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## OPTIMISATION OF HYDROGEN TRANSPORT ROUTES

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**Abstract.** This article examines issues relating to the safe and cost-effective transport of hydrogen across the Caspian Sea, taking into account natural-geographical, technical, environmental and infrastructural factors. Particular attention is paid to the selection of technologies for the storage and transport of hydrogen, including compressed and liquid hydrogen, ammonia, liquid organic hydrogen carriers and metal hydrides. The specific features of their application in the Caspian region are highlighted; this region is characterised by significant spatial variation in depth, shallow waters in the northern part, seasonal ice cover, high sedimentation loads and sea-level fluctuations.

The Caspian Sea is of particular interest for the development of trans-regional hydrogen corridors, as it links the energy resources of Central Asia with the markets of the Caucasus and Europe. At the same time, the ecological sensitivity of the basin, the presence of endemic species—including the Caspian seal—as well as the potential risks of hydrogen and ammonia leaks necessitate the application of enhanced safety requirements for transport infrastructure.

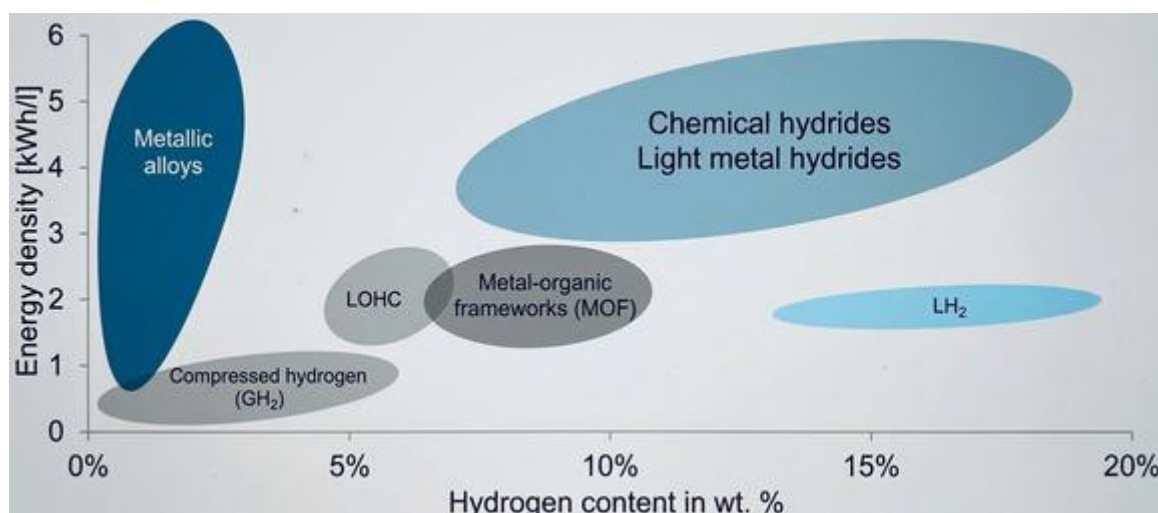
This paper proposes a comprehensive approach to route optimisation, based on consideration of bathymetry, sediment accumulation, seismic hazard, ice and hydrometeorological conditions, shipping traffic, environmental vulnerability and technical and economic indicators. The necessity of using geoinformation and multi-criteria modelling to identify optimal hydrogen corridors is justified. The potential of hybrid transport solutions and dynamic routing using modern monitoring and forecasting systems is demonstrated. The findings can be utilised in the development of concepts for safe hydrogen logistics and the establishment of international energy corridors in the Caspian region.

**Keywords:** hydrogen energy; hydrogen transport; hydrogen storage; the Caspian Sea; route optimisation; geoinformation modelling; risk assessment; environmental safety; ammonia; LOHC; hydrogen logistics; decarbonisation.

### Introduction

Hydrogen storage schemes in the Caspian region require a balance between technical characteristics and environmental constraints. These include the presence of brackish and hypersaline water, extensive shallow-water shelves in the north, high sedimentation rates in the deltas of major rivers, and seasonal ice cover [1]. The northern Caspian has an average depth of just 4–8 m, with a maximum of around 20 m, and receives around 88 per cent of the total river inflow, mainly from the Volga, which results in high turbidity and sedimentation loads on coastal and nearshore infrastructure [2]. Salinity across the basin averages approximately 1.28 per cent, but ranges from around 0.1 per cent near river mouths to much higher values in evaporitic bays, such as Kara-Bogaz-Gol [3].

These gradients, together with winter ice, which can persist from November to March in the north, make the choice of storage location and materials highly complex. Reub et al. [4] demonstrated the suitability of LOHC for small-scale mobility, whilst Figure 82 highlights the trade-offs between LOHC, MOF,  $\text{GH}_2$  and  $\text{LH}_2$  in terms of performance and stability.



**Figure 1** – Comparison of various hydrogen storage technologies, including liquid organic hydrogen carriers (LOHC), metal-organical frameworks (MOF), gaseous hydrogen (GH<sub>2</sub>) and liquid hydrogen (LH<sub>2</sub>) [4].

These factors are crucial for deployment in the high-salinity and high-precipitation 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 hubs. Modern systems operate at pressures of 350 or 700 bar, providing a practical volumetric energy density of approximately

2.1–4.8 MJ/l and enabling rapid charging and discharging without the need to manage phase transitions. However, large onshore storage tanks and offshore skids are subject to salt spray, biofouling and abrasion from sediment. In shallow northern waters, the gaps between platforms are limited, and the risk of grounding increases during storm surges or ice movements, raising the likelihood of impact loads on Type III or IV vessels with manifolds [5]. From a materials perspective, the pressure boundary is typically carbon fibre over a polymer liner; these composites are resistant to chloride attack but require the use of stainless or coated steel in valves and fittings to minimise pitting and stress corrosion in salt aerosols. The ease of storing CH<sub>2</sub>, combined with minimal cryogenic demands, is advantageous in conditions of power shortages or supply disruptions. However, the unit cost per unit of stored energy is high, which poses a challenge given the limited coastal corridors around Baku, Atyrau and Turkmenbashi.

