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# Modern Methods of Hydrogen Transportation

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## Abstract

This research provides a detailed study of modern methods of hydrogen transportation in the context of a forthcoming global hydrogen economy. With rising visibility as a multi-purpose energy carrier with the capacity to reduce fossil fuel consumption, viable transport means are now critical for bridging production and consumption locations. This study compares five major transport options—compressed gaseous hydrogen, pipelines, liquid hydrogen, ammonia, and Liquid Organic Hydrogen Carriers (LOHCs) within a framework considering economic sustainability, technical readiness, and scalability in varying distances and application environments. Findings reveal that the best transportation means vary greatly with conditions. Pipelines are the most economical means for short distances (<500 km), with transport prices for existing infrastructure starting from \$0.1-0.2 USD/kg for routes under 100 km. Chemical carriers like ammonia are favored for overseas transport beyond 5,000 km. Each method has specific challenges to overcome; material compatibility and hydrogen embrittlement are universal concerns; liquefaction consumes 30-40% of the hydrogen's energy value; and chemical carriers have conversion inefficiencies of 15-35%. The development of infrastructure is constrained by high capital investment, geography, and uneven regulation. The research recommends developing intermodal transport networks with complementary modes, strategic investment in high-usage corridors, acceleration in technical research in priority areas, establishment of harmonized international standards, and application of targeted policy support measures. These combined actions can address existing challenges and help deliver effective, economic hydrogen transport networks to achieve worldwide clean energy objectives. No single transport means can be a panacea; a situation-specific, combined solution has the best possibility to be a leader.

## Keywords

Hydrogen transportation; Hydrogen economy; Hydrogen pipelines; Energy carriers; LOHCs; Ammonia

## 1. Introduction

Hydrogen has emerged as a critical component in the global transition toward sustainable energy systems. As a versatile energy carrier with a current market value of \$183 billion as of 2022, hydrogen supports crucial industries, including agriculture and petrochemicals, while offering significant potential to reduce dependence on fossil fuels [1]. Furthermore, despite its promising applications, hydrogen's status as the smallest and lightest element in the universe presents substantial challenges for transportation and delivery systems.

## 1.1 Definition of Hydrogen as a Sustainable Fuel

Hydrogen represents a promising sustainable fuel option that produces only water when combusted or used in fuel cells, making it attractive for clean energy applications. Unlike conventional fossil fuels, hydrogen can be produced through various methods, including renewable energy sources, positioning it as a key element in future energy systems [2].

### 1.1.1 Physical and chemical properties relevant to transport

Hydrogen's physical and chemical properties significantly impact transportation logistics, as studies demonstrate. Nevertheless, with a density of only 0.09 kg/m³ at standard temperature and pressure, hydrogen requires compression, liquefaction, or chemical bonding to achieve practical energy density for transportation. Its small molecular size leads to challenges related to material compatibility, as hydrogen molecules can permeate through many conventional materials, resulting in leakage and potential embrittlement of metals [3].

### 1.1.2 Green, Blue, and Gray hydrogen classifications

The environmental impact of hydrogen varies based on its production method, reflected in color-based classifications:

Green hydrogen is produced via electrolysis powered by renewable energy sources, resulting in minimal carbon emissions throughout its lifecycle [4].

Blue hydrogen is derived from natural gas through steam methane reforming, with carbon capture and storage (CCS) technology to reduce emissions [2].

Gray hydrogen is produced from fossil fuels without carbon capture, representing the most common but environmentally problematic production method [5].

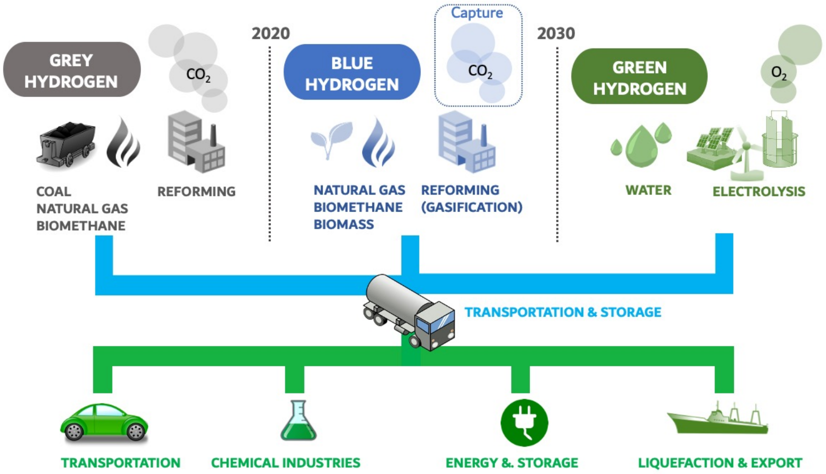


**Figure 1. Visualization of the 3 hydrogen ($H_2$) production routes.**

These classifications are critical when evaluating the overall sustainability of hydrogen transportation systems, as the environmental benefits of clean hydrogen can be diminished if transportation methods are energy-intensive or inefficient.

