

# Green hydrogen transport across the Caspian Sea: geomorphological constraints and strategic maritime routing

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## ABSTRACT

Transition toward a low-carbon economy has positioned green hydrogen as a key vector for sustainable energy systems. Large-scale deployment remains constrained by transportation and storage challenges, particularly across complex inland water bodies such as the Caspian Sea. This study presents a comprehensive overview of existing strategies and emerging innovations for transporting green hydrogen across the Caspian Sea, with emphasis on geomorphological and hydrological constraints. The Caspian Sea, the world's largest enclosed inland water body, spans approximately 371000 km<sup>2</sup> with an average depth of 211 m, and features extensive shallow zones along its northern and eastern coasts. These physical characteristics, combined with variable salinity, seasonal currents (averaging 5 to 25 cm s<sup>-1</sup>), and sediment transport, complicate the establishment of reliable and secure transport routes. Influence of these geographical factors on marine infrastructure planning, pipeline installation, and shipping routes were analysed in this study. The present review explores innovative maritime hydrogen transport technologies, including cryogenic liquid hydrogen tankers and ammonia-based carriers, while assessing their feasibility in high-sediment zones. The study also evaluates optimal storage methods, such as compressed hydrogen, metal hydrides, and liquid organic hydrogen carrier systems, against criteria of safety, cost efficiency, and environmental resilience. Geospatial analyses and comparative route modelling highlight critical corridors that minimize exposure to geomorphological hazards, enabling reductions in energy loss and logistical risk. Optimization approaches may also lower hydrogen losses during transport (with indicative estimates of up to ~18%) and reduce infrastructure costs by 12 – 20% relative to conventional routing strategies. This study also identifies gaps, provides future research perspectives and policy development supporting trans-Caspian green hydrogen infrastructure. Findings from this study are of strategic importance for regional energy cooperation, particularly among Central Asian and Caucasus states aiming to establish themselves as hydrogen exporters to Europe.

## 1. Introduction

The global transition toward a low-carbon economy has positioned green hydrogen as a critical energy carrier capable of decoupling energy systems from fossil fuel dependence. Produced via electrolysis powered by renewable energy sources, green hydrogen offers a carbon-neutral pathway to meet rising global energy demands. According to the International Energy Agency (IEA), global hydrogen demand reached

approximately 95 million tonnes in 2022, with projections indicating an increase to over 130 million tonnes by 2030 under current policy frameworks [1,2]. Green hydrogen is expected to comprise a substantial share of this total, supported by more than 30 countries that have published national hydrogen strategies, including several in the Caspian region. Figure 1 presents the main technological routes for hydrogen production, highlighting the diverse feedstocks and energy sources utilized, including non-renewable fossil fuels and renewable resources such

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as biomass, wind, and solar energy. Despite growing interests and advancements in hydrogen production technologies, large-scale deployment of green hydrogen remains constrained by transport and storage challenges [3–9]. Hydrogen's low volumetric energy density, estimated at approximately  $3.0 \text{ kWh L}^{-1}$  as compressed gas at 700 bar or  $2.4 \text{ kWh L}^{-1}$  in liquefied form at cryogenic temperatures of  $-253^\circ\text{C}$ , presents logistical hurdles for long-distance transmission [9–12]. Hosseini et al. [13] reported that during compressed hydrogen tank filling, exergy efficiency increases from 86% to 89% as the initial pressure rises from 0.2 to 20 bar at  $20^\circ\text{C}$ , though less hydrogen is dispensed at higher pressures. The study further showed that lowering the tank's initial temperature by  $80^\circ\text{C}$  at 1 MPa increases heat removal by 4.3%, and by 9.2% at 2 MPa, to reach the target of 35 MPa and  $20^\circ\text{C}$ . These constraints are amplified in regions with complex physical and geopolitical settings. The Caspian Sea region shows such complexity, combining varied marine topography, dynamic hydrological behaviour, and a politically fragmented basin into a single geographical corridor of strategic importance.

The Caspian Sea is the world's largest enclosed inland water body, covering a surface area of roughly  $371000 \text{ km}^2$ , stretching approximately 1200 km from north to south [15]. Bordered by Kazakhstan, Russia, Turkmenistan, Iran, and Azerbaijan, the sea serves as a vital hub for energy trade, maritime logistics, and ecological resources. It also presents considerable geomorphological and hydrological variability. The northern and eastern coastlines are dominated by shallow zones with extensive sedimentation, while the southern basin reaches depths exceeding 1000 m [16–18]. Complexity of the seabed, irregular depth gradients, and seasonal hydrodynamic fluctuations result in major design and operational challenges for hydrogen transport infrastructure. Surface currents in the Caspian Sea are predominantly wind-driven and seasonally dependent, typically ranging between 5 and  $25 \text{ cm s}^{-1}$  [16, 19]. These variables affect the stability of subsea pipelines and the navigability of shipping routes. Countries such as Kazakhstan and Turkmenistan possess substantial renewable energy potential that could be harnessed for green hydrogen production. Kazakhstan, for instance, has a technical renewable energy capacity exceeding 760 GW, mainly

from wind and solar resources, and has committed to producing one million tonnes of green hydrogen annually by 2030 [20,21]. Turkmenistan, with its high solar irradiance and flat desert topography, also has favourable conditions for renewable hydrogen generation. However, transporting hydrogen from these inland production hubs to external markets remains a critical bottleneck. With the European Union targeting ten million tonnes of renewable hydrogen consumption by 2030 and aiming to import a significant portion from neighbouring regions, the Caspian Sea becomes a potential corridor of continental significance [22]. The ability to transport hydrogen efficiently across this body of water could unlock new energy partnerships and economic diversification opportunities for Central Asian states. Figure 2 presents an overview of the Caspian Sea and its extensive catchment basin. A satellite view highlights the sea's geographic position relative to surrounding regions, including the Greater Caucasus, Alborz Mountains, and major countries such as Russia, Kazakhstan, Turkmenistan, Iran, Azerbaijan, Turkey, and Georgia.

The Caspian Sea presents several challenges due to its hydrodynamic regime, which is characterized by significant heterogeneity. Coastal shallows, particularly in the north, are less than 5 m deep in some areas, complicating the deployment of hydrogen transport vessels and submarine infrastructure [24,25]. Sediment dynamics in river delta systems such as the Volga and Ural estuaries introduce further risks of seabed instability and corrosion, threatening the integrity of pipelines and other seabed installations. Variable salinity, ranging from 1 to 13 ‰ depending on location and depth, also influences material selection and design for hydrogen systems [26,27]. The geopolitical landscape of the Caspian region adds an additional layer of complexity. Although the 2018 Convention on the Legal Status of the Caspian Sea attempted to formalize legal jurisdiction and seabed rights among the littoral states, issues of boundary demarcation, transit rights, and environmental regulation remain sources of tension [28,29]. As shown in Table 1, the hydrogen strategies of Caspian littoral states differ in scale and maturity. Kazakhstan and Russia have established quantitative production targets, whereas countries such as Turkmenistan and Azerbaijan are still

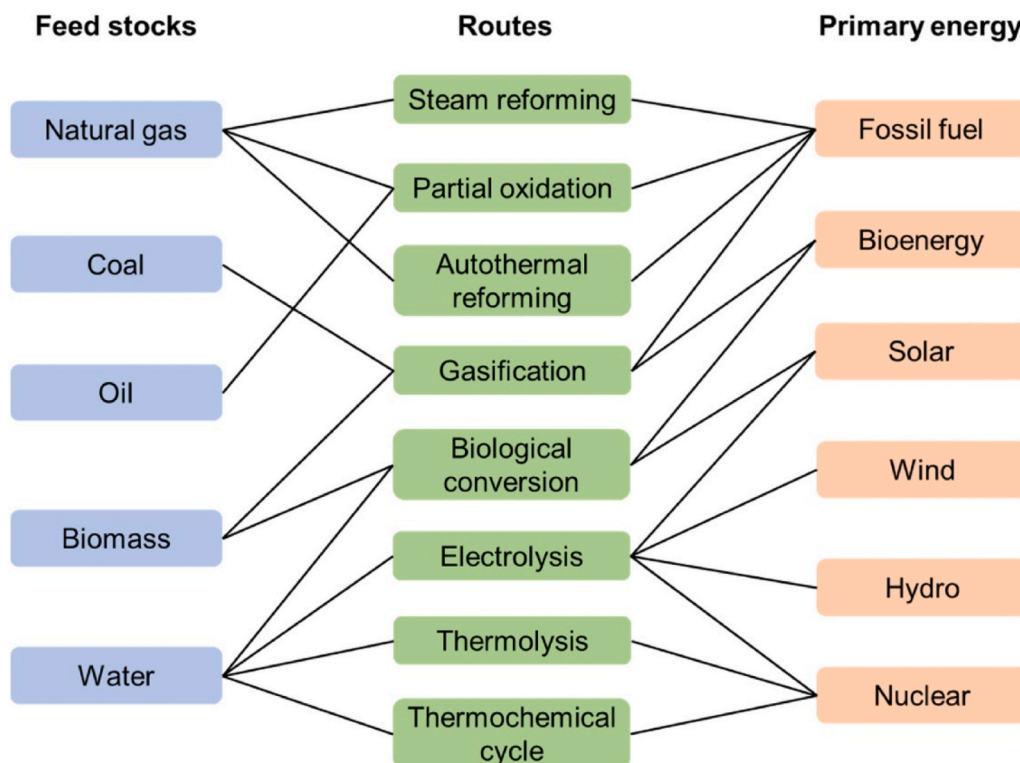


Fig. 1. Primary energy sources, feedstocks, and technological pathways for hydrogen production [14].

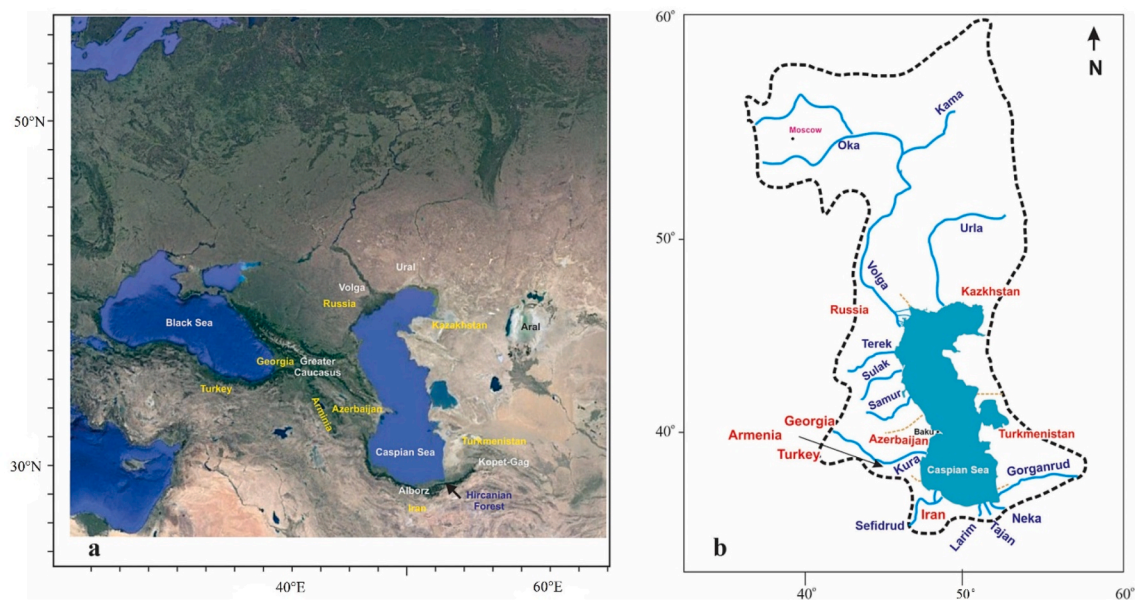


Fig. 2. Spatial overview showing (a) the Caspian Sea with its principal physiographical characteristics, and (b) the catchment basin and major tributary rivers [23].

**Table 1**  
National hydrogen strategies and policy targets of Caspian littoral states.

| Country      | Hydrogen target (Year)       | Renewable potential (GW)         | Export ambition        | Ref. |
|--------------|------------------------------|----------------------------------|------------------------|------|
| Kazakhstan   | 1 Mt/year by 2030            | >760 GW (solar/wind)             | EU, regional           | [20] |
| Turkmenistan | Emerging targets             | -                                | Energy diversification | [30] |
| Azerbaijan   | Green hydrogen in roadmap    | 135 GW (land), 157 GW (offshore) | EU                     | [31] |
| Russia       | 2 Mt/year by 2035 (combined) | Hydropower, wind                 | Global (via ammonia)   | [32] |
| Iran         | R&D and regional pilot plans | Solar, wind                      | Regional cooperation   | [33] |

developing policy frameworks and strategic plans for hydrogen deployment and export. These differences reflect the broader energy transition dynamics and infrastructure readiness across the region. Past infrastructure projects, such as the Trans-Caspian Pipeline, faced years of delay due to legal ambiguities and opposition from regional stakeholders. The implementation of transboundary hydrogen infrastructure, whether via pipelines or marine transport fleets, will similarly require coordinated legal and diplomatic frameworks to ensure success.

