consumption, lower-cost materials, and greater commercial maturity, making it suitable for stable and large-scale operation. The faster dynamic response of PEM makes it better suited to fluctuating wind and solar power, but it still has higher material and component costs. The comparison of the performance of AWE and PEM, as reviewed, indicates about $58.94\ kWh\ kg^{-1}$ H2 for AWE and $62.44\ kWh\ kg^{-1}$ H2 for PEM under the cited conditions, which shows their performance is relatively comparable and efficiency alone should not determine technology selection.

AEM offers another possible route because it can use less expensive transition metal catalysts. However, its chemical stability, membrane durability, and industrial lifetime remain insufficiently established for large-scale deployment. Hence AWE is preferred for stable baseload renewable electricity and PEM where renewable intermittency is significant.

5.3 Storage, Safety, and Supply-Chain Integration

Storage cannot be regarded as an isolated stage as its pressure, temperature, energy requirements and safety characteristics directly influence transportation and the overall performance of the supply chain. CGH_2 requires relatively low energy for storage compared to liquefaction and chemical carriers, and is therefore suitable for small to medium quantities and shorter distances. LH2 has a significantly higher volumetric density, but requires ~6–10 kWh kg–1 H2 for liquefaction and has boil-off losses. Cryo-compressed hydrogen provides higher density while reducing some boil-off limitations but requires more complex vessels.

For very large and seasonal storage, underground salt caverns are the most favourable option where suitable geology is available, due to their low permeability and relatively low levelized storage cost. LOHCs and ammonia are more suitable for long distance hydrogen transportation, although additional energy is required for reconversion processes. Metal hydrides have higher volumetric density and improved intrinsic safety, but suffer from high desorption temperature and sluggish kinetics.

Safety requirements also vary considerable. Compressed hydrogen requires protection against high-pressure vessel failure and hydrogen embrittlement, while LH_2 adds cryogenic hazards and boil-off management. Chemical carriers bring in more toxicity and environmental problems. Therefore, the choice of storage has to be coupled with the mode of transport, the demand for hydrogen and the distance, rather than be optimized separately.

5.4 Transportation Pathway Selection

Transportation performance depends strongly on hydrogen quantity and delivery distance. Road transportation using CGH_2 or LH_2 is flexible and suitable for small and medium demand, but increasing demand increases truck requirements and transportation costs. Pipeline transportation is more suitable for large and continuous regional demand, although dedicated infrastructure requires significant investment.

For the long-distance, large-scale transportation, seaway transport is more attractive. LH_2 has a high hydrogen density but requires cryogenic handling, while ammonia has existing shipping infrastructure but requires energy intensive synthesis and cracking. LOHCs avoid boil-off and provide convenient liquid handling, which makes them attractive for long-distance transport when suitable heat is available for dehydrogenation.

Therefore, CGH_2 road transport is appropriate for early local demand, pipelines for large continuous domestic demand, and LOHC-based seaway transport for large-scale long-distance delivery.

5.5 Overall Supply-Chain Competitiveness

The combined analysis shows that the lowest cost of hydrogen production path is not always the lowest cost supply chain. Electricity consumption, electrolyzer utilization and degradation, water treatment, storage capacity, compression, transportation distance, and infrastructure all influence overall hydrogen supply cost. Storage capacity can also improve system flexibility by promoting electrolysis to operate when renewable electricity is plentiful, but excessive storage can increase capital costs.

For coastal Bangladesh, this integrated perspective is especially relevant. In choosing the side we should consider renewable-resource availability, seawater conditions, industrial demand, port access, infrastructure,

and cyclone exposure. The existing literature shows the potential of renewable hydrogen in Bangladesh but there is no fully integrated coastal model that takes into account these factors along with storage, transportation and cost of delivered hydrogen.

5.6 Limitations and Future Research

The main uncertainties arise from differences in- electricity price, renewable capacity factor, financing, infrastructure, electrolyzer lifetime, storage conditions, and transportation distance. For longer times, validation of direct seawater electrolysis is needed under realistic seasonal seawater conditions,. Future work should therefore focus on- industrial-current-density testing, chlorine and fouling control, membrane durability, integrated storage sizing, and site-specific techno-economic assessment. For Bangladesh, future research should develop a complete coastal supply-chain model considering these factors: renewable generation, seawater treatment, electrolysis, storage, transportation, cyclone resilience, industrial demand, and cost of delivered hydrogen.

6. Conclusion and Policy Recommendations

The study compared different ways of producing, storing and transporting green hydrogen from seawater and and identified the configuration that provides the best practical compromise between efficiency, reliability, safety and cost.