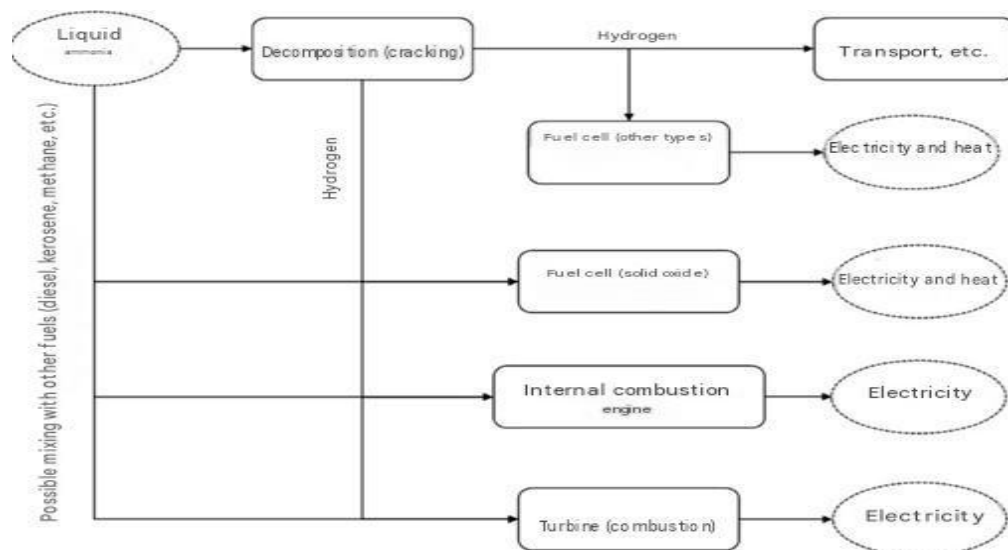
### Materials and methods

LH<sub>2</sub> offers a high volumetric hydrogen content and rapid discharge, but its cryogenic requirements at a temperature of approximately 20 K impose stringent demands on thermal management and precise control of materials. The density of LH<sub>2</sub> is approximately 70.8 kg-H<sub>2</sub>m<sup>-3</sup>, which allows for compact storage compared to CH<sub>2</sub>; however, outgassing remains a design and operational challenge, particularly for terminals subject to seasonal temperature fluctuations and dynamic loading from waves and ice [6]. Minimising boil-off requires multi-layer insulation and deep-vacuum annular spaces, together with a reliable power supply to maintain the vacuum and re-condensation or re-liquefaction facilities—constraints that may be difficult to meet at remote Caspian facilities with an unstable grid. Exposure to low-temperature hydrogen can cause embrittlement in certain steels; therefore, aluminium-deoxidised fine-grained steels or cryogenically compatible alloys are often required for offshore LH<sub>2</sub> tanks and pipelines, which increases weight and cost. The combination of cold leaks and oxygen condensation poses a safety hazard, exacerbated by wind-borne salt aerosols, which deposit hygroscopic salts on cold surfaces, intensifying icing and corrosion at penetration points. In northern offshore waters, where ice formation and fast ice are common, the design of jetties and secondary protective hulls must account for differential thermal movements and ice ploughing. Ammonia and liquid LOHCs provide liquid-phase logistics, which

are often better suited to shallow-water ports with high precipitation levels [7]. Anhydrous ammonia liquefies under mild conditions and, per unit volume of storage tank, can store more hydrogen equivalents than  $\text{LH}_2$ , since liquid  $\text{NH}_3$  contains approximately 17.6 mass % hydrogen and has a density of about 0.68 kg/l under ambient conditions, which is equivalent to approximately  $0.12 \text{ kg-H}_2/\text{l}$  [8]. This results in a high volumetric energy density at the system level and is one of the reasons why the maritime literature reports that the volumetric energy density in tanks is approximately twice that of  $\text{LH}_2$  for comparable protective casings. The toxicity and corrosive nature of ammonia necessitate the careful selection of materials, such as austenitic stainless steels for wetted components, as well as reliable leak detection and ventilation, particularly in enclosed valve boxes exposed to salt spray. For the Caspian Sea, the possibility of mooring shallow-draught ammonia tankers in the river delta ports is attractive. However, onshore dehydrogenation plants consume 20–30 per cent of the energy content, depending on heat conversion and integration, whilst the presence of  $\text{NO}_x$  resulting from combustion requires after-treatment if any direct combustion of ammonia is used [9]. Figure 4 illustrates the dual role of ammonia in the hydrogen economy, acting either as a direct fuel or as a carrier for hydrogen production through decomposition. Where hydrogen is used for industrial purposes, for example in steel production or at oil refineries, the direct use of ammonia as a feedstock or fuel may make it possible to bypass cracking, but this shifts the focus on safety towards the management of toxic risks in densely populated coastal areas.

Among low-concentration hydrocarbons (LOHCs), methylcyclohexane (MCH) and dibenzyltoluene (DBT, often used in perhydrophthalic form) are the most relevant. They are liquid at ambient temperature, compatible with traditional fuel infrastructure and resistant to saline environments when using standard marine materials. Typical reversible hydrogen storage capacities are around 6 mass % for MCH in toluene and 6–7 mass % for perhydrogenated DBT in DBT, although practical values at the system level are reduced when catalysts and heat exchangers are used [10]. The main penalty is thermal: hydrogenation is an exothermic process, whilst dehydrogenation requires temperatures of 250–320 °C and catalysts with a large surface area, consuming a significant portion of the energy content unless high-quality waste heat is available. During the cold and windy Caspian winters, heat losses from dehydrogenation lines increase, making insulation necessary, whilst in summer, high ambient temperatures and warm cooling water on the southern coast can limit condensation and product recovery. LOHC spills are less hazardous than ammonia, and their non-cryogenic storage simplifies the design of jetties in shallow-water ports with shifting seabed conditions. However, repeated cycles can lead to carrier degradation and the formation of by-products, requiring carrier replenishment logistics which increase the life-cycle cost.