In order to address these geopolitical and geophysical challenges, the choice of hydrogen transport and storage technology plays a vital role in determining overall feasibility. Gaseous hydrogen pipelines demand advanced materials resistant to hydrogen embrittlement, particularly in saline and corrosive marine environments. Liquefied hydrogen transport, though offering higher volumetric efficiency, requires complex cryogenic systems and results in substantial energy losses during liquefaction and boil-off [34–36]. Alternative carriers such as ammonia and liquid organic hydrogen carriers provide more stable and manageable transport media but introduce conversion inefficiencies and safety risks associated with toxicity and chemical handling. Each transport modality presents trade-offs in terms of energy efficiency, economic cost, operational complexity, and environmental impact. Geographical configuration of the Caspian Sea further complicates the identification of optimal transport routes. The northern shelf is particularly problematic due to ice cover in winter months, shallow depths, and dense sediment load. The central and southern basins, though deeper and more

stable, may involve longer transit distances and higher installation costs for underwater infrastructure. Moreover, the absence of a universally accepted maritime boundary system means that some potential routes may cross disputed zones, further escalating political sensitivities.

Despite these barriers, the development of a trans-Caspian hydrogen transport corridor remains a compelling opportunity for energy transition. Emerging technologies such as remote sensing, bathymetric mapping, and hydrodynamic modelling enable the detailed characterization of marine environments, providing a scientific basis for infrastructure planning and risk mitigation [37–39]. Geographic Information Systems (GIS) and computational modelling can support comparative analysis of route scenarios by simulating factors such as sediment transport, seasonal current shifts, and pipeline stress loads under different seabed conditions. These tools are essential for designing resilient hydrogen transport networks that align with environmental and economic objectives. Strategic benefits of such a corridor extend beyond regional gains. Establishing a functional hydrogen transport route across the Caspian could provide a blueprint for similar inland water bodies around the world. It would enhance energy connectivity between Central Asia, the South Caucasus, and Europe, diversify hydrogen supply chains, and contribute to the global scaling of clean hydrogen technologies. According to a recent study by DNV, the cost of offshore hydrogen pipeline construction in shallow marine environments ranges from €1.2 million to €2.5 million per kilometer, depending on bathymetric and geological conditions [40]. These high capital expenditures necessitate careful route selection and risk assessment to ensure return on investment and long-term infrastructure viability.

Given the growing interest in hydrogen-based energy systems, a critical assessment of the feasibility of hydrogen transport across the Caspian Sea is both timely and essential. This review study aims to synthesize existing scientific, technical, and policy literature to identify viable hydrogen transport strategies in this complex setting. To strengthen this objective, the review introduces a perspective that is largely absent from current scholarship by integrating geomorphological constraints with strategic maritime routing considerations. While previous works address hydrogen production potential and regional energy infrastructure, they do not examine how seabed morphology, coastal gradients, sediment stability, and navigational conditions shape the practical feasibility of transporting green hydrogen across the basin. Figure 3 illustrates the screening methodology used in this study. The review methodology employed in this study followed a systematic multi-

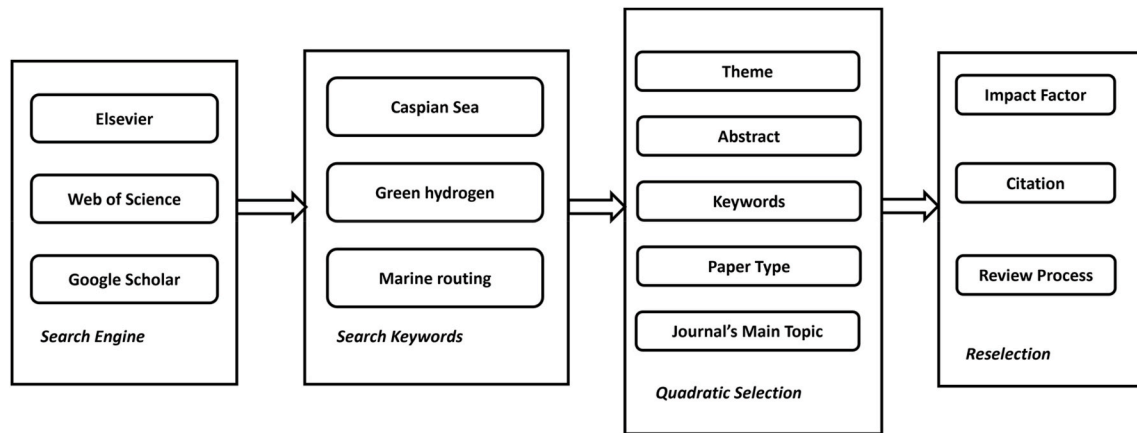


Fig. 3. Methodology used for literature screening in this study.

stage process to ensure the selection of relevant and high-quality literature. Initially, leading academic databases, including Elsevier, Web of Science, and Google Scholar, were utilized as primary search engines. Specific keywords such as Caspian Sea, green hydrogen, and marine routing guided the literature retrieval. A quadratic selection process was subsequently applied, considering the theme, abstract, keywords, paper type, and journal scope to refine the pool. Studies that were not directly related to green hydrogen development, maritime transport systems, or regional energy logistics were excluded from further consideration. The reselection stage then evaluated impact factor, citation relevance, and review process quality. Through this structured screening and reselection process, a total of 157 references were identified and retained for detailed analysis in this review. Similar studies have also adopted this rigorous approach [41–44]. This review study is the first to systematically examine the prospects of green hydrogen transport across the Caspian Sea by integrating geomorphological constraints with strategic maritime routing. Thus, providing new insights into the technical, geographical, and infrastructural factors shaping regional hydrogen supply chains.

Despite growing global interest in hydrogen supply chains, the implications of basin-scale geomorphology for maritime hydrogen transport in enclosed inland seas remain insufficiently examined. This review addresses this gap by providing a Caspian Sea-specific assessment of geomorphological constraints and opportunities for green hydrogen transport. The study synthesizes existing knowledge on hydrogen transport technologies and evaluates their applicability within the distinctive bathymetric structure, seabed conditions, and coastal configurations of the Caspian basin. Linking these geomorphological characteristics with maritime logistics considerations, this study develops a strategic routing perspective for potential hydrogen transport corridors across the Caspian Sea. The analysis therefore offers a regionally focused framework that clarifies key physical constraints, identifies feasible routing pathways, and outlines planning considerations for the development of future low-carbon hydrogen transport networks in the basin.

## 2. Geopolitical-economic significance and physical features of the caspian sea region

The Caspian Sea region is among the most strategically important areas in Eurasia due to its substantial hydrocarbon reserves and emerging renewable energy potential. Its geographical position also provides a vital physical link between Europe, Central Asia, and the Middle East. Five littoral states, namely Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan, exercise sovereign control over the basin's energy resources and transport routes [45,46]. Since the late nineteenth century, the Caspian region has been a significant center for oil production, beginning with onshore developments around Baku and later

expanding offshore. In the post-Soviet period, the discovery and development of large offshore fields, such as Azeri Chirag Gunashli in Azerbaijan and Kashagan and Tengiz in Kazakhstan, transformed the region into a critical player in global energy markets [47]. This transformation was supported by major infrastructure developments aimed at linking the Caspian to global markets. Baku Tbilisi Ceyhan pipeline, with a capacity of 1.2 million barrels per day, offers a direct export route to the Mediterranean that bypasses both Russia and Iran [48]. Caspian pipeline consortium route presently transports approximately 1.3 million barrels per day from Kazakhstan's oil fields to the Black Sea. These export corridors have reduced dependency on a single transit country and increased geopolitical flexibility for regional producers. In 2018, the Convention on the Legal Status of the Caspian Sea marked a turning point in regional governance. It established clear legal principles for dividing seabed resources among littoral states while designating surface waters for common use [49,50]. Thus, this framework has enabled cooperative exploitation of hydrocarbon reserves and regulated maritime navigation. However, important issues remain unresolved, particularly in relation to environmental protection, procedures for undersea pipeline construction, and regulation of projects that could alter the marine ecosystem. Disagreement over trans-Caspian pipeline projects that could supply Europe directly continues to shape regional political dynamics. Table 2 presents selected infrastructure capacities, production indicators, and international targets that influence potential hydrogen transport routes and export logistics.

Energy cooperation among littoral states reflects a mix of national priorities and external market demand. National hydrogen strategies are becoming a key dimension of this cooperation. Kazakhstan's national hydrogen concept sets production goals of 10000 tonnes of hydrogen by 2027, increasing to 18000 tonnes per year by 2029 and 25000 tonnes per year by 2030 [55]. A substantial portion of this production is expected to be green hydrogen generated using renewable energy sources, supporting both domestic decarbonisation goals and export diversification. Azerbaijan's national hydrogen strategic outlook, released in 2025, prioritises incorporating low-carbon hydrogen into industrial

Table 2

Key infrastructure and geopolitical parameters influencing hydrogen transport and export routes in the Caspian region.

| Parameter                     | Value                                                          | Ref. |
|-------------------------------|----------------------------------------------------------------|------|
| Kazakhstan hydrogen targets   | 10 000 t by 2027; 18 000 t/year by 2029; 25 000 t/year by 2030 | [51] |
| EU renewable hydrogen targets | 10 Mt production; 10 Mt imports by 2030                        | [52] |
| BTC pipeline capacity         | 1.2 million barrels per day                                    | [53] |
| CPC pipeline exports (2024)   | ~1.3 million barrels per day                                   | [54] |

processes, replacing grey hydrogen in refining, and building export capabilities [31]. Turkmenistan's energy study has identified high potential for offshore wind and solar energy that could support green hydrogen production [56]. Iran's plans include both blue hydrogen generated from natural gas with carbon capture and green hydrogen based on renewable energy sources [57]. Russia has retained hydrogen in its national energy policy, but its export ambitions face challenges due to sanctions and limited access to European markets. The European Union (EU) renewable hydrogen strategy, established under the sustainable Europe framework, defines ambitious goals. It seeks to produce 10 million tonnes of renewable hydrogen and to import an additional 10 million tonnes by 2030 [58,59]. For Caspian producers, these targets present a significant export opportunity but require cost competitiveness, compliance with EU certification standards, and the development of long-distance transport infrastructure. Potential export pathways include ammonia conversion, liquefied hydrogen shipping, liquid organic hydrogen carriers, and dedicated pipelines, each with distinct technical, regulatory, and logistical implications.

As illustrated in Figure 4, the Caspian region hosts an extensive network of oil and gas pipelines, including existing, under-construction, and proposed routes, spanning approximately 25°E – 75°E longitude and 35°N – 55°N latitude. Beyond energy production, the geopolitical and economic importance of the Caspian region extends into trade, strategic connectivity, and environmental governance. The trans-Caspian international transport route, or middle corridor, is gaining significance for trade between China and Europe [60]. This corridor uses a combination of rail and maritime links that traverse Kazakhstan, cross the Caspian Sea, pass through Azerbaijan, and continue to Georgia and Turkey. Its expansion supports diversification of trade routes away from traditional northern passages through Russia. Maritime security, fisheries regulation, and environmental conservation also inform regional policy. Energy diplomacy in the Caspian region serves as a multi-purpose tool for attracting investment, transferring technology, and enhancing each littoral state's international standing.

The Caspian Sea is the world's largest enclosed inland water body, covering approximately 371000 to 387000 km<sup>2</sup>, depending on water level fluctuations, and stretching about 1200 km from north to south [62]. It is an endorheic basin with no natural outflow. Geomorphologically, it is divided into three distinct sub-basins: the northern Caspian, the central Caspian, and the southern Caspian. The northern basin is shallow, with an average depth of only 5–6 m and a flat seabed [63]. The central basin reaches depths of several hundred metres. The southern basin attains a maximum depth of approximately 1025 m [64]. These depth variations profoundly affect offshore and subsea engineering design, influencing platform stability, pipeline route selection, and sediment dynamics. Hydrologically, the Caspian Sea is dominated by the Volga River, which contributes more than 80% of the total freshwater inflow [65]. Other important rivers include the Ural, Kura, and Terek. Because the Caspian has no outlet to the oceans, its water balance is governed by the interplay of river inflow and evaporation. Recently, a decline in the water level has been observed, driven by climate-induced increases in evaporation and reduced river inflow [66, 67]. Seasonal fluctuations also occur, with higher water levels typically observed in late spring and early summer due to snowmelt in the Volga catchment.