### 1.1.3 Energy density considerations for transportation

Energy density fundamentally impacts transportation economics and practicality. Hydrogen's volumetric energy density varies dramatically across different states:

Compressed gaseous hydrogen (200 bar): approximately 14.94 kg/m³

Liquid hydrogen: approximately 70.96 kg/m³

Hydrogen bound in carriers like Liquid Organic Hydrogen Carriers (LOHCs): up to 56 kg/m³

Hydrogen in ammonia (assuming 80% recovery): higher density equivalent

These differences in energy density directly influence infrastructure requirements, transportation costs, and overall system efficiency [6].

## 1.2 Importance of Hydrogen Transportation in Renewable Energy Development

### 1.2.1 Hydrogen as energy vector and storage medium

Hydrogen functions as an energy vector, enabling the conversion of renewable electricity into a storable, transportable form. This capability addresses the intermittency challenges associated with renewable energy sources like solar and wind power. As global hydrogen production is projected to reach 240 million metric tons annually by 2040—double today's production—efficient transportation systems become increasingly critical to connect production sites with end-users [7].

### 1.2.2 Role in decarbonizing hard-to-abate sectors

Industries such as steel manufacturing, heavy transportation, and high-temperature industrial processes present significant decarbonization challenges. Hydrogen offers one of the few viable pathways to reduce emissions in these hard-to-abate sectors (i.e., industries where reducing greenhouse gas emissions is technologically difficult or prohibitively expensive), particularly when electrification is impractical. Developing cost-effective hydrogen transportation systems is essential to delivering clean hydrogen to these industries [8].

### 1.2.3 Enabling international clean energy trade

The geographic disparity between optimal hydrogen production locations (areas with abundant renewable resources) and major consumption centers necessitates robust international trade networks. As illustrated in Figure 2 from an IRENA report, we can see how interdependent and interconnected the world's hydrogen imports and exports are. The longest route of transport on the map is the port of Rotterdam in the Netherlands to Australia that spans 23,957 kilometers, and other shipping routes range between 5,000-7,000 kilometers, highlighting the need for efficient long-distance transportation solutions [9].

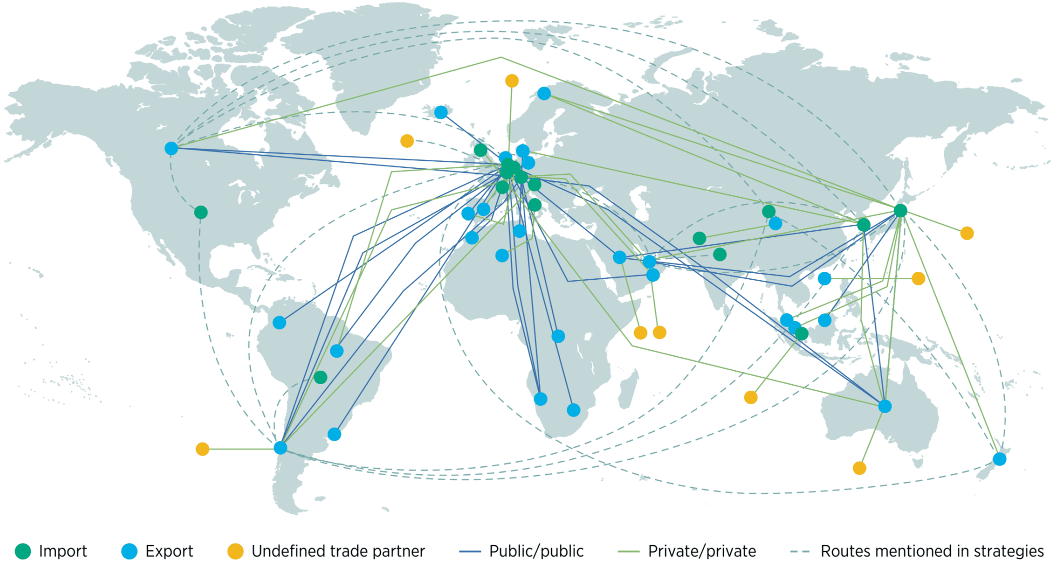


**Figure 2. Bilateral trade announcements for global hydrogen trade until March 2022 [9].**

## 1.3 Research Objective

This research aims to provide a comprehensive analysis of modern hydrogen transportation methods, evaluating their relative advantages, limitations, and potential applications across various scenarios. By examining current technologies and emerging solutions, this study seeks to identify the most promising approaches for enabling the global hydrogen economy while acknowledging that no single transportation method represents a universal solution.