Metal hydrides and other solid-state options offer the prospect of compact, intrinsically safe storage at low operating pressures, which may be attractive for onshore buffering near sensitive coastal habitats and industrial consumers. Magnesium hydride offers a theoretical capacity of 7.6 mass %, but practical reversible capacities of around 3–5 mass % at useful rates are typical without the use of advanced catalysts [12]. Intermetallic hydrides, such as systems based on  $\text{LaNi}_5\text{H}_6$  or Ti, operate at approximately –50–200 °C with fast kinetics, but their gravimetric capacities are typically 1–2 mass %, which increases transport mass and cost [13]. Temperature control is crucial, as both hydrogenation and dehydrogenation are thermally intensive processes, and in shallow-water areas with large amounts of sediment, where intake screens are prone to clogging, reliable cooling with seawater cannot be guaranteed. Corrosion from salt spray and chloride-rich soils can compromise the longevity of the heat exchanger unless duplex stainless steels or polymer-coated heat exchangers are used. At offshore or remote sites, the low pressure in hydride reservoirs reduces the risk of hydrogen ingress and leakage during ice events or ground heave, but modular skids remain heavy, making installation on soft deltaic deposits without deep foundations difficult.



**Figure 2** – Possible uses for ammonia, covering both direct application and decomposition into hydrogen [11].

To account for the physical and environmental conditions of the Caspian Sea, several selection criteria are of interest. Draught restrictions and seabed mobility favour storage concepts that minimise the need for large-displacement cryogenic tankers or deep-water berths in the north. In this context, ammonia or LOHC, handled using conventional chemical tankers, are logistically more suitable than LH<sub>2</sub>, which typically relies on specialised vessels and reliable cryogenic supply lines. Winter ice and strong winds increase mechanical stresses and power supply disruptions at terminals [14]. Technologies with low standby power consumption, such as CH<sub>2</sub> and metal hydrides, are more resilient than LH<sub>2</sub>, whose boil-off control is highly sensitive to power supply. Salt aerosols and sediment abrasion increase the rate of corrosion and fouling; therefore, storage systems with fewer cold surfaces and simpler insulation systems, such as CH<sub>2</sub>, LOHC and hydrides, reduce the maintenance burden compared with LH<sub>2</sub>. Proximity to industrial consumption clusters around Baku, Aktau and Turkmenbashi favours the use of gas storage facilities, which can be integrated directly into process heat or hydrogen networks; LOHC and ammonia can utilise existing petrochemical infrastructure, whilst CH<sub>2</sub> is suitable for consumers connected to pipelines.

Environmental risk profiles also differ. Ammonia raises concerns regarding acute toxicity, which must be weighed against its reduced explosion range compared with gaseous hydrogen. LH<sub>2</sub> minimises toxicity but presents specific cryogenic and oxygen-condensation hazards. LOHCs reduce acute risks but require high-temperature reactors with catalytic control. Hydrides minimise the need for high-pressure tanks but have increased thermal and weight constraints.

For areas with high salinity, shallow waters and high precipitation, such as the Northern Caspian shelf, liquid-phase carriers used in conventional chemical logistics—particularly ammonia and certain LOHCs—offer practical advantages in terms of mooring, compact storage and material compatibility, provided that issues relating to the energy costs of dehydrogenation and toxicity risks are clearly addressed. CH<sub>2</sub> remains a reliable choice for short-term buffer storage, refuelling and use in the vicinity of pipelines, particularly where there is land available for large sites. LH<sub>2</sub> is best reserved for deep-water southern locations with reliable energy sources and specialised berths, where cryogenic storage facilities can be protected from erosion by ice and precipitation. Solid hydrides show promise for creating safety-critical buffer zones near populated areas, but their bulk transport capacity is currently limited. The heterogeneity of the Caspian Sea, with salinity ranging from approximately 0.1 per cent at river mouths to over 1.2 per cent in the open sea, depths ranging from less than 10 m in the north to over 1,000 m in the south, and winter ice in the north, suggests that the most effective solution to address local constraints and the trade-offs between costs and risks

would be a portfolio approach, rather than relying on a single storage technology [15].

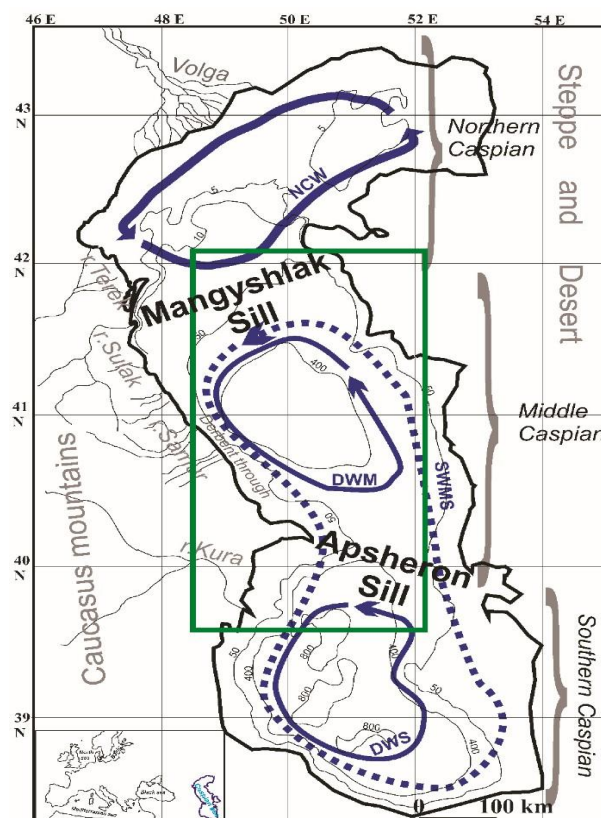
Optimising hydrogen corridors across the Caspian Sea requires the integration of bathymetry, sediment dynamics, seismic hazard, shipping risk and technical and economic indicators into a single geospatial framework. The basin's triple morphology—the shallow Northern Caspian ( $\leq 20$  m), the deep Central Caspian ( $\sim 788$  m) and the ultra-deep Southern Caspian ( $\sim 1025$  m)—creates highly differentiated constraints on routes for pipelines and shipping [16]. A multi-criteria GIS model for the Caspian Sea must weigh up bathymetric value (penalising depths  $< 10$  m in the north), sedimentation zones (the Volga and Ural estuaries), seismic hazard and active faults encircling the southern and western margins (Elburz, Talysh/Talysh). Protected and sensitive habitats, the density of shipping lanes and storm wave conditions should also be included. Capital and operating cost levels for pipelines compared with vessels. Bathymetric grids and shelf breaks are well defined; the southern basin contains  $> 65\%$  of the total water volume with a maximum depth of approximately 1,025 m, whilst the northern shelf is extremely shallow, averaging  $\sim 5\text{--}6$  m and rarely exceeding 20 m, which complicates both navigation and pipeline submergence [17]. Geological and oceanographic mapping further reveals significant contourite/turbidite activity on the basin's slopes, indicating the need to avoid corridors prone to mass transport. Figure 4 illustrates the bathymetric configuration and current systems of the Caspian Sea, which are critical factors in assessing potential hydrogen transport routes, taking into account the influence of basin depth, bottom currents and river sedimentation on the stability of the infrastructure.