Salinity varies significantly from north to south. The northern basin is nearly fresh owing to high river input. The southern basin's salinity is approximately 12 to 13 ‰, roughly one-third that of average ocean water [68]. This gradient has important ecological implications, influencing fish species distribution and other aquatic ecosystems. Infrastructure wise, salinity impacts corrosion rates for steel components and informs the design of seawater electrolysis systems for hydrogen generation. Sediment deposition patterns vary across the basin. The northern shelf receives large volumes of fine sediment from river discharge, leading to high sedimentation rates [69]. This process can rapidly fill navigation channels and increase dredging needs. Fine sediments may bury subsea pipelines or, alternatively, become exposed through erosion. In contrast, the southern basin demonstrates more



Fig. 4. Existing, under-construction, and proposed oil and gas pipelines in the Caspian region [61].

stable conditions. Nonetheless, tectonic activity and the presence of submarine canyons present geohazard risks to subsea infrastructure. Circulation currents in the southern basin generally follow a counter-clockwise pattern [70]. This circulation influences both sediment transport and the dispersion of pollutants such as hydrocarbons. Figure 5 illustrates the geomorphological and bathymetric layout of the Caspian Sea, showing its three major sub-basins: the shallow northern basin, the deeper middle (central) basin, and the southern basin, which contains the greatest depths of more than 1000 m. It also indicates the major rivers discharging into the sea, including the Volga River, the Ural River, the Kura River, and the Terek River, which play significant roles in freshwater input, sediment delivery, and the development of coastal morphology.

Navigation conditions in the Caspian Sea are governed by its physical characteristics. In the shallow northern basin, vessel size is limited by draft constraints [72]. Ice formation during winter restricts operations and requires ice-class vessels or seasonal limitations. Declining water levels increase these challenges, potentially stranding port facilities or rendering them inoperative. Deeper southern basin permits operation of larger vessels, although bathymetric complexity and potential slope instability necessitate careful route planning for shipping and pipeline laying [73]. These geomorphological and hydrological properties exert direct influence on energy export infrastructure planning. Subsea pipelines must account for seabed composition, sediment movement, and geohazard potential. Maritime hydrogen transport will require port facilities capable of handling specialized cargo carriers. The shallow

northern area may not support such infrastructure without costly dredging and fortification. Environmental protection concerns, including habitat disruption and pollution risk, add a layer of complexity to infrastructure decision-making. Table 3 highlights the Caspian Sea's physical and hydrological features, emphasizing the southern basin's depth, the northern basin's shallowness, and the Volga River's critical contribution to inflow.

3. Principles, constraints, and shipping applications of hydrogen transport technologies

Hydrogen's low volumetric energy density, high diffusivity, and reactivity make its long-distance transport fundamentally different from that of methane or conventional liquid fuels. Two main technical pathways are currently practiced, consisting of pipeline transport of

Table 3  
Summary of selected physical dimensions, depth profiles, salinity levels, and river inflow contributions of the Caspian Sea.

| Parameter                      | Value                           | Ref. |
|--------------------------------|---------------------------------|------|
| Surface area                   | 386000 – 387000 km <sup>2</sup> | [72] |
| Maximum depth                  | ~1025 m (southern basin)        | [64] |
| Average depth (northern basin) | 5 – 6 m                         | [74] |
| Mean salinity (southern basin) | 12 – 13 ‰                       | [75] |
| Volga River share of inflow    | >80 %                           | [76] |

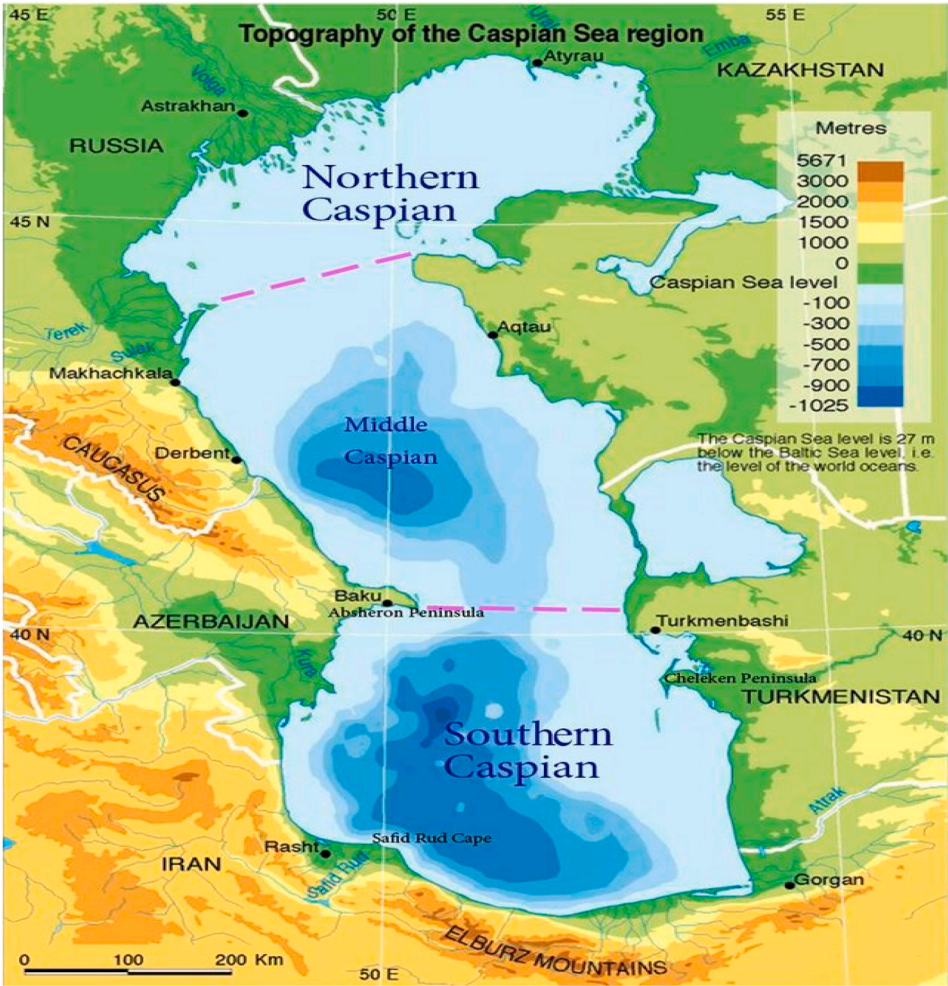


Fig. 5. Map of the Caspian Sea illustrating its subdivision into the northern, middle (central), and southern Caspian regions. Dashed lines indicate the boundaries between these sections [71].

compressed gaseous hydrogen, including subsea corridors, and maritime shipping in the form of derivative energy carriers [77]. These include liquefied hydrogen (LH<sub>2</sub>), ammonia, or liquid organic hydrogen carriers (LOHCs) [78]. Each pathway imposes distinct thermodynamic penalties, materials challenges, logistics requirements, and risk profiles that influence cost and environmental performance. Pipeline systems move hydrogen as a compressed gas. At a given pressure, hydrogen's volumetric energy density is approximately one-third that of methane. To deliver equivalent energy flow, a hydrogen pipeline must operate at higher velocities and larger diameters, which increases frictional pressure losses and compressor power demand [79]. Hydrogen's lower density and higher velocity for a given mass flux cause greater pressure drops than methane under comparable conditions. Compression energy requirements depend on pressure levels, station spacing, and efficiency. Practical compression work for high pressures can be 2.5 to 4.0 kWh per kilogram to reach 250 – 1000 bar in station applications, while trunk pipelines typically operate at 80 – 200 bar [80]. At the system level, the European hydrogen backbone reports transport costs of €0.11 – 0.21 per kilogram per 1000 km for large-scale networks that integrate repurposed and newly constructed lines under high utilization. In comparison, a World Bank technical report estimates costs of approximately \$0.20 – 0.30 per kilogram per 1000 km for high-capacity new-build lines [81]. Figure 6 provides a system-level schematic of the hydrogen supply chain, illustrating the full sequence from production to end-use applications. It outlines the major hydrogen production pathways, including electrolysis, steam methane reforming, coal gasification, biomass gasification, and pyrolysis.

Hydrogen leakage is an important consideration. Even with best-practice construction, long-distance pipelines may experience non-zero leakage. Spatolisano et al. [83] investigated the techno-economic performance of ammonia, liquefied hydrogen, and liquid organic hydrogen carriers, finding lower costs for industrial use and higher compression and safety challenges for mobility applications. As shown in Figure 7, the study revealed the competitiveness of hydrogen transport value chains for industrial applications is highly dependent on seaborne transport distance, with future scenarios indicating potential cost advantages over present conditions. Hydrogen leakage indirectly increases atmospheric methane and ozone lifetimes, reducing hydroxyl radicals, and resulting in an effective 100-year global warming [84,85]. This

reinforces the importance of tight networks and robust leak detection. Subsea hydrogen trunklines are technically feasible, building on offshore gas pipeline experience, but cost and materials requirements are demanding. The Medgaz pipeline from Algeria to Spain spans seabed depths up to 2160 m over a 210 km route, while Nord Stream's twin 1200 km Baltic Sea lines were laid mostly at 80 – 110 m depth with more than 1 m diameter pipes [86]. For hydrogen, additional fracture-control, weld quality, and coating constraints are necessary. Hydrogen embrittlement of high-strength steels, especially at welds and stress concentrators, is the dominant materials risk. Recommended practices such as DNV-RP-F112 emphasize fracture control, crack arrest, and toughness requirements [87]. Steel grades and weld procedures may require derating or redesign when converting from methane to hydrogen. Cathodic protection and coating systems must account for hydrogen permeation because overprotection can increase ingress rates [88]. In subsea environments, corrosion stresses coating integrity, and seabed geotechnical conditions, such as free-spans and upheaval buckling, add mechanical fatigue loads that interact with hydrogen-induced cracking.

Figure 8 illustrates a hydrogen pipeline transport system, where overall feasibility is largely determined by transport distance, pressure requirements, and infrastructure costs. Hydraulically, higher velocities for hydrogen increase erosion and pressure-drop constraints. Recompression for offshore hydrogen pipelines may be required at intervals of 175 – 350 km for smaller diameters, though large export trunklines use much greater diameters and different spacing [89]. Lessons from existing large subsea gas pipelines include the importance of careful route selection, mattresses, and trenching to control spans and buckling, as well as robust integrity management to address third-party interference and rapid line-pack depressurization. Large-diameter pipelines above 40 inches achieve low transport costs when fully utilized, but capital lock-in is high [90]. Export corridors from offshore hydrogen hubs to shore can be cost-optimal above several hundred kilotonnes per year and below 1000 km, while shipping can be more competitive for lower flows or longer distances. Shipping avoids fixed linear assets by moving hydrogen in liquid form or as a chemical derivative. Liquefied hydrogen increases volumetric density to approximately 70.8 kg m<sup>-3</sup> at 1 bar and 20 K, or about one-eighth the volume of gaseous hydrogen at standard conditions [91]. The HySTRA pilot demonstrated an end-to-end chain between Australia and Japan using the Suiso Frontier, a purpose-built

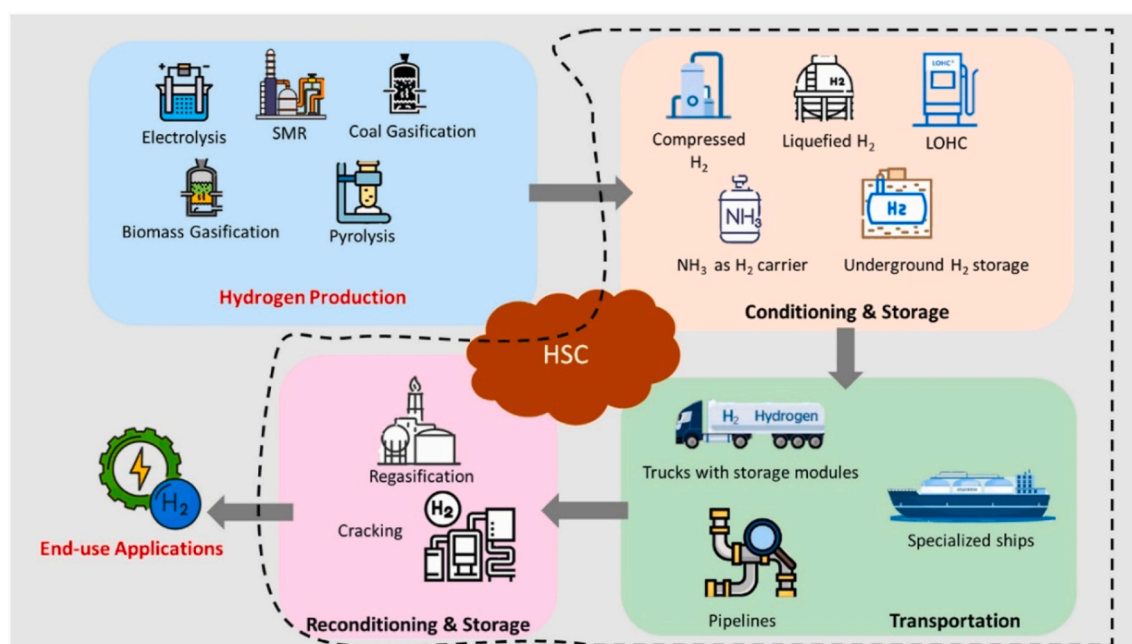


Fig. 6. Process flow schematic of the hydrogen supply chain [82].