## 1.4 Comparison Framework

To effectively assess hydrogen transportation methods, this report employs a structured framework examining three critical dimensions:

### 1.4.1 Economic viability metrics

The economic analysis considers levelized transportation costs ($/kg $H_2$), infrastructure investment requirements, operational expenses, and potential future cost reductions through technological learning and economies of scale. Cost evaluations account for distance-dependent factors, recognizing that optimal transportation methods vary significantly across short (<500 km), medium (500-5000 km), and long-distance (>5000 km) applications [10].

### 1.4.2 Technological readiness assessment

Each transportation method is evaluated based on its technology readiness level (TRL), commercial deployment status, remaining technical challenges, and projected timeline for widespread implementation. This assessment helps distinguish between established technologies like compressed gas transport and emerging options such as novel liquid organic hydrogen carriers [11].

### 1.4.3 Scalability criteria

Scalability evaluation examines each method's capacity to meet projected hydrogen demand growth, including volumetric efficiency, infrastructure expansion potential, material constraints, and compatibility with existing energy transportation systems. The assessment considers both near-term implementation feasibility and long-term scaling capabilities to support a mature hydrogen economy [12].

## 2. Methods of Hydrogen Transportation

Hydrogen, being the smallest and lightest element in the universe, presents unique challenges for transportation and delivery. Despite regional variations in resources, technology, and infrastructure, millions of metric tons of hydrogen are transported globally each year instead of being produced locally [1]. This section examines the primary methods of hydrogen transportation, evaluating each based on technical specifications, economic viability, technological readiness, and scalability potential.

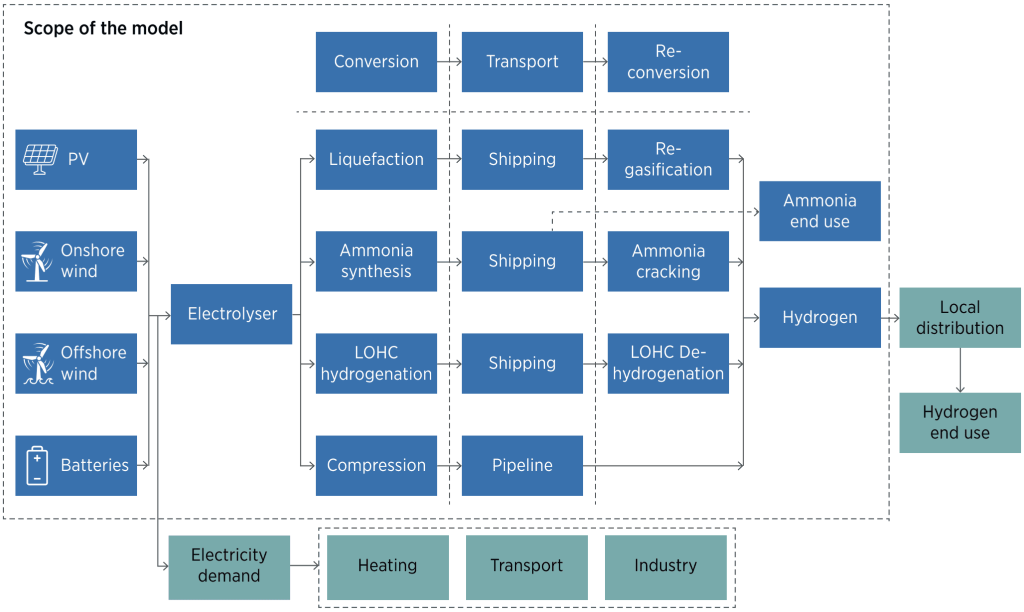


**Figure 3. Scope of the modeling framework used for global hydrogen [9].**

## 2.1 Gaseous Hydrogen Transportation

### 2.1.1 Compressed gaseous hydrogen tanks

#### 2.1.1.1 Technical specifications and storage systems

Compressed gaseous hydrogen represents the most common transportation method in today's market [12]. Hydrogen is typically produced at 20 to 50 bar pressure and must be further compressed to 180 bar or higher for effective storage and transportation economics. The primary vehicle for transport is specialized trucks known as tube trailers, which carry high-pressure cylinders designed to withstand the required pressures while maintaining safety standards.