The most important task is to minimise risks and optimise costs when selecting storage technologies and routes. To this end, multi-criteria models are used, which take into account leakage rates, the probability of accidents and the economics of construction. For example, the use of ammonia or LOHC reduces capital expenditure on port infrastructure by 10–15 per cent, whilst the use of compressed hydrogen ( $\text{CH}_2$ ) is more appropriate near industrial clusters, where operational efficiency and low leakage risks are critical. Optimising routes to account for geomorphological hazards reduces infrastructure costs by 12–20 per cent, whilst simultaneously improving the safety of maritime transport.

The Volga Delta has historically developed rapidly, with documented expansion of the delta plain ranging from  $\sim 2.3$  to  $\sim 180 \text{ km}^2$  per year during phases of Caspian Sea level decline [18]. This indicates active sedimentation zones, which can bury or expose infrastructure and alter fairways on a decadal timescale. Therefore, corridors crossing sections of the delta or the mouths of canals warrant higher risk factors for operation and maintenance, as well as real-time monitoring

of the seabed topography. Seismically, the southern and western margins exhibit recurring events of magnitude  $M6\text{--}7+$  [19]. The 1990 Manjil–Rudbar earthquake ( $M_w 7.4$ ) devastated the Elburz foothills bordering the Caspian Sea, whilst the 2012 Akhar–Varzagan doublet reached  $M_w 6.4\text{--}6.5$  in north-western Iran near the Azerbaijan–Iran sector [20,21]. Pipeline corridors running parallel to these zones, or landfall points in Gilan/Mazandaran or the Talysh Range, require the design of fault crossings, geological hazard clearances and shutdown segmentation tailored to local peak ground accelerations. Navigation in the northern Caspian is restricted by shallow waters ( $\sim 5$  m) and winter ice; a 1-metre drop in water level results in underloading of vessels and increases transport costs per tonne [22]. With the observed and forecast drop in the Caspian Sea level, ports such as Aktau are reporting underloading due to shallow water; this operational risk will directly affect hydrogen carriers ( $\text{LH}_2$  or tankers carrying hydrogen derivatives) departing from the north-eastern shelf.

The main bottom currents are indicated: NCW (North Caspian Water Mass, covering all water levels), SWMS (Surface Water Mass of the Central and Southern Sub-basins), DWM (Deep Water Mass of the Central Sub-basin) and DWS (Deep Water Mass of the Southern Sub-basin). The river network is shown, originating in the Caucasus Mountains to the west and in the Volga River delta to the north. The rectangle marks the area of seismic surveys carried out between 2004 and 2012 [23].



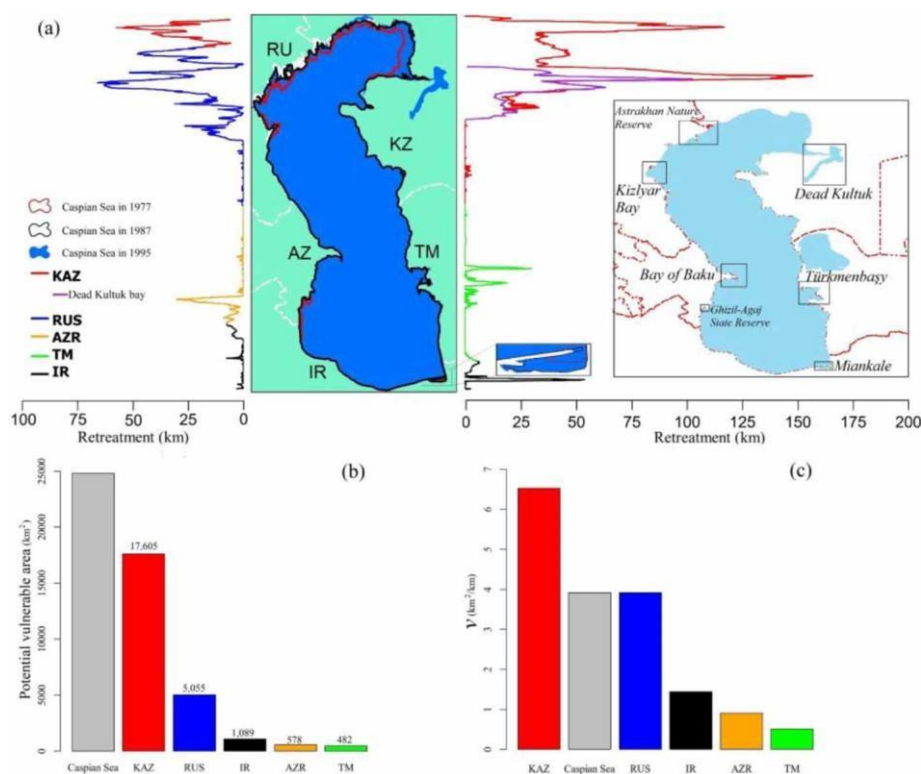
**Figure 3** – Bathymetric map (m) of the Caspian Sea, showing the northern, central and southern basins, as well as key geographical features, including major mountain ranges, river systems and steppe regions.