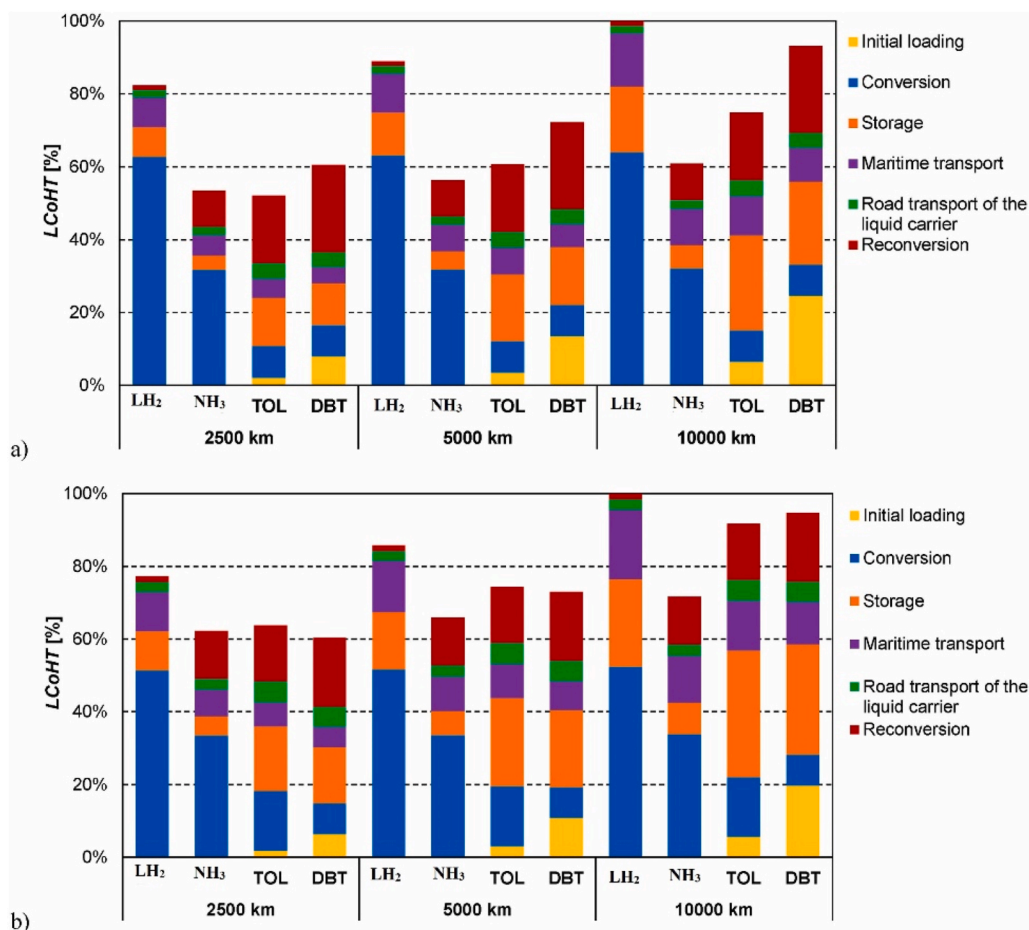


Fig. 7. Comparison of hydrogen transport value chains for industrial applications (hydrogen valley) as a function of seaborne transport distance (D) under a) present and b) future scenarios [83].

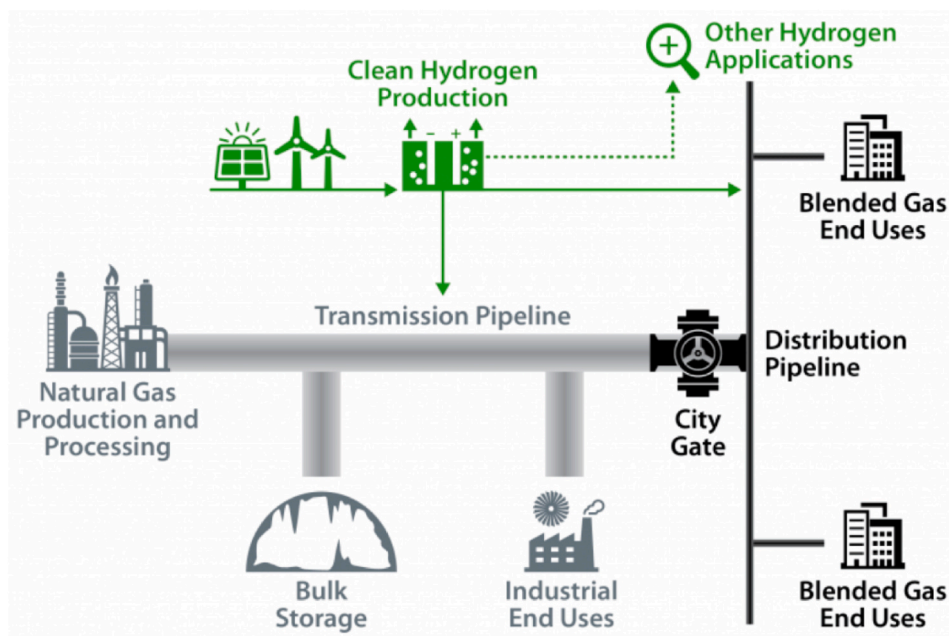


Fig. 8. Layout of the hydrogen pipeline transport network [92].

LH<sub>2</sub> carrier with a 1250 m<sup>3</sup> vacuum-insulated spherical tank, and the Hy touch Kobe terminal with a 2250 m<sup>3</sup> spherical LH<sub>2</sub> tank. The Kobe

terminal achieved boil-off rates around 0.06%/day, consistent with high-quality double-shell vacuum insulation. The major penalty for LH<sub>2</sub>

is liquefaction energy, typically 10 – 13 kWh per kilogram, which represents 25 – 35% of the hydrogen's higher heating value. Transport energy for the vessel is relatively small per kilogram-kilometer compared to liquefaction. New designs aim for boil-off rates below 0.1% per day with tank sizes of 20000 – 100000 m<sup>3</sup>. Shell has set targets for large LH<sub>2</sub> storage at capital costs under 150% of LNG equivalents.

Ammonia binds hydrogen in a carbon-free liquid with 17.6 wt% hydrogen content. It is liquid at –33 °C at 1 bar or under moderate pressure at ambient temperature and benefits from a century-old global shipping and storage system [93]. The main energy costs come from producing hydrogen, synthesizing ammonia via Haber-Bosch at about 7 – 12 MWh per tonne. Cracking ammonia back to hydrogen when required adds a 10 – 15% penalty [94]. Ammonia is particularly attractive when it can be used directly as fuel or feedstock, avoiding the cracking penalty. Large-scale ammonia cracking facilities are now under demonstration in Europe, for example, in Germany and at the port of Rotterdam, to supply pure hydrogen at the point of use. LOHCs such as methylcyclohexane store hydrogen via reversible hydrogenation and dehydrogenation, with typical hydrogen contents around 6 wt% [95]. Moving one tonne of hydrogen requires shipping 15 – 17 tonnes of carrier. Dehydrogenation is strongly endothermic, with duties around 10 – 15 kWh per kilogram of hydrogen released [96]. LOHCs offer ambient-condition handling, compatibility with conventional tanker infrastructure, and zero boil-off during storage. Their main drawbacks are low effective hydrogen density per ship volume, the energy penalty for dehydrogenation, and the need to ship the spent carrier back unless a closed loop is in place. Infrastructure needs differ across carriers. LH<sub>2</sub> ports require cryogenic pipelines, large vacuum-insulated tanks, and specialized loading arms, with Kobe's facility demonstrating reliable operation and low boil-off [97]. Ammonia can utilize existing refrigerated storage and port infrastructure, while LOHC systems may rely on conventional oil-handling facilities with minor modifications. In the Caspian region, however, infrastructure must account for shallow depths, high salinity, seasonal ice in the northern basin, mobile sediments, and seismicity, which influence port operations and pipeline stability. Safety considerations also differ across carriers. Pipelines face risks of embrittlement and leakage. LH<sub>2</sub> involves cryogenic and venting hazards, ammonia requires strict controls due to toxicity, and LOHCs present flammability risks during high-temperature dehydrogenation.

From an energy efficiency perspective, pipelines avoid liquefaction or synthesis penalties and can be very efficient over moderate distances, with main losses from compression and leakage. LH<sub>2</sub> incurs a liquefaction penalty of 25 – 35% of HHV, though good boil-off control keeps voyage losses low [98]. Ammonia has moderate synthesis penalties, but if used directly, total delivered energy can be higher than LH<sub>2</sub>. LOHCs have negligible storage losses but significant dehydrogenation penalties and low hydrogen mass fractions. Studies often report end-to-end efficiencies of about 30 – 33% for LH<sub>2</sub>, 34 – 37% for ammonia without cracking, and 25% for LOHCs, though results vary [99–102]. Cost comparisons depend on distance, volume, and utilization. Fully utilized pipelines can transport hydrogen for €0.11– €0.21 per kilogram per 1000 km in Europe [103]. LH<sub>2</sub> shipping costs are dominated by liquefaction plant and cryogenic infrastructure, with shipping costs typically smaller than liquefaction costs. Ammonia infrastructure is mature, with the main new costs arising from cracking plants. LOHC infrastructure costs are centred on hydrogenation and dehydrogenation facilities, with low port capital needs but high operational penalties. No single transport pathway is universally superior. Pipelines are most efficient and cost-effective for short to medium distances with high, steady flows, provided rights-of-way and suitable materials exist. Ammonia is advantageous for intercontinental trade when direct ammonia use is possible, while LH<sub>2</sub> suits applications requiring pure hydrogen at import points with access to low-cost electricity for liquefaction [104]. LOHCs offer flexibility for smaller-scale or distributed imports where existing liquid-bulk infrastructure can be reused. Strategic energy trade systems are likely to adopt a portfolio approach, matching the transport method

to the specific distance, volume, end-use, and infrastructure readiness of each corridor. Figure 9 shows that leakage assumptions strongly affect the eligibility of hydrogen production pathways for U.S. inflation reduction act tax credits (a), while the choice of climate metric and inclusion of indirect hydrogen effects (b) significantly influence their perceived environmental performance.

### 3.1. Storage technologies and compatibility with Caspian conditions

Hydrogen storage pathways for the Caspian region require balancing technical performance against environmental constraints. This includes brackish to hypersaline waters, extensive shallow shelves in the north, heavy sediment loads from major river deltas, and seasonal ice cover [60]. The northern Caspian averages only 4 – 8 m in depth with a maximum near 20 m and receives about 88% of total river inflow, primarily from the Volga, creating high turbidity and sedimentation pressures on coastal and nearshore infrastructure [106]. Basin-wide salinity averages approximately 1.28‰ but ranges from about 0.1‰ near river mouths to far higher values in evaporitic embayments such as Kara-Bogaz-Gol [107]. These gradients, together with winter ice that can persist from November to March in the north, make storage siting and materials selection highly challenging. Reub et al. [108] showed LOHC suitability for small-scale mobility, with Figure 10a highlighting trade-offs among LOHC, MOF, GH<sub>2</sub>, and LH<sub>2</sub> in performance and resilience. Figure 10b compares hydrogen storage systems by volumetric and gravimetric densities relative to U.S. DOE targets. These factors are critical for deployment under the high-salinity and sediment-heavy conditions of the Caspian region. Compressed hydrogen (CH<sub>2</sub>) remains the most mature option for distributed applications and for buffering at production or refuelling nodes. Modern systems operate at 350 or 700 bar, yielding practical volumetric energy densities of approximately 2.1 – 4.8 MJ L<sup>-1</sup> and enabling rapid charge-discharge without the need for phase change management. However, large aboveground tanks and offshore-located skids are exposed to salt spray, biofouling, and sediment abrasion. In shallow northern waters, platform clearances are limited, and grounding risks rise during storm surges or ice shove events, increasing the probability of impact loading on manifolded Type III or IV vessels [109]. From a materials standpoint, the pressure boundary is typically carbon fibre over a polymer liner; these composites resist chloride attack but require stainless or coated steel in valves and fittings to mitigate pitting and stress corrosion in saline aerosols. Simplicity of CH<sub>2</sub> storage, combined with minimal cryogenic duty, is advantageous where electrical power is scarce or intermittent. Nevertheless, the footprint per unit of stored energy is large, which is challenging in constrained nearshore corridors around Baku, Atyrau, and Turkmenbashi. Table 4 presents a comparative overview of the cost and energy consumption associated with various hydrogen storage technologies.