A standard 42,000-liter tube trailer operating at 200 bar pressure can transport approximately 627.48 kg of hydrogen, achieving a volumetric density of 14.94 kg/m³ [9]. This relatively low density highlights one of the fundamental challenges of gaseous hydrogen transportation—the limited quantity that can be moved per shipment compared to other methods.

#### 2.1.1.2 Economic viability

The economic profile of compressed gaseous hydrogen transportation varies significantly with distance. According to industry analyses, transportation costs range between 0.1-1 USD/kg for distances up to 100 km, increasing to 1-2 USD/kg for distances between 100-500 km [11]. This makes compressed hydrogen economically viable primarily for short to medium distances.

While the operational costs are relatively high compared to pipelines, the initial capital expenditure is significantly lower. A hydrogen trailer mounted on a semi-truck typically costs between $50,000-100,000, making it accessible to smaller operations that cannot afford the substantial infrastructure investments associated with alternative methods [7].

#### 2.1.1.3 Technological readiness

With a global tube trailer market valued at approximately $276.3 million in 2020, the technology for compressed gaseous hydrogen transportation is well-established and commercially available [12]. The industry has developed standardized systems with robust safety features to address the unique challenges of hydrogen's high diffusivity and wide flammability range.

Current technology development focuses on increasing storage pressures (up to 700 bar for some applications) and improving composite materials for tank construction to reduce weight while enhancing safety [3].

#### 2.1.1.4 Scalability assessment

The scalability of compressed gaseous hydrogen faces significant limitations, particularly for large-volume or long-distance transportation needs. The low volumetric density means that substantial quantities require numerous trailer shipments, quickly rendering the economics unfavorable beyond 500 km [7].

For the emerging global hydrogen economy with transportation distances often exceeding 5,000 km, as illustrated in IRENA's international trade projections, compressed gaseous transportation becomes prohibitively expensive and logistically impractical. This limitation has driven the development of alternative transportation methods better suited for large-scale, long-distance hydrogen movement [6].

### 2.1.2 Pipeline transportation

#### 2.1.2.1 Technical aspects and infrastructure

Pipeline transportation represents the most established method for continuous, high-volume hydrogen delivery. Currently, approximately 1,600 miles (2,575 kilometers) of dedicated hydrogen pipelines exist in the United States and about 13,760 miles (22,145 kilometers) in the European Union, with Germany leading at 2,378 miles (3,827 kilometers) [13].

The world's first industrial hydrogen pipeline was constructed in 1938 in Germany's Rhine-Ruhr region, spanning 240 km. This early system, built from steel pipe with a diameter of 25-30 cm, operated at relatively low pressures of 10-20 bar [13]. Modern hydrogen pipelines typically operate at higher pressures, between 30-100 bar, to improve transportation efficiency.

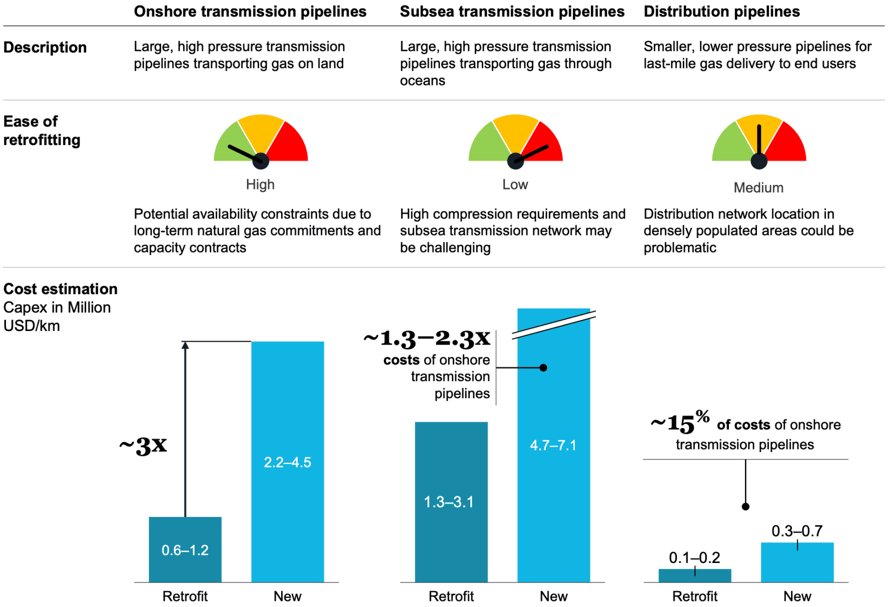
A significant technical challenge for hydrogen pipelines is the phenomenon of hydrogen embrittlement, where hydrogen molecules penetrate the metal structure, causing reduced ductility and potential premature failure. This requires specialized pipeline materials or protective coatings to ensure long-term operational safety [3].