Although long-term analyses indicate a decline in average ice extent and severity (a reduction in extreme winters), hazardous ice formations (stamukhi) are still recorded along northern routes, necessitating ice class or seasonal planning in corridor models to account for these risks. Simulation of wave surges (ADCIRC+WAVEWATCH III) for 1979–2020 provides spatial fields of wave heights and significant wave heights; integrating these into hydrometeorological ‘penalty’ layers enables probabilistic route planning and LNG-style weather windows for LH2tankers [24–26].

As shown in Figure 4, sea-level fluctuations (SWL) pose varying degrees of risk to the coastal zones of the Caspian Sea, with significant coastal retreat predicted along both the western and eastern coasts.

Vulnerability mapping shows that several bays and low-lying areas are at particular risk, whilst the calculated vulnerability coefficients highlight marked differences between the neighbouring countries, with the most vulnerable areas observed in Kazakhstan and Russia.

The conversion of selected gas corridors adjacent to the Caspian Sea to the transport of hydrogen or mixtures must take into account the hydrogen embrittlement of steels and increased permeability. Recent reviews and experimental studies demonstrate the susceptibility of high-pressure steel pipelines to hydrogen embrittlement, which necessitates rigorous material qualification in accordance with emerging regulations and standards [28–30].



**Figure 4** – Spatial vulnerability of the Caspian Sea's coastal zones to sea-level fluctuations (SLF): (a) projected shoreline retreat in the western and eastern sectors, including maps indicating the main bays, (b) potentially vulnerable zones within the Caspian Sea and neighbouring countries; and (c) the vulnerability coefficient ( $v$ ) for the Caspian Sea and each bordering state (KAZ – Kazakhstan, RUS – Russia, IR – Iran, AZR – Azerbaijan, TM – Turkmenistan) [27]

Where necessary, fibre-reinforced polymer or lined solutions should be used at junctions. For leak modelling, literature values range from ~0.3–0.4% for pipeline segments in baseline assessments, although value chain studies range from <2 per cent to nearly 20 per cent in a worst-case future scenario, highlighting the need for empirical detection and quantification of leaks during deployment in the Caspian Sea. Therefore, corridor planners should factor in a priori leakage rates of ~0.3 per cent for well-maintained hydrogen-only transmission systems, with a sensitivity range of 1–3 per cent for mixed or retrofitted assets pending integrity checks. In concepts for the transport of liquid hydrogen across the Caspian Sea (for example, from Kazakhstan or Turkmenistan to Azerbaijan), the dominant transport loss is the boil-off rate (BOR).

Current empirical and techno-economic sources report a BOR of between ~0.1 and 0.5 per cent per day for transport vessels, with best-in-class demonstrations at around 0.2–0.3 per cent per day, and for onshore storage, as low as ~0.06 per cent per day. Research-level systems with active cooling can approach ~0% under laboratory or NASA conditions [31]. For corridor models, a conservative central estimate of 0.3 per cent per day at sea and 0.06–0.2 per cent per day in terminal storage tanks is justified, whilst weather conditions along the route reduce the heat influx caused by sloshing [32]. As regards pipeline transport, the loss conditions combine steady-state permeability/leakage (of the order of ~0.3–0.4% over distance/time intervals) and leakage scenarios caused by failures, both of which can be reduced through the use of coatings, materials with lower permeability, pressure optimisation and continuous leak detection using line-packet system telemetry.

The cost-optimal route must jointly minimise CAPEX for pipeline laying/burial or vessel acquisition, OPEX for compression/liquefaction and boil-off recovery, and expected losses ( $R \cdot C$ ), taking into account the risk from geological hazards and the climatic externalities of leakage.

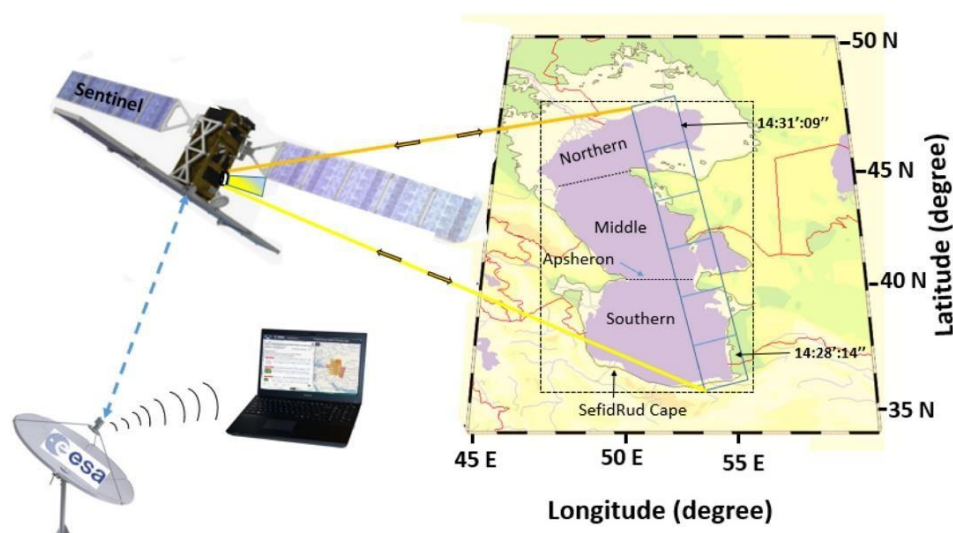
Liquefaction penalties (25–30 per cent of HHV for LH<sub>2</sub>) exceed the Caspian-specific volume but dominate on maritime routes; thus, short maritime legs ( $\leq 500$  km) are cost-effective provided the terminal location avoids shallow-water or ice-prone sectors, which impose draught and scheduling penalties. Integration of the latest unloading cost estimates and BOR control options shows that compression/re-liquefaction of boil-off on larger LH<sub>2</sub> vessels may be cost-effective, increasing the effective BOR to  $\sim 0.2\%$ /day and reducing the variance in delivery costs under rough sea conditions. For pipelines, the development of codes and standards now offers clearer procedures for the qualification of steel, welds and components in gaseous hydrogen environments, which may reduce contingency allowances in cost estimates as test data accumulates. Another critically important factor for the corridor is the emerging consensus regarding the rapid decline in the level of the Caspian Sea. Route optimisation must therefore be dynamic, utilising bathymetry and coastline forecasts to reassess costs and, where necessary, relocate terminals southwards or to deeper straits.