A comparative analysis of Table 4 shows that compressed hydrogen remains the most cost-effective option (0.5 – 1.5 USD·kg<sup>-1</sup> H<sub>2</sub>), though compression requires 10 – 15 kWh·kg<sup>-1</sup> H<sub>2</sub>. Liquid hydrogen offers higher volumetric density but incurs significant liquefaction penalties, consuming 30 – 40% of the hydrogen's energy content at a cost of 1.0 – 2.0 USD·kg<sup>-1</sup> H<sub>2</sub>. Metal and chemical hydrides demonstrate lower operational energy requirements (5 – 12 kWh·kg<sup>-1</sup> H<sub>2</sub>) and favourable gravimetric capacities. However, their deployment is limited by material cost, synthesis complexity, and regeneration challenges, resulting in higher overall costs (2.0 – 8.0 USD·kg<sup>-1</sup> H<sub>2</sub>).

LH<sub>2</sub> offers high volumetric hydrogen content and fast discharge, but its cryogenic requirement at approximately 20 K imposes stringent thermal management and exacting materials control. LH<sub>2</sub> density is about 70.8 kg·H<sub>2</sub> m<sup>-3</sup>, allowing compact storage relative to CH<sub>2</sub>. However, boil-off gas remains a design and operational liability, especially for terminals exposed to seasonal temperature swings and dynamic loading from waves and ice [115]. Minimizing boil-off demands multilayer insulation and deep vacuum annuli, along with reliable power for vacuum maintenance and recondensing or reliquefaction

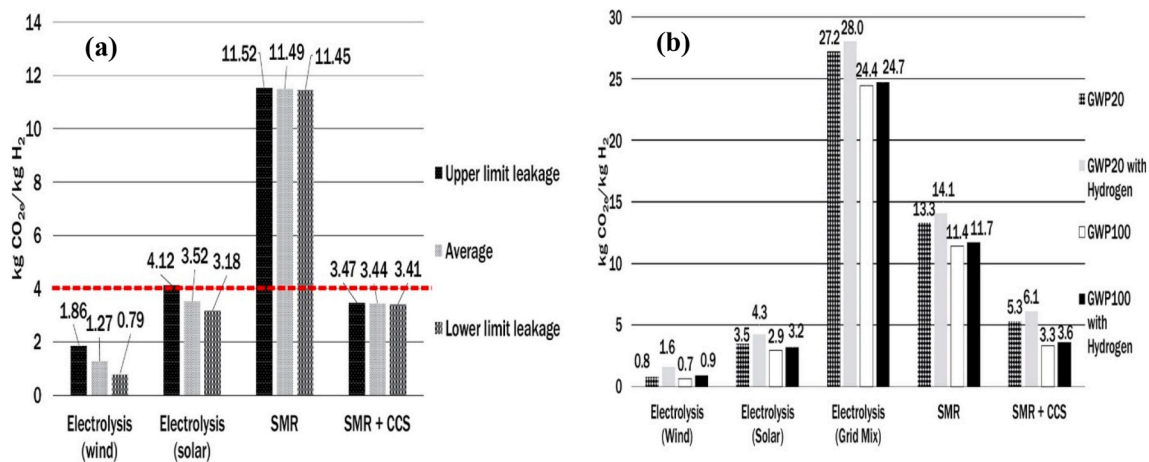


**Fig. 9.** a) High, average, and low leakage rates for Electrolysis (left: 9.2%, 4.6%, 2%), SMR (centre: 1%, 0.8%, 0.5%), and SMR + CCS (right: 1.5%, 0.8%, 0.6%), with the red horizontal dashed line indicating the U.S. Inflation Reduction Act tax credit eligibility threshold based on GWP100. b) Results for four climate metrics: GWP20 (cross-hatched), GWP20 with hydrogen indirect impacts (solid grey), GWP100 (solid white), and GWP100 with hydrogen indirect impacts (solid black) [105]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

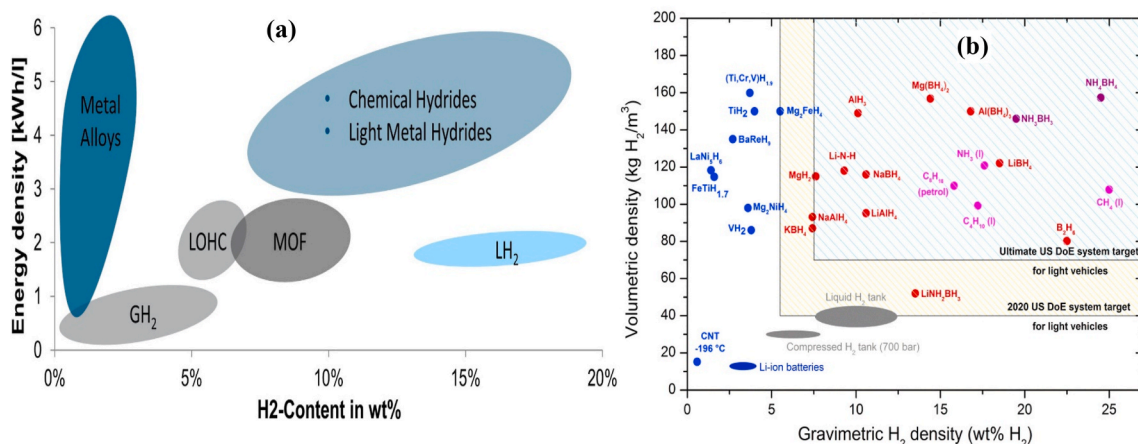


**Fig. 10.** (a) Comparison of various hydrogen storage technologies, including Liquid Organic Hydrogen Carriers (LOHC), Metal-Organic Frameworks (MOF), Gaseous Hydrogen (GH<sub>2</sub>), and Liquid Hydrogen (LH<sub>2</sub>) [108]. (b) Comparison of hydrogen storage systems in terms of volumetric and gravimetric densities, with U.S. DOE system targets shown for reference [114].

**Table 4**  
Comparison of cost and energy consumption of different hydrogen storage technologies.

| Storage technology                                                       | Storage conditions                          | Energy consumption (kWh·kg <sup>-1</sup> H <sub>2</sub> )                      | Indicative cost (USD·kg <sup>-1</sup> H <sub>2</sub> stored) | Ref.  |
|--------------------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------|-------|
| Compressed Gas (CGH <sub>2</sub> )                                       | 350 – 700 bar                               | 10 – 15                                                                        | 0.5 – 1.5                                                    | [110] |
| Liquid Hydrogen (LH <sub>2</sub> )                                       | – 253 °C, ambient pressure                  | 30 – 40% of H <sub>2</sub> LHV (≈12 – 15 kWh·kg <sup>-1</sup> H <sub>2</sub> ) | 1.0 – 2.0                                                    | [10]  |
| Metal Hydrides (MgH <sub>2</sub> , LaNi <sub>5</sub> H <sub>6</sub> )    | 25 – 350 °C, moderate pressure (1 – 30 bar) | 5 – 10                                                                         | 2.0 – 5.0                                                    | [111] |
| Chemical Hydrides (NaBH <sub>4</sub> , NH <sub>3</sub> BH <sub>3</sub> ) | Ambient-mild conditions                     | 5 – 12                                                                         | 4.0 – 8.0                                                    | [112] |
| Cryo-Compressed (CcH <sub>2</sub> )                                      | 250 – 300 bar at cryogenic T                | 12 – 18                                                                        | 1.5 – 2.5                                                    | [113] |

units, constraints that may be difficult to meet in remote Caspian sites

with grid instability. Low-temperature hydrogen exposure can embrittle certain steels, so marine LH<sub>2</sub> tanks and piping often require aluminium-killed, fine-grain steels or cryo-compatible alloys, adding weight and cost. The combination of cold leaks and oxygen condensation presents safety hazards exacerbated by wind-borne saline aerosols that deposit hygroscopic salts on cold surfaces, increasing icing and corrosion at penetrations. In northern shelf waters where ice formation and fast-ice are common, jetty and secondary containment designs must account for differential thermal movements and ice gouging. Ammonia and liquid LOHCs provide liquid-phase logistics that are often better matched to shallow, sediment-laden ports [116]. Anhydrous ammonia liquefies under mild conditions and, per unit tank volume, can store more hydrogen equivalents than LH<sub>2</sub> because liquid NH<sub>3</sub> contains roughly 17.6 wt% hydrogen and has a density near 0.68 kg L<sup>-1</sup> at ambient conditions, equating to about 0.12 kg-H<sub>2</sub> L<sup>-1</sup> [117]. This translates to high volumetric energy density at the system level and is one reason marine literature reports tank volumetric energy density roughly double that of LH<sub>2</sub> for comparable containment envelopes. Ammonia's toxicity and corrosivity require careful materials selection, such as austenitic stainless steels for wetted components, and robust leak detection and ventilation, particularly in enclosed valve boxes exposed to salt fog. For the Caspian, the ability to berth modest-draft ammonia

tankers at river-delta ports is attractive. However, dehydrogenation units onshore consume 20 – 30% of the contained energy depending on conversion and heat integration, and the presence of NO<sub>x</sub> in combustion contexts demands aftertreatment if any direct ammonia firing is used [118]. Figure 11 illustrates the dual role of ammonia in the hydrogen economy, serving either as a direct fuel or as a carrier for hydrogen release through decomposition. Where hydrogen end-use is industrial, such as in steel production or refineries, direct ammonia use as a feed or fuel could bypass cracking, but this shifts the safety case toward toxic risk management in densely populated coastal zones.

Among LOHCs, methylcyclohexane (MCH) and dibenzyltoluene (DBT, often used in its perhydro form) are the most relevant. They are liquid at ambient conditions, compatible with conventional fuel infrastructure, and tolerant of saline environments when standard marine materials are applied. Typical reversible hydrogen capacities are about 6 wt% for MCH to toluene and 6 – 7 wt% for perhydro-DBT to DBT, with practical system-level values lower once catalysts and heat exchangers are included [119]. The main penalty is thermal: hydrogenation is exothermic, while dehydrogenation requires 250 – 320 °C and high-surface-area catalysts, drawing a significant fraction of the energy content unless high-grade waste heat is available [120]. In cold and windy Caspian winters, heat losses from dehydrogenation trains increase, making insulation essential, while in summer, high ambient temperatures and warm cooling water on the southern shores can constrain condensation and product recovery. LOHC spills are less acutely hazardous than ammonia, and their non-cryogenic storage simplifies jetty design in shallow ports with sediment mobility. However, repeated cycles can lead to carrier degradation and by-product formation, necessitating carrier make-up logistics that add to lifecycle costs.

Metal hydrides and other solid-state options promise compact, intrinsically safer storage with low operating pressures, which can be attractive for onshore buffering near sensitive coastal habitats and industrial users. Magnesium hydride provides a theoretical capacity of 7.6 wt%, but practical reversible capacities nearer 3 – 5 wt% at useful rates are common without advanced catalysts [121]. Intermetallic hydrides such as LaNi<sub>5</sub>H<sub>6</sub> or Ti-based systems operate between roughly –50 and 200 °C with fast kinetics, but their gravimetric capacities are typically 1 – 2 wt%, increasing transport mass and costs [122]. Thermal management is crucial because both hydriding and dehydriding are thermally

intense, and in shallow, sediment-heavy zones where intake strainers clog easily, reliable seawater cooling is not guaranteed. Corrosion from saline aerosol and chloride-rich soils can undermine heat exchanger longevity unless duplex stainless steels or polymer-lined exchangers are used. For offshore or isolated sites, the low pressure of hydride beds reduces hydrogen permeation and leak risk during ice events or ground heave, but modular skids remain heavy, complicating installation on soft deltaic sediments without deep foundations.