Recommended production pathway

Among DSE, ISE, and hybrid/selective-membrane pathways, ISE is selected as the best near-term production pathway:

Seawater → Screening → RO desalination → Polishing → AWE/PEM electrolysis

ISE is preferred because it avoids the major chloride-related corrosion, chlorine evolution, and cathodic fouling problems associated with direct seawater electrolysis while adding only a relatively small pretreatment energy and cost requirement under the reported conditions. DSE remains promising for future low-footprint systems, but requires further validation of catalyst selectivity, corrosion resistance, fouling control, and membrane durability.

Recommended electrolyzer

Within the ISE pathway:

- **AWE** is preferred for stable, large-scale renewable electricity.
- **PEM** is preferred for highly variable solar/wind power.
- **AEM** remains an emerging option requiring further durability validation.

Recommended storage pathway

Storage should be selected according to scale and application. **CGH_2 is preferred for small-to-medium quantities and short-distance applications**, while **LH_2 or LOHC becomes more attractive for larger-volume and longer-distance applications**. For very large seasonal storage, **salt-cavern storage is the preferred option where suitable geology exists**.

Recommended transportation pathway

The preferred transport mode depends on the demand scenario:

Application	Recommended option
Small/medium local demand	CGH_2 road transport
Large continuous domestic demand	Pipeline
Large-scale long-distance/export	LOHC-based seaway transport

Overall preferred supply-chain pathway

Considering the combined production, storage, safety, and transportation analysis, the most practical near-term pathway is:

Renewable solar/wind → Seawater screening → RO + polishing → AWE/PEM → H_2 purification → Compression → CGH_2 storage → Road/Pipeline transport → End user

For **large-scale international or long-distance export**, the downstream pathway can instead be:

Renewable solar/wind → Seawater treatment → AWE/PEM → H_2 → LOHC conversion → Seaway transport → Dehydrogenation → End user

This approach allows the production technology to remain commercially mature while selecting storage and transportation according to demand and distance.

Final conclusion

In summary, the most effective way of producing green hydrogen sustainably in the short term is through indirect seawater electrolysis using an AWE or PEM electrolyzer. The findings also indicate that storage and transportation must be designed together with production because energy losses, safety requirements, storage capacity, and transport distance directly affect the final competitiveness of hydrogen.

For Bangladesh, a phased strategy beginning with **ISE + commercial AWE/PEM + CGH_2-based regional distribution** is the most practical starting point, while **direct seawater electrolysis, advanced storage, and LOHC-based export systems** can be developed through pilot-scale validation. This method offers a realistic path to establishing a safer, more efficient and economically competitive seawater-to-green-hydrogen supply chain.

References

Dash, S. K., Chakraborty, S., & Elangovan, D. (2023). A brief review of hydrogen production methods and their challenges. Energies, 16(3), 1141. https://doi.org/10.3390/en16031141

Juthi, I. J., Prithy, N. T., & Jonma, S. I. (2025). Assessing carbon footprint reduction strategies for last-mile delivery in emerging economies: An interpretive structural modelling (ISM) approach. Supply Chain Insider, 15(1), 75–92. https://doi.org/10.5281/zenodo.17284471

Mazumder, G. C., Ibrahim, A. S. M., Rahman, M. H., & Huque, S. (2021). Estimation of hydrogen demand potential in Bangladesh by 2030. ELK Asia Pacific Journal of Project Management and Control, 6(1).

Rahman, M. J., Sajahan, & Tuser, M. R. S. (2024). Green hydrogen revolution: A comprehensive analysis and future outlook for sustainable energy transition in Bangladesh. 2024 7th International Conference on Development in Renewable Energy Technology (ICDRET). https://doi.org/10.1109/ICDRET60388.2024.10504021

Tao, M., Azzolini, J. A., Stechel, E. B., Ayers, K. E., & Valdez, T. (2022). Review: Engineering challenges in green hydrogen production systems. Journal of The Electrochemical Society, 169(5), 054503. https://doi.org/10.1149/1945-7111/ac6983

Wang, C., Shang, H., Jin, L., Xu, H., & Du, Y. (2021). Advances in hydrogen production from electrocatalytic seawater splitting. Nanoscale, 13, 7897–7912. https://doi.org/10.1039/D1NR00784J

Barthelemy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, *42*(11), 7254–7262. https://doi.org/10.1016/j.ijhydene.2016.03.178

Chand Mazumder, G., Md Habibur Rahman, P., Saiful Huque Professor, S., & Md Habibur Rahman Professor, C. (2023). *DEVELOPMENT AND PERFORMANCE ANALYSIS OF A GREEN HYDROGEN PRODUCTION SYSTEM FOR HYDROGEN DEMAND OF BANGLADESH BY 2040 Originality Statement*.