A hydrogen export corridor running from east to west across the Caspian Sea a geospatially stable option is a hybrid pipeline or a short-distance barge route from shallow-water northern producers to deep-water consolidation centres, followed either by an underwater pipeline laid along stable slope sectors of the Central/Southern basins, avoiding active faults and steep mass-transport corridors, or LH<sub>2</sub> shuttle services (or hydrogen carriers) following great circle arcs, taking storms into account and avoiding the ice season. When assessing the corridor, northern routes should be penalised during low-water periods and the ice season, additional loads should be applied for crossings of seismic faults along the southern edge, and BOR/leakage conditions should be explicitly included in the energy supply model. Where a trans-Caspian subsea route is under consideration, the same seabed constraints that define the long-discussed gas pipeline apply to hydrogen, with additional precautions regarding material compatibility and environmental acceptability specific to hydrogen. In practice, the model must incorporate selective dredging and fairway maintenance in the north. It must also include ice-class vessels and dynamic planning to avoid ice jams. Continuous forecasts of current waves and swells are required for voyage planning. The qualification of pipeline steel and welds to hydrogen standards is crucial, alongside the design of crack-stopping measures and fault crossings along the Elburz/Talysh sections. BOR management should apply multi-layer insulation, on-board compression/re-liquefaction and chilled loading at terminals. Real-time leak detection with rapid isolation is crucial for maintaining an effective leakage rate of around or below  $\sim 0.3$  per cent for pipelines and  $\sim 0.2\text{--}0.3$  per  $\text{day}^{-1}$  for offshore LH<sub>2</sub> [33]. The integration of these measures into a probabilistic, updatable GIS stack—re-evaluated as sea level, ice climatology and traffic patterns change—provides a secure, transparent basis for decision-making regarding siting, licensing and investment in Caspian hydrogen corridors. Effective corridor optimisation will depend on traffic density across the entire basin, derived from AIS data, high-resolution digital seabed mapping to identify hazards associated with mass movements, and comprehensive seismic microzonation near landfall sites. Until this data has been systematised, planners should apply conservative safety factors and prioritise routes that utilise the depths of the Central and Southern basins, whilst minimising the impact of northern ice dynamics and precipitation.

### **Research findings.**

The Caspian Sea's landlocked nature, strong vertical stratification and high concentration of endemic species make the management of environmental risks a paramount consideration for any hydrogen transport corridor passing through its coastal regions. This ecosystem is the habitat of the Caspian seal (*Pusa caspica*), a species listed as endangered, whose population has declined from historical estimates of around one million to approximately 70,000 individuals in recent years [34]. This population continues to face pressures from disease, by-catch, pollutants and habitat loss. The basin has also demonstrated how quickly the ecological balance can be disrupted. The introduction of the invasive comb jelly *Mnemiopsis leidyi* in the mid-1990s led to a sharp decline in anchovy-like sprat catches from approximately 95,000 tonnes in 1999 to less than 20,000 tonnes in the early 2000s, which had a serious impact on the fishing industry and the economy of coastal regions. Against this ecological backdrop, the potential consequences of spills and leaks in hydrogen supply

chains—particularly when ammonia is used as a carrier and gaseous hydrogen is transported via pipelines—require careful analysis. In an aquatic environment, total ammonia nitrogen (TAN) at certain concentrations can be extremely toxic to aquatic organisms [35]. At pH 7 and 20°C, the acute toxicity thresholds for freshwater species are around 17 mg TAN/l, whilst the chronic exposure thresholds are around 1.9 mg TAN/l [36]. These limits become stricter at higher pH values due to the increased presence of more toxic non-ionised forms of ammonia ( $\text{NH}_3$ ). This is of particular concern in sensitive areas such as the Volga Delta, river estuaries and brackish coastal systems. As shown in Figure 86, the Sentinel-1A satellite captured high-resolution images of the Caspian Sea during its flyover on 24 October 2019, enabling an analysis of the spatial coverage encompassing the basin's boundaries and key geographical features.



**Figure 5** – Schematic representation of the Caspian Sea and the Sentinel-1A satellite's flyover of the water area on 24 October 2019.

The data were collected along an ascending trajectory, starting from the eastern part of the southern waters at 14:28:14 GMT and ending in the northern waters at 14:31:09 GMT, covering approximately three minutes. Six data files corresponding to the areas covered are shown. Additional flights over other parts of the Caspian Sea on 25, 28, 29 and 30 October are not shown for the sake of clarity. Key features such as the boundaries of the water area, Cape Sefidrude and the Absheron Strait are marked [37].

In the event of a release of anhydrous ammonia vapour during bunkering or transshipment, established exposure guidelines indicate that serious health effects may occur at concentrations as low as 220 ppm for short periods and around 110 ppm over several hours [38]. Life-threatening effects may occur at levels ranging from 2,700 ppm for short-term exposure to 390 ppm for prolonged exposure [39]. Occupational safety thresholds, such as the Immediate Danger to Life or Health (IDLH) level of 300 ppm, are crucial for planning emergency response and ensuring adequate personal protective equipment. The integrity of hydrogen gas pipelines is another key environmental safety measure. Hydrogen can accelerate the growth of fatigue cracks and reduce the fracture toughness of many pipeline steels. Consequently, current design standards specify reduced allowable stresses and require fracture control measures specifically for hydrogen service. Updated pipeline codes, such as ASME B31.12, include specific requirements for hydrogen, including material performance factors that restrict the use of certain steels and specify minimum target fracture toughness values in hydrogen environments [40]. These measures directly reduce the likelihood and severity of leaks, thereby helping to protect the environment.