To address the Caspian's physical and environmental conditions, several selection criteria are of interest. Draft limitations and seabed mobility favour storage concepts that minimize the need for large-displacement cryogenic carriers or deepwater jetties in the north. Here, ammonia or LOHCs, handled with conventional chemical-tanker drafts, are logistically more suitable than LH<sub>2</sub>, which typically relies on specialized ships and robust cryogenic supply lines. Winter ice and strong winds increase mechanical loads and power interruptions at terminals [123]. Technologies with low parasitic energy demand in idle states, such as H<sub>2</sub> and metal hydrides, are more resilient than LH<sub>2</sub>, whose boil-off control is highly power-sensitive. Saline aerosols and sediment abrasion elevate corrosion and fouling rates, so storage systems with fewer cold surfaces and simpler insulation systems, such as CH<sub>2</sub>, LOHCs, and hydrides, reduce maintenance exposure compared to LH<sub>2</sub>. Proximity to industrial demand clusters around Baku, Aktau, and Turkmenbashi favours carriers that can be integrated directly into process heat or hydrogen networks; LOHCs and ammonia can leverage existing petrochemical infrastructure, while CH<sub>2</sub> is suited to pipeline-connected users. Environmental risk profiles also differ. Ammonia introduces acute toxicity concerns that must be weighed against the reduced explosion envelope relative to gaseous hydrogen. LH<sub>2</sub> minimizes toxicity but raises unique cryogenic and oxygen-condensation hazards. LOHCs reduce acute risk but require high-temperature reactors with catalyst stewardship. Hydrides minimize high-pressure inventories but carry thermal and weight penalties.

For high-salinity, shallow, and sediment-heavy zones such as the northern Caspian shelf, liquid-phase carriers handled in conventional chemical logistics, particularly ammonia and selected LOHCs, offer pragmatic advantages in berthing, storage compactness, and materials compatibility, provided that dehydrogenation energy penalties and toxic risk management are explicitly addressed. CH<sub>2</sub> remains a robust choice for short-duration buffering, refuelling, and pipeline-adjacent

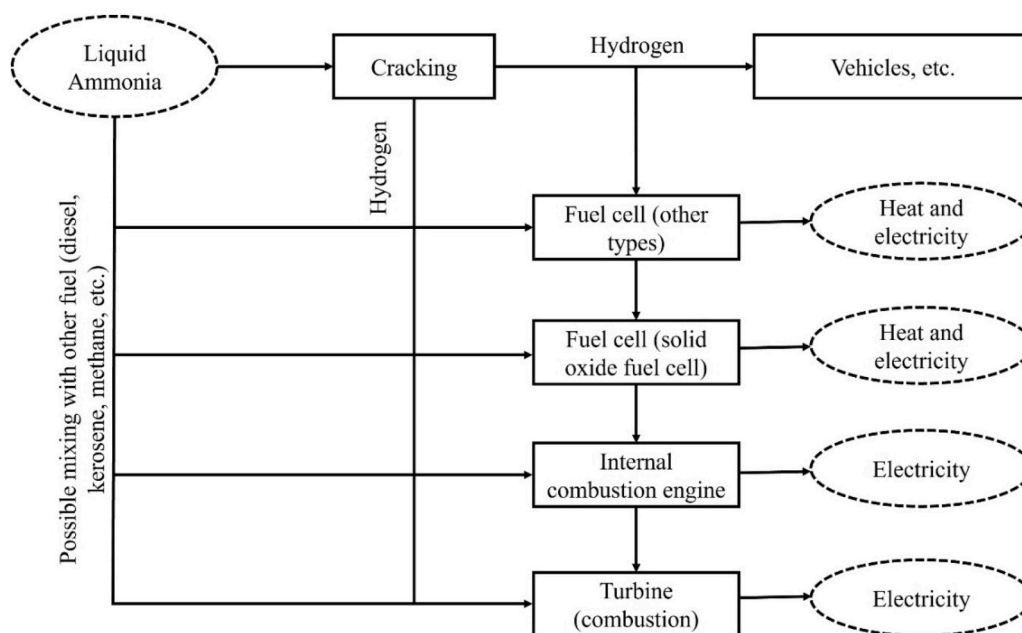


Fig. 11. Potential pathways for ammonia use, encompassing both direct application and decomposition into hydrogen.

users, especially where land is available for larger footprints. LH<sub>2</sub> is best reserved for deepwater southern sites with reliable power and specialized jetties, where cryogenic containment can be protected from ice and sediment scour. Solid-state hydrides are promising for safety-critical buffers near population centres but are currently mass-limited for bulk transport. The heterogeneity of the Caspian, with salinity from approximately 0.1% at river mouths to over 1.2% offshore, depths from less than 10 m in the north to more than 1000 m in the south, and winter ice in the north, indicates that a portfolio approach, rather than reliance on a single storage technology, will most effectively match local constraints and cost-risk trade-offs [124]. Storage suitability varies across the northern, central, and southern Caspian sub-basins due to differences in water depth, ice conditions, and geological structure. A simplified decision matrix linking basin characteristics with appropriate storage options is presented in Table 5.

4. Route optimization and risk analysis

The discussion of route optimization and risk considerations in this section is based on a synthesis of spatial datasets and published studies on Caspian energy infrastructure. Key geographic factors considered include existing pipeline networks, major port infrastructure, bathymetry, seismic activity, and shipping corridors. These spatial layers were qualitatively assessed to identify potential hydrogen transport corridors and associated risks within the Caspian basin. Consideration was given to factors such as proximity to existing infrastructure, environmental sensitivity, and geophysical hazards, which are commonly incorporated in GIS-based multi-criteria assessments in the literature to evaluate route suitability and relative risk.

Evaluating potential hydrogen corridors across the Caspian Sea requires consideration of bathymetry, sediment dynamics, seismic hazard, shipping risk, and techno-economic performance within a geospatial framework. The basin's threefold morphology, shallow Northern Caspian (<20 m), deep middle (~788 m), and ultradeep southern basin (~1025 m), creates strongly differentiated route constraints for pipelines and shipping [129]. A multi-criteria GIS model for the Caspian should weight bathymetric cost (penalizing <10 m depths in the north), sedimentation belts (Volga and Ural inputs), seismic hazard and active faults ringing the southern and western margins (Alborz, Talysh/Talysh). Protected and sensitive habitats, shipping lane density and storm-wave climate should also be included. Capital and operating expenditure layers for pipelines versus ships. Bathymetric rasters and shelf breaks are well constrained, the southern basin holds >65% of total water volume with a maximum depth near 1025 m, while the northern shelf is extremely shallow, averaging ~5–6 m and rarely exceeding 20 m, which complicates both navigation and burial of pipelines [17]. Geologic and oceanographic mapping further shows strong contourite/turbidite activity on basin slopes, informing avoidance of mass-transport prone corridors. Figure 12 illustrates the bathymetric configuration and current systems of the Caspian Sea, which are critical factors in evaluating potential hydrogen transport routes, given the influence of basin depth, bottom currents, and riverine sedimentation on infrastructure stability.

The Volga delta has historically advanced rapidly, documented delta-plain expansion from ~2.3 to as high as ~180 km<sup>2</sup> yr<sup>-1</sup> during phases of falling Caspian level [131]. This signals active sedimentation belts that can bury or expose infrastructure and alter fairways on

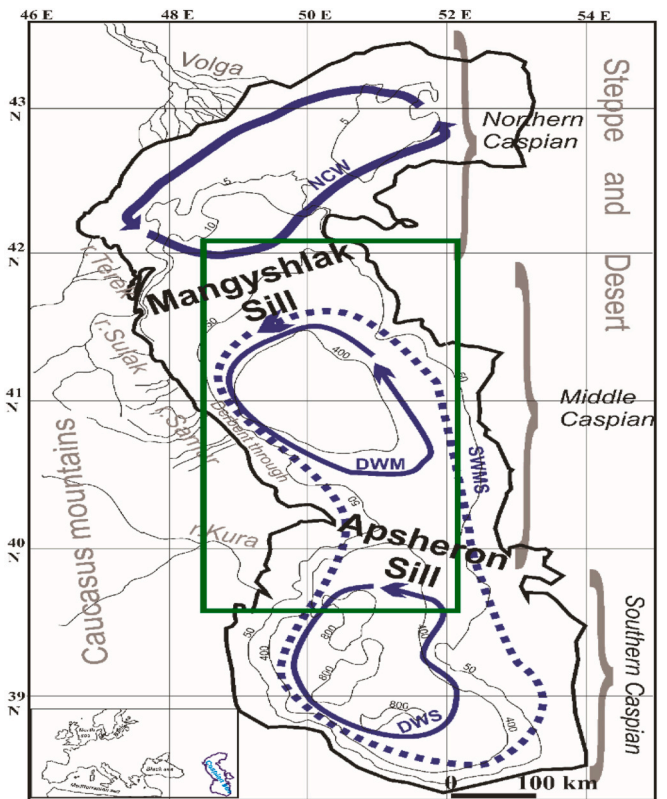


Fig. 12. Bathymetric map (m) of the Caspian Sea showing the northern, middle, and southern basins, along with key geographical features including major mountain ranges, river systems, and steppe regions. Principal bottom currents are indicated: NCW (North Caspian water mass, encompassing all water levels), SWMS (surface-water mass of the middle and southern sub-basins), DWM (deep-water mass of the middle sub-basin), and DWS (deep-water mass of the southern sub-basin). The river network originating from the Caucasus Mountains in the west and the Volga River delta in the north is depicted. The rectangle outlines the seismic survey area investigated between 2004 and 2012 [130].

decadal horizons. Corridors crossing prodelta lobes or channel mouths merit higher O&M risk factors and real-time bedform monitoring. Seismically, the southern and western margins exhibit recurrent M 6–7+ events [132]. The 1990 Manjil-Rudbar earthquake (Mw 7.4) devastated the Alborz foothills bordering the Caspian, and the 2012 Ahar-Varzaghan doublet reached Mw 6.4–6.5 in NW Iran near the Azerbaijan-Iran sector [133,134]. Pipeline corridors paralleling these belts, or landfall nodes in Gilan/Mazandaran or the Talysh range, require fault-crossing designs, geohazard setbacks, and shut-off segmentation tuned to local peak ground acceleration. Northern Caspian navigation is limited by shallow depths (~5 m) and winter ice, a 1 m fall in water level forces under-loading of vessels and increases per-ton transport costs [135]. With observed and projected Caspian level decline, ports such as Aktau report under-loading due to low water, an operational risk that would directly affect hydrogen carriers (LH<sub>2</sub> or hydrogen-derivative tankers) staging from the NE shelf. Although long-term analyses indicate a decline in mean ice area and severity

Table 5  
Indicative suitability of hydrogen storage options across Caspian sub-basins.

| Storage option                              | North Caspian | Central Caspian | South Caspian | Constraints                                       | Ref.  |
|---------------------------------------------|---------------|-----------------|---------------|---------------------------------------------------|-------|
| Compressed H <sub>2</sub> storage           | Limited       | Moderate        | Moderate      | Sediment mobility, offshore infrastructure limits | [125] |
| Liquefied H <sub>2</sub> (LH <sub>2</sub> ) | Moderate      | Moderate        | High          | Cryogenic handling, port infrastructure           | [126] |
| Ammonia storage                             | High          | High            | High          | Toxicity management, terminal safety              | [127] |
| LOHC systems                                | High          | Moderate        | Moderate      | Dehydrogenation energy demand                     | [128] |

(reducing extreme winters), hazardous ice structures (stamukhas) remain documented along northern routes, requiring ice-class or seasonal scheduling in risk-aware corridor models. Wave-surge modelling (ADCIRC + WAVEWATCH III) for 1979–2020 provides spatial fields of surge heights and significant wave heights, integrating these into metocean “penalty” layers enables probabilistic voyage routing and LNG-style weather windows for LH<sub>2</sub> carriers [136–138]. As shown in Figure 13, fluctuations in sea water level (SWL) pose varying degrees of risk to the Caspian Sea's coastal zones, with pronounced coastline retreat projected along both western and eastern shores. Vulnerability mapping indicates that several gulfs and low-lying areas are particularly at risk, while the calculated vulnerability ratios highlight notable differences among the bordering nations, with Kazakhstan and Russia exhibiting the largest susceptible areas.

Converting selected Caspian-adjacent gas corridors to carry hydrogen or blends must confront hydrogen embrittlement in steel and elevated permeation. Recent reviews and experimental investigation reveal the susceptibility of high-pressure steel pipelines to embrittlement, mandating rigorous materials qualification to emerging codes and standards [139–141]. Where necessary, fiber-reinforced polymer or

lined solutions should be applied at crossings. For leakage modelling, literature values span  $\sim 0.3 - 0.4\%$  per pipeline segment in baseline assessments, though system or value-chain studies bracket from  $<2\%$  to nearly 20% in worst-case futures, emphasizing the need for empirical leak detection and quantification in Caspian deployments. Corridor planners should therefore include leakage priors of  $\sim 0.3\%$  at the pipeline segment level for well-maintained hydrogen-only transmission, with sensitivity to 1–3% for blended or retrofit assets pending integrity verification.