Dash, S. K., Chakraborty, S., & Elangovan, D. (2023). A Brief Review of Hydrogen Production Methods and Their Challenges. In *Energies* (Vol. 16, Number 3). MDPI. https://doi.org/10.3390/en16031141

Dincer, I., & Acar, C. (2014). Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, *40*(34), 11094–11111. https://doi.org/10.1016/j.ijhydene.2014.12.035

Dokhani, S., Assadi, M., & Pollet, B. G. (2023). Techno-economic assessment of hydrogen production from seawater. *International Journal of Hydrogen Energy*, *48*(26), 9592–9608. https://doi.org/10.1016/j.ijhydene.2022.11.200

Henry, A., McStay, D., Rooney, D., Robertson, P., & Foley, A. (2023). Techno-economic analysis to identify the optimal conditions for green hydrogen production. *Energy Conversion and Management*, *291*. https://doi.org/10.1016/j.enconman.2023.117230

Salam, M. A., Shaikh, M. A. A., & Ahmed, K. (2023). Green hydrogen based power generation prospect for sustainable development of Bangladesh using PEMFC and hydrogen gas turbine. *Energy Reports*, *9*, 3406–3416. https://doi.org/10.1016/j.egyr.2023.02.024

Zhang, Y., Zhang, Y., Li, Z., Yu, E., Ye, H., Li, Z., Guo, X., Zhou, D., Wang, C., Sha, Q., & Kuang, Y. (2024). A Review of Hydrogen Production via Seawater Electrolysis: Current Status and Challenges. In *Catalysts* (Vol. 14, Number 10). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/catal14100691

Gorre, J., Ruoss, F., Karjunen, H., Schaffert, J., & Tynjälä, T. (2020). Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. Applied Energy, 257, 113967. https://doi.org/10.1016/j.apenergy.2019.113967

Mehr, A.S., Phillips, A.D., Brandon, M.P., Pryce, M.T., & Carton, J.G. (2024). Recent challenges and development of technical and technoeconomic aspects for hydrogen storage, insights at different scales; A state of art review. International Journal of Hydrogen Energy, 70, 786–815. https://doi.org/10.1016/j.ijhydene.2024.05.182

Moran, C., Deane, P., Yousefian, S., & Monaghan, R.F.D. (2024). The hydrogen storage challenge: Does storage method and size affect the cost and operational flexibility of hydrogen supply chains? International Journal of Hydrogen Energy, 52, 1090–1100. https://doi.org/10.1016/j.ijhydene.2023.06.269

Phan-Van, L., Takano, H., & Nguyen Duc, T. (2023). A comparison of different metaheuristic optimization algorithms on hydrogen storage-based microgrid sizing. Energy Reports, 9, 542–549. https://doi.org/10.1016/j.egyr.2023.05.152

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., & Wang, B. (2023). A review of hydrogen storage and transport technologies. Clean Energy, 7(1), 190–216. https://doi.org/10.1093/ce/zkad021

Lu, X., Krutoff, A.-C., Wappler, M., & Fischer, A. (2025). Key influencing factors on hydrogen storage and transportation costs: A systematic literature review. International Journal of Hydrogen Energy, 105, 308–325. https://doi.org/10.1016/j.ijhydene.2025.01.196

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., & Wang, B. (2023). A review of hydrogen storage and transport technologies. Clean Energy, 7(1), 190–216. https://doi.org/10.1093/ce/zkad021

Apendix:

Table 1. The main technical characteristics of hydrogen vs. other fuels (Santanu et al.,2023)

Parameter	Hydrogen	Diesel	Methane
Density at STP (kg/m3)	0.089	830.0	0.720

Volumetric energy at STP (MJ/m^3)	1.07× 10	3.5 × 10^4	3.3 × 10
Net Lower Heating value (MJ/kg)	119.9	42.5	45.8
Boiling point (K)	20.0	453–633	111.0
Auto-ignition temperature (K)	853	~523	813
Minimum ignition energy in air at 1 bar stoichiometry (mJ)	0.020	0.240	0.290 &
Stoichiometry air/fuel mass ratio	34.4	14.5	17.2
Quenching distance at NTP (mm)	0.64	-	2.1
Laminar flame speed in air at NTP (m/s)	1.85	0.37–0.43	0.38
Diffusion coefficient in air at STP (m2/s)	85 ×10^{-7}	-	19 × 10^{-7}
Flammability limits in air (% vol)	4–76	0.6–5.5	5.3–15
Adiabatic flame temperature at NTP (K)	2480	~2300	2214