The regulatory framework in the Caspian region has 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 framework for cooperation

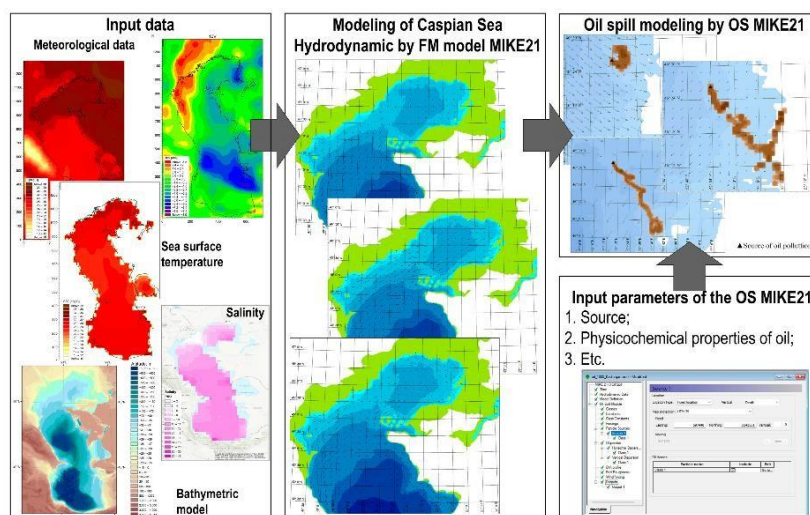
between the five littoral states [41]. Environmental protection is governed by the Tehran Convention and its protocols, which focus on preparedness and response to pollution incidents, control of land-based discharges and the conservation of biodiversity. Although these agreements provide for notification, monitoring and response mechanisms, they do not yet include specific provisions on hydrogen or ammonia as fuels, creating a regulatory gap for new operations involving low-carbon fuels. From a maritime perspective, global conventions continue to apply, as the Caspian states are parties to key international agreements. MARPOL regulates the prevention of pollution, the SOLAS framework addresses ship safety, and the IMO IGC Code regulates the carriage of liquefied gases such as anhydrous ammonia [42]. The IGF Code applies to ships using fuel with a low flash point, and the IMO has issued interim guidelines on alternative fuels, including ammonia. However, there is no unified port State control system in the Caspian region, and compliance with safety and cargo-handling standards can vary significantly between different ports.

A multi-tiered approach is recommended to ensure effective environmental protection and compliance with regulatory requirements. Hydrogen pipelines must be designed in accordance with the standards governing the handling of hydrogen, with stringent measures to control failure. Ammonia storage and transshipment facilities should be constructed in accordance with international safety standards for gas carriers, and emergency response planning zones should be defined on the basis of recognised toxicity and exposure thresholds. To predict the spread of ammonia in the event of a spill, particularly in vulnerable estuary and delta areas, modelling that takes into account the specific characteristics of individual sites should be used. Furthermore, regional cooperation mechanisms should be updated to include scenarios specific to hydrogen and ammonia in national emergency response plans, and joint emergency response exercises should be conducted between countries. Ports on the Caspian Sea must harmonise their regulations on the handling of alternative fuels and safety, ensuring consistency in operations and emergency preparedness. The high environmental sensitivity of the Caspian Sea, the inherent toxicity of ammonia and the structural vulnerability of hydrogen infrastructure necessitate a design philosophy based on the principle of 'fail-safe' systems. Preventive engineering solutions, harmonised regulatory standards and cross-border coordination are crucial for the safe and sustainable deployment of hydrogen transport systems in this unique and fragile environment. Figure 6 illustrates how the spread of oil pollution in the Caspian Sea can be modelled using spatial modelling that takes into account hydrodynamic conditions, prevailing currents and seasonal variability.

The potential for the development of hydrogen energy in the Caspian region is based on a combination of technological innovations with effective management and integration into Eurasian and European energy corridors. From a technological perspective, three areas offer significant potential. Firstly, hybrid storage and transport systems could help reduce cost volatility in both the shallow northern and deeper southern basins. One practical option is to switch flexibly between pipelines carrying gaseous hydrogen for short distances and ammonia for export shipments, with re-liquefaction or utilisation of off-gas at terminals to minimise losses on board vessels. Secondly, artificial intelligence-based routing and dispatching systems can optimise maritime and pipeline operations by utilising forecasts of wind, waves and currents, as well as port congestion and seasonal ice conditions, to minimise energy losses and delays by dynamically managing route capacity. Thirdly, advances in materials and monitoring, such as crack-resistant steels, fibre-reinforced cladding, distributed acoustic sensors and continuous monitoring of ammonia and hydrogen zones, can significantly reduce the likelihood of leaks and enhance safety.

### **Discussion**

European demand for hydrogen is one of the key factors shaping the Caspian region's export strategies. The European Union plans to produce 10 million tonnes of renewable hydrogen within the EU by 2030 and to import a further 10 million tonnes per year [44]. By 2050, renewable hydrogen could account for around 10 per cent of the EU's final energy consumption, primarily in sectors that are difficult to decarbonise, including heavy industry and transport [45]. The achievement of these targets will determine the requirements for the quality, certification and supply infrastructure of hydrogen from the Caspian region.



**Figure 6** – Schematic representation of the modelling approach used to simulate the spread and spatial distribution of oil spills in the Caspian Sea [43].

A promising avenue is the integration of Caspian exporters into the emerging European hydrogen infrastructure. For Kazakhstan and Turkmenistan, routes through the South Caucasus, the Black Sea and Eastern Europe will be of particular importance, as will ensuring that production projects comply with European technical and regulatory requirements.

The development of large-scale trade requires a phased approach. Pilot projects will enable the testing of port infrastructure, storage and transshipment systems, seasonal logistics and cross-border transport mechanisms. The modernisation of ports, the harmonisation of safety requirements and the mutual recognition of technical standards can reduce infrastructure and regulatory barriers.