Liquid hydrogen shipping concepts across the Caspian (e.g., from Kazakhstan or Turkmenistan to Azerbaijan), boil-off rates (BOR) are the dominant in-transit loss. Contemporary empirical and techno-economic sources report BORs from  $\sim 0.1$  to  $0.5\%/day$  for carriers, with best-in-class demonstrations around  $0.2 - 0.3\%/day$  and onshore storage as low as  $\sim 0.06\%/day$ , research-grade systems with active refrigeration can approach  $\sim 0\%$  under laboratory or NASA-style conditions [142]. For corridor models, a conservative central estimate of  $0.3\%/day$  at sea and  $0.06 - 0.2\%/day$  in terminal tanks is defensible, with weather routing reducing sloshing-induced heat ingress [143]. As for pipeline transport, loss terms combine steady-state permeation/leakage (order

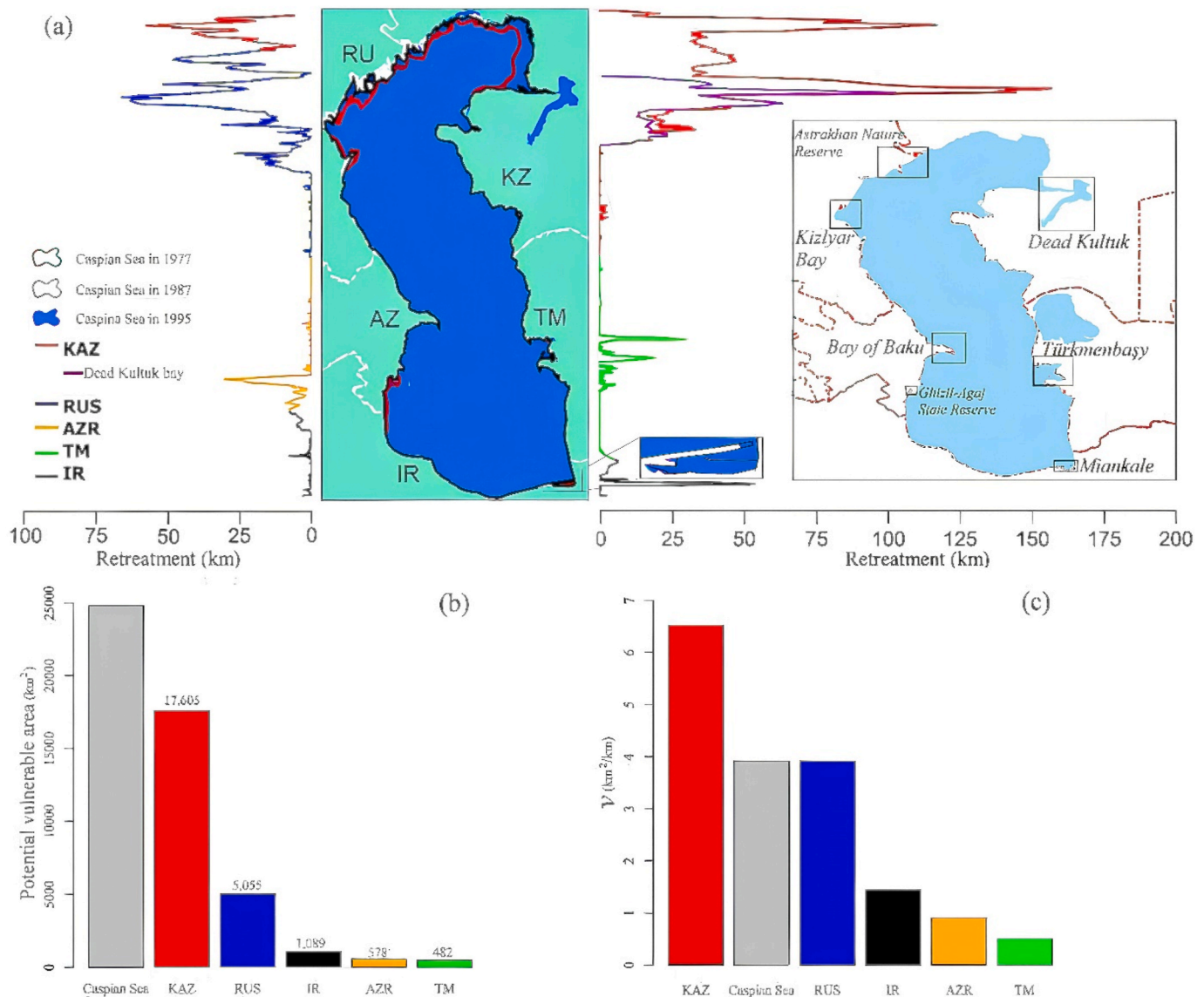


**Fig. 13.** Spatial vulnerability of Caspian Sea coastal zones to sea water level (SWL) fluctuations: (a) projected coastline retreat in the western and eastern sectors, including maps indicating major gulfs, (b) potential vulnerable zones within the Caspian Sea and adjacent countries, and (c) vulnerability ratio ( $v$ ) for the Caspian Sea and each bordering nation (KAZ – Kazakhstan, RUS – Russia, IR – Iran, AZR – Azerbaijan, TM – Turkmenistan) [16].

~0.3 – 0.4% over distance/time bins) and outage-driven release scenarios, both of which can be cut by coatings, lower-permeability materials, pressure optimization, and continuous leak detection leveraging line-pack telemetry.

Route selection frameworks typically aim to balance CAPEX for pipeline lay/burial or carrier acquisition, OPEX for compression/liqefaction and boil-off recovery, risk-weighted expected loss (R-C) from geohazards, and climate externalities of leakage. Liquefaction penalties (25 – 30% of HHV for LH<sub>2</sub>) are outside the Caspian-specific scope but dominate maritime pathways, thus short sea legs (<500 km) are advantageous if terminal siting avoids shallow/icy sectors that impose draught and schedule penalties. Integrating recent landed-cost assessments and BOR control options suggests that boil-off compression/reliquefaction on larger LH<sub>2</sub> vessels can be economic, pushing effective BOR toward ~0.2%/day and reducing delivered cost variance under rough-sea conditions. For pipelines, codes and standards development now offers clearer qualification routes for steels, welds, and components under gaseous hydrogen, which can narrow contingency allowances in cost estimates as data accumulates from trials. A further corridor-critical factor is the emerging consensus on rapid Caspian Sea-level decline. Route planning frameworks should therefore remain adaptive, with rolling bathymetry/shoreline projections used to re-weight costs and, where necessary, shift terminals southward or into deeper channels.

Hydrogen export corridor spanning east-west across the Caspian, one potential configuration is a hybrid, short-haul pipeline or barge from shallow northern producers to deep-water consolidation hubs, followed by either a subsea pipeline aligned with stable slope sectors of the middle/southern basins that avoids active fault traces and steep mass-transport corridors, or LH<sub>2</sub> (or hydrogen-carrier) shuttle services routed along storm-aware great-circle tracks with ice-season avoidance. Corridor assessment should penalize northern routes during low water and ice seasons, add seismic-fault crossing surcharges along the southern rim, and incorporate BOR/leakage terms explicitly into delivered-energy models. Where a Trans-Caspian subsea alignment is contemplated, the same seabed constraints that govern the long-discussed gas pipeline apply to hydrogen, with added caution for materials compatibility and environmental acceptance specific to hydrogen. Practically, the model should bundle selective dredging and fairway maintenance in the north. It should also include ice-class vessels and dynamic scheduling to dodge stamukhas. Continuous wave-surge nowcasts are needed for voyage planning. Pipeline steel and weld qualification to hydrogen standards are essential, together with crack-arrest and fault-crossing designs along Alborz/Talysh segments. BOR management should apply multilayer insulation, onboard compression/reliquefaction, and chilled loading at terminals. Real-time leak detection with rapid isolation is critical to keep effective leakage near or below ~0.3% for pipelines and ~0.2 – 0.3% day<sup>-1</sup> for LH<sub>2</sub> at sea [144]. Embedding these measures into a probabilistic, updateable GIS stack, re-weighted as sea level, ice climatology, and traffic patterns evolve, provides a defensible, transparent basis for siting, permitting, and investment decisions in Caspian hydrogen corridors. Future corridor optimization studies would benefit from basin-wide AIS-derived traffic density, high-resolution digital seafloor mapping for mass-movement hazards, and integrated seismic microzonation near landfalls. Until these data are systematized, planners should apply conservative safety factors and prioritize routes that leverage the Middle/Southern basins' depth while minimizing exposure to northern ice and sediment dynamics.

## 5. Environmental and regulatory considerations

The Caspian Sea an endorheic basin, with strong vertical stratification, and a high concentration of endemic species make environmental risk management a primary consideration for any hydrogen transport corridor across its coastal areas. The ecosystem is home to the Caspian seal (*Pusa caspica*), listed as endangered, with a population decline from historical estimates near a million to roughly 70000 individuals in

recent years [145]. This population continues to face pressure from disease, bycatch, contaminants, and habitat loss. The basin has also shown how quickly ecological balance can be disrupted. The introduction of the invasive ctenophore *Mnemiopsis leidyi* in the mid-1990s led to a collapse in anchovy kilka catches from about 95000 metric tons in 1999 to below 20000 metric tons in the early 2000s, severely affecting fisheries and coastal economies. Due to this ecological background, the potential consequences of spills and leaks in hydrogen supply chains, particularly from ammonia as a carrier and gaseous hydrogen in pipelines, require thorough analysis. In aquatic environments, dissolved total ammonia nitrogen (TAN) at certain concentrations can be highly toxic to aquatic life [146]. At pH 7 and 20 °C, acute toxicity limits for freshwater species are around 17 mg TAN L<sup>-1</sup>, while chronic exposure limits are about 1.9 mg TAN L<sup>-1</sup> [147]. These limits become stricter at higher pH values due to the increased presence of the more toxic unionized ammonia species (NH<sub>3</sub>). This is of particular concern in sensitive areas such as the Volga delta, river inlets, and brackish nearshore systems. As shown in Figure 14, the Sentinel-1A satellite captured high-resolution imagery of the Caspian Sea during its October 24, 2019 pass, enabling spatial coverage analysis across basin boundaries and key geographical features.

In the event of vapour releases from anhydrous ammonia during bunkering or transshipment, established exposure guidelines indicate that serious health effects may occur at concentrations as low as 220 ppm for short durations and around 110 ppm for several hours [149]. Life-threatening effects can occur at levels from 2700 ppm for brief exposure to 390 ppm for prolonged exposure [150]. Occupational safety thresholds, such as the Immediately Dangerous to Life or Health (IDLH) level of 300 ppm, are critical for planning emergency response and ensuring adequate personal protective equipment. Pipeline integrity for gaseous hydrogen is another key environmental safeguard. Hydrogen can increase fatigue crack growth and reduce fracture toughness in many pipeline steels. As a result, current design standards impose reduced allowable stresses and require fracture control measures specifically for hydrogen service. Updated pipeline codes, such as ASME B31.12, include hydrogen-specific requirements, including material performance factors that limit the use of certain steels and specify minimum fracture toughness targets in hydrogen environments [151]. These measures directly reduce the likelihood and severity of leaks, contributing to the protection of the surrounding environment.

The regulatory framework in the Caspian region presents both strengths and gaps. The sea is not governed by the 1982 United Nations Convention on the Law of the Sea. Instead, the 2018 Convention on the Legal Status of the Caspian Sea provides the legal basis for cooperation among the five littoral states [152]. Environmental protection is addressed through the Tehran Convention and its protocols, which focus on preparedness and response to pollution incidents, controls on land-based discharges, and conservation of biodiversity. While these agreements provide mechanisms for notification, monitoring, and response, they do not yet include specific provisions for hydrogen or ammonia as fuel, creating a regulatory gap for emerging low-carbon fuel operations. From a maritime perspective, global conventions still apply, as Caspian states are party to key international agreements. MARPOL governs pollution prevention, the SOLAS framework addresses ship safety, and the IMO IGC Code regulates the carriage of liquefied gases such as anhydrous ammonia [153]. The IGF Code applies to ships using low-flashpoint fuels, and the IMO has issued interim guidelines for alternative fuels, including ammonia. However, the Caspian region lacks a unified port-state control system, and enforcement of safety and handling standards can vary significantly between ports.