Long-term contracts, price support mechanisms and export credit financing are further factors contributing to competitiveness. In the long term, hybrid projects capable of adapting the production of hydrogen, ammonia or methanol to market changes may prove promising. The use of digital monitoring, predictive maintenance and intelligent routing will improve reliability and reduce logistics costs. Thus, the coordinated development of infrastructure, technologies and the regulatory framework is an important prerequisite for the integration of the Caspian region into the emerging European hydrogen market.

### Conclusions.

The transport of ‘green’ hydrogen across the Caspian Sea is determined by a combination of geomorphological, technological, environmental and geopolitical factors. The bathymetry, sedimentation processes, seismic risks and environmental vulnerability of the Caspian Sea significantly influence the selection of optimal pipeline and shipping routes.

Geospatial modelling and multi-criteria risk assessment are promising tools for optimising hydrogen corridors. However, further research is needed into the environmental consequences of potential hydrogen and ammonia leaks, as well as the use of modern materials, hybrid storage systems and intelligent routing models.

The potential of the Caspian region as part of the Eurasian hydrogen infrastructure also depends on the harmonisation of safety requirements and international cooperation among the littoral states. The implementation of pilot projects could facilitate the testing of safe and cost-effective hydrogen transport technologies and the establishment of sustainable hydrogen corridors.

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## СУТЕКТІ ТАСЫМАЛДАУ МАРШРУТТАРЫН ОҢТАЙЛАНДЫРУ

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**Аңдатпа.** Мақалада Каспий теңізі арқылы сутекті қауіпсіз әрі экономикалық тұрғыдан тиімді тасымалдау мәселелері табиғи-географиялық, техникалық, экологиялық және инфрақұрылымдық факторларды ескере отырып қарастырылады. Сутекті сақтау және тасымалдау технологияларын, соның ішінде сығылған және сұйытылған сутекті, аммиакты, сұйық органикалық сутек тасымалдаушыларын (ЛОНС) және металл гидридтерін таңдауға ерекше назар аударылады. Каспий өңірінің теңіз түбі тереңдігінің айтарлықтай кеңістіктік әркелкілігімен, солтүстік бөлігінің тайыз сулы болуымен, маусымдық мұз жамылғысымен, шөгінділердің жоғары жиналу қарқындылығымен және теңіз деңгейінің өзгеруімен сипатталатын жағдайларында оларды қолданудың ерекшеліктері көрсетілген.

Каспий теңізі Орталық Азияның энергетикалық ресурстарын Кавказ және Еуропа нарықтарымен байланыстыратын трансөңірлік сутек дәліздерін қалыптастыру тұрғысынан ерекше қызығушылық тудырады. Сонымен қатар бассейндік экологиялық сезімталдығы, эндемик түрлердің, соның ішінде каспий итбалығының болуы, сондай-ақ сутек пен аммиактың ықтимал ағып кету қаупі көлік инфрақұрылымының қауіпсіздігіне қойылатын жоғары талаптарды сақтауды қажет етеді.

Жұмыста маршруттарды оңтайландыруға арналған кешенді тәсіл ұсынылған. Ол батиметрияны, шөгінділердің жиналуын, сейсмикалық қауіптілікті, мұздық және гидрометеорологиялық жағдайларды, кеме қатынасының жүктемесін, экологиялық осалдықты және техникалық-экономикалық көрсеткіштерді ескеруге негізделген. Оңтайлы сутек дәліздерін анықтау үшін геоакпараттық және көпкритерийлі модельдеуді қолдану қажеттілігі негізделген. Заманауи мониторинг және болжау жүйелерін пайдалана отырып, гибридік көлік шешімдері мен динамикалық маршруттаудың перспективалылығы көрсетілген. Алынған тұжырымдар Каспий өңірінде қауіпсіз сутек логистикасының тұжырымдамаларын әзірлеу және халықаралық энергетикалық дәліздерді қалыптастыру кезінде пайдаланылуы мүмкін.

**Түйін сөздер:** сутек энергетикасы; сутекті тасымалдау; сутекті сақтау; Каспий теңізі; маршруттарды оңтайландыру; геоакпараттық модельдеу; тәуекелдерді бағалау; экологиялық қауіпсіздік; аммиак; ЛОНС; сутек логистикасы; декарбонизация.

## ОПТИМИЗАЦИЯ МАРШРУТОВ ТРАНСПОРТИРОВКИ ВОДОРОДА

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**Аннотация.** В статье рассматриваются вопросы безопасной и экономически эффективной транспортировки водорода через Каспийское море с учетом природно-географических, технических, экологических и инфраструктурных факторов. Особое внимание уделено выбору технологий хранения и транспортировки водорода, включая сжатый и жидкий водород, аммиак, жидкие органические носители водорода и металлические гидриды. Показаны особенности их применения в условиях Каспийского региона, характеризующегося значительной пространственной неоднородностью глубин, мелководьем северной части, сезонным ледовым покровом, высокой седиментационной нагрузкой и изменениями уровня моря.

Каспийское море представляет особый интерес для формирования трансрегиональных

водородных коридоров, поскольку связывает энергетические ресурсы Центральной Азии с рынками Кавказа и Европы. При этом экологическая чувствительность бассейна, наличие эндемичных видов, включая каспийского тюленя, а также потенциальные риски утечек водорода и аммиака требуют применения повышенных требований к безопасности транспортной инфраструктуры.

В работе предложен комплексный подход к оптимизации маршрутов, основанный на учете батиметрии, осадконакопления, сейсмической опасности, ледовой и гидрометеорологической обстановки, судоходной нагрузки, экологической уязвимости и технико-экономических показателей. Обоснована необходимость применения геоинформационного и многокритериального моделирования для определения оптимальных водородных коридоров. Показана перспективность гибридных транспортных решений и динамической маршрутизации с использованием современных систем мониторинга и прогнозирования. Полученные положения могут быть использованы при разработке концепций безопасной водородной логистики и формировании международных энергетических коридоров в Каспийском регионе.

**Ключевые слова:** водородная энергетика; транспортировка водорода; хранение водорода; Каспийское море; оптимизация маршрутов; геоинформационное моделирование; оценка рисков; экологическая безопасность; аммиак; ЛОНС; водородная логистика; декарбонизация.