To ensure effective environmental protection and regulatory compliance, a multi-layered approach is recommended. Hydrogen pipelines should be designed according to hydrogen-specific codes, with strict fracture control measures. Ammonia storage and handling facilities should be built in compliance with international gas carrier safety standards, and emergency planning zones should be established based

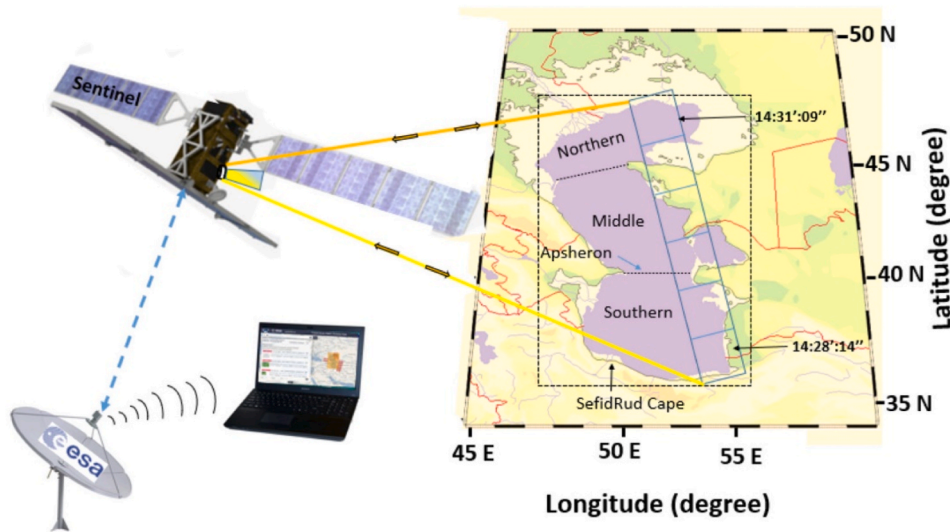


**Fig. 14.** Schematic representation of the Caspian Sea and the Sentinel-1A satellite pass over the basin on October 24, 2019. Data were collected in an ascending path, beginning in the eastern part of the southern basin at 14:28:14 GMT and concluding in the northern basin at 14:31:09 GMT, covering approximately 3 min. Six data files corresponding to the covered areas are shown. Additional passes over other parts of the Caspian Sea on 25, 28, 29, and 30 October are not depicted for clarity. Key features such as basin boundaries, the Sefidrude Cape, and the Apsheron Strait are indicated [148].

on recognized toxicity and exposure thresholds. Site-specific modeling should be used to predict the spread of ammonia in the event of a spill, particularly in sensitive estuarine and delta regions. In addition, regional cooperation mechanisms should be updated to include hydrogen and ammonia-specific scenarios in national contingency plans, and joint emergency drills should be conducted between countries. Ports across the Caspian should harmonize their handling and safety regulations for alternative fuels, ensuring consistency in operations and emergency preparedness. The high ecological sensitivity of the Caspian Sea, the quantified toxicity of ammonia, and the structural vulnerabilities of hydrogen infrastructure require a design philosophy that assumes minimal tolerance for accidents. Preventive engineering,

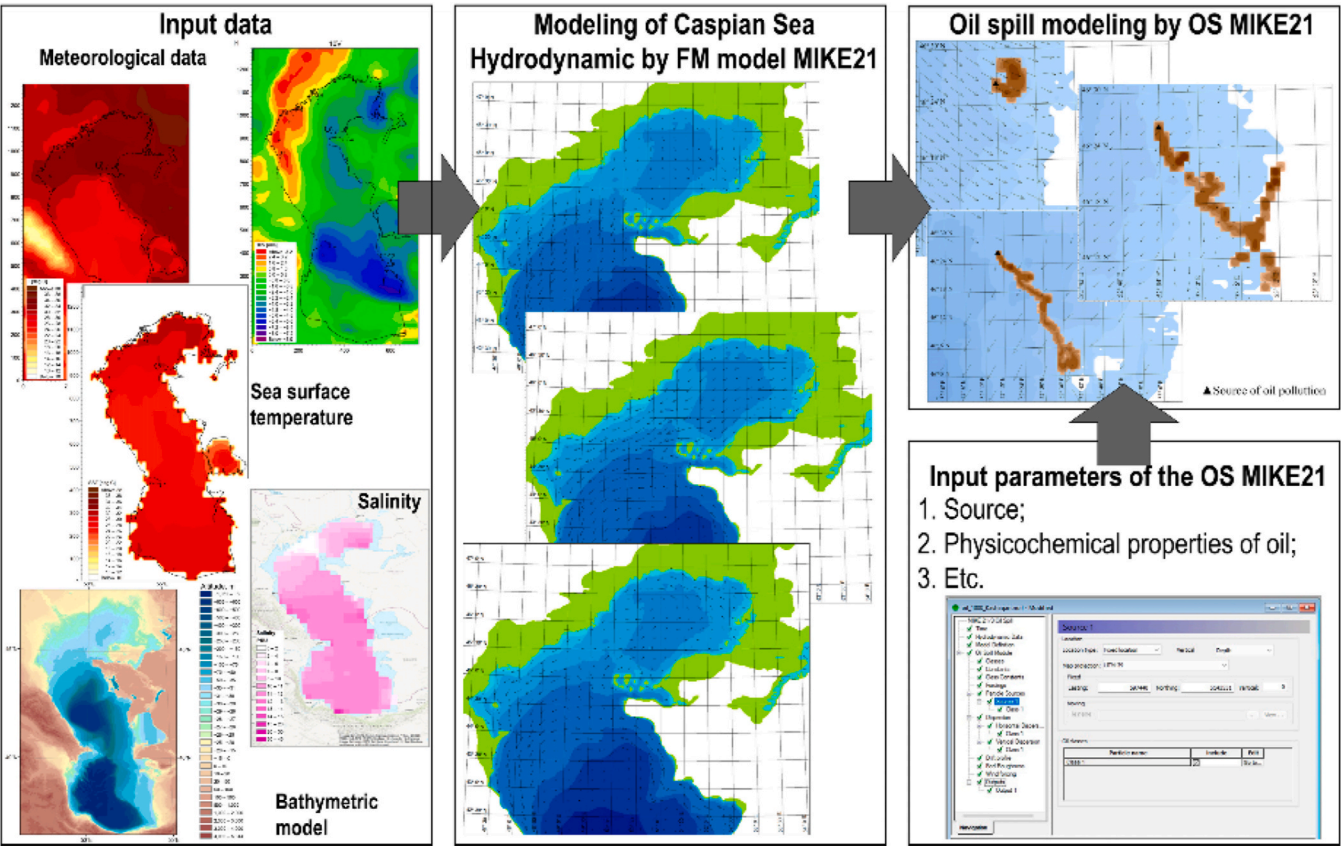


**Fig. 15.** Schematic representation of the modelling approach used to simulate the dispersion pathways and spatial distribution of oil pollution in the Caspian Sea [154].

harmonized regulatory standards, and transboundary coordination are essential for the safe and sustainable deployment of hydrogen transport systems in this unique and fragile environment. Figure 15 shows the dispersion of oil pollution in the Caspian Sea can be simulated using a spatial modelling framework that accounts for hydrodynamic conditions, prevailing currents, and seasonal variability.

Furthermore, mitigation strategies should be linked to the specific hydrogen transport modes. In pipeline transport, environmental protection focuses on leak prevention through robust material selection, corrosion control, and continuous monitoring systems. For LH<sub>2</sub> transport, mitigation measures should address boil-off losses and energy-intensive liquefaction through improved cryogenic insulation and efficient handling systems. In the case of ammonia transport, the primary concern is toxicity; thus, strict containment, gas detection systems, and clearly defined emergency response procedures are essential to minimize environmental exposure.

## 6. Opportunities and future directions

Opportunities for hydrogen development in the Caspian region rely on combining technological innovation with effective governance and integration into Eurasian and European energy corridors. On the technology side, three areas offer significant potential. First, hybrid storage and transport systems can help reduce cost volatility across both shallow northern and deeper southern basins. One practical option is flexible switching between gaseous hydrogen pipelines for shorter distances and ammonia for export cargos, with reliquefaction or boil-off gas recovery at terminals to minimize shipboard losses. Second, AI-driven routing and dispatch systems can optimize maritime and pipeline operations by using forecasts of wind, waves, and currents, as well as port congestion and seasonal ice patterns, to minimize energy loss and delays while dynamically managing route capacity. Third, advances in materials and monitoring, such as fracture-resistant steels, fiber-reinforced liners, distributed acoustic sensing, and continuous area monitoring for ammonia and hydrogen, can significantly reduce leak probability and improve safety.

European hydrogen demand will play a decisive role in shaping Caspian export strategies. The EU plans to produce 10 million tonnes of renewable hydrogen domestically and import another 10 million tonnes per year by 2030 [155]. By 2050, renewable hydrogen is expected to provide around 10% of the EU's final energy consumption, with priority in hard-to-abate sectors such as heavy industry and transport [156]. These targets are backed by funding programs, infrastructure initiatives, and clear specifications for hydrogen quality and certification, which will influence investment decisions in the Caspian. The European Hydrogen Backbone initiative provides a potential pathway for integration. This plan envisions tens of thousands of kilometers of hydrogen pipelines by 2040, much of it repurposed from existing natural gas infrastructure [157]. For Caspian exporters, connecting to these networks via routes through the South Caucasus and Black Sea or through Eastern Europe will determine where and how hydrogen can be delivered at scale. Planning should align production hubs in Kazakhstan or Turkmenistan with the technical and regulatory requirements of these entry points.

International consortia are emerging to support large-scale hydrogen trade. Mechanisms such as long-term contract auctions offer price stability for producers and reduce investor risk. Caspian projects that align with such frameworks can secure predictable revenues, unlock export credit support, and lower financing costs. Pilot initiatives in the region can test large-scale production and export logistics. For example, phased developments could begin with smaller volumes to trial port handling systems, seasonal shipping strategies, and cross-border transport arrangements. Upgrading ports with refrigerated storage, spill containment, and harmonized safety rules, along with maritime trials under challenging conditions, will provide valuable operational data. Policy support should focus on improving bankability, simplifying permitting,

and ensuring interoperability. Long-term offtake contracts and regional support schemes can stabilize early cash flows. Mutual recognition of safety and technical standards among Caspian states can shorten development timelines, while alignment with European hydrogen quality and certification schemes will ensure market access. In the long term, flexibility will be critical. Modular projects that can shift between hydrogen, ammonia, or methanol production depending on market conditions will be better positioned to adapt. Integration of AI-based predictive maintenance and routing will help reduce costs and improve reliability. By aligning technological, policy, and infrastructure developments, the Caspian region could secure a meaningful share of Europe's hydrogen import targets in the coming decades.

## 7. Conclusions

Analysis of green hydrogen transport across the Caspian Sea highlights the links between geomorphological constraints, technological feasibility, and geopolitical realities that collectively shape the region's potential as a strategic energy corridor. The bathymetric and sedimentation patterns of the Caspian, along with seismic hazards and vulnerable coastal ecosystems, set clear limits on the optimal routing of pipelines and shipping lanes. These natural conditions intersect with operational challenges such as hydrogen embrittlement in high-pressure pipelines, the toxicity risks associated with ammonia as a carrier, and the susceptibility of shipping routes to seasonal storms. Together, these factors reveal the importance of geospatial modelling for route optimization and risk assessment, as well as the need for resilient infrastructure capable of adapting to both environmental and economic pressures. Despite progress in simulation techniques and preliminary infrastructure planning, significant research gaps remain. The environmental sensitivity of the Caspian ecosystem demands more comprehensive studies on the potential impacts of hydrogen and ammonia leaks, particularly their interactions with unique habitats and fisheries that sustain local economies. Long-term monitoring of sedimentation belts, sea-level fluctuations, and seismic risks is equally essential to anticipate vulnerabilities in planned corridors. On the technological side, innovations such as hybrid storage systems, advanced pipeline materials, and AI-driven routing models are promising, but empirical validation under Caspian-specific conditions is still limited. In terms of governance, regulatory fragmentation among littoral states and the absence of harmonized safety codes remain barriers to integrated hydrogen transport planning. Moving forward, the Caspian Sea holds a pivotal position in connecting central Asian producers with European demand centres through green hydrogen trade. With growing investment in hydrogen alliances and transcontinental energy corridors, the Caspian is likely to emerge as a critical link in Eurasian supply chains. Strategic pilot projects, supported by international consortia, can serve as testbeds to demonstrate safe and cost-effective transport technologies while building trust among stakeholders. At the policy level, closer alignment with international maritime and safety frameworks would strengthen the reliability of Caspian routes and help attract broader investment. Regional progress requires harmonized regulatory frameworks and coordinated environmental monitoring among Caspian littoral states. Pilot projects, advanced modelling, cross-border investment consortia, and alignment with wider Eurasian and European hydrogen corridors will be essential to support safe and efficient infrastructure deployment. Findings from this study provide important insights for the design of resilient hydrogen transport infrastructure under complex marine and geological conditions. The study highlights the need for coordinated regional policies and harmonized safety regulations, while emphasizing the importance of further research on ecosystem impacts, long-term geohazard monitoring, and the validation of emerging hydrogen transport technologies under Caspian-specific conditions.

## CRediT authorship contribution statement

**Kenzhebatyr Bekmyrza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Asset Kabyshev:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marzhan Kubenova:** Writing – review & editing, Visualization, Validation, Funding acquisition, Formal analysis, Conceptualization. **Kairat A. Kuterbekov:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Aliya Baratova:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **Lukman Ahmed Omeiza:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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