#### 2.1.2.2 Economic viability

Pipeline transportation offers the lowest operational costs for hydrogen delivery, particularly for distances under 500 km, where costs can fall below 0.1 USD/kg [11]. However, the economic equation is significantly impacted by the substantial capital expenditure required for pipeline construction or conversion.

Retrofitting existing natural gas pipelines for hydrogen service costs between $600,000-$1.2 million per kilometer for onshore transmission, $1.3 to $3.1 million per kilometer for subsea transmission, and $100,000 to $200,000 per kilometer for distribution pipelines. New dedicated hydrogen pipeline construction costs are even higher: $2.4 to $4.5 million per kilometer for onshore transmission, $4.7 to $7.1 million per kilometer for subsea transmission, and $300,000 to $700,000 per kilometer for distribution networks [13].

These high upfront costs explain why major pipeline projects typically involve billion-dollar investments, requiring substantial long-term volume commitments to achieve economic viability.



| | **Onshore transmission pipelines** | **Subsea transmission pipelines** | **Distribution pipelines** |
|---|---|---|---|
| **Description** | Large, high pressure transmission pipelines transporting gas on land | Large, high pressure transmission pipelines transporting gas through oceans | Smaller, lower pressure pipelines for last-mile gas delivery to end users |
| **Ease of retrofitting** | High<br>Potential availability constraints due to long-term natural gas commitments and capacity contracts | Low<br>High compression requirements and subsea transmission network may be challenging | Medium<br>Distribution network location in densely populated areas could be problematic |

**Figure 4. Comparing Hydrogen Pipelines.**

### 2.1.2.3 Technological readiness

While hydrogen pipeline technology is mature and commercially deployed, ongoing research focuses on reducing hydrogen permeation rates and improving containment efficiency. Companies like ADNOC (Abu Dhabi National Oil Company) are partnering with research institutions to develop advanced coatings for existing pipelines to enhance performance for hydrogen service [3].

The environmental implications of hydrogen leakage have gained increased attention following research from the CICERO Center for International Climate Research, which identified hydrogen as having a GWP100 (Global Warming Potential over 100 years) of 11.6 ± 2.8. This means that one metric ton of hydrogen released into the atmosphere has a warming effect equivalent to approximately 11.6 metric tons of $CO_2$, highlighting the importance of minimizing leakage from transportation systems [14].

### 2.1.2.4 Scalability assessment

The scalability of pipeline infrastructure represents both a significant challenge and an opportunity. With over 3 million miles of natural gas pipelines in the United States and over 2 million miles in the European Union, the potential for repurposing existing infrastructure for hydrogen transport is substantial [13].

However, hydrogen's smaller molecular size compared to methane creates challenges for direct use without modifications. Current safe blending limits in natural gas pipelines typically range from 5-20% hydrogen by volume, depending on the specific pipeline characteristics and regulatory environment [15]. Research from UC Riverside found that a 10% hydrogen blend increases leak flow rates by approximately 5% compared to pure methane, while a 20% blend increases leak rates by about 10% [3].

For dedicated hydrogen service or higher blend percentages, significant pipeline upgrades are necessary, involving substantial time and investment. This transition challenge represents one of the primary barriers to rapidly scaling hydrogen pipeline infrastructure to meet projected future demand.

## 2.2 Liquid Hydrogen Transportation

### 2.2.1 Cryogenic liquid hydrogen

#### 2.2.1.1 Technical process and requirements

Cryogenic liquid hydrogen transportation involves cooling hydrogen to its liquefaction temperature of -253°C (-423°F), just 20 degrees above absolute zero. At this temperature, hydrogen transitions from gas to liquid state, achieving a volumetric density approximately 800 times greater than ambient gaseous hydrogen [16].

The liquefaction process requires specialized equipment with multiple stages of compression and cooling. Modern liquefaction plants typically utilize the Claude or modified Claude cycle, employing a combination of compression, expansion, and heat exchange to achieve the extremely low temperatures required [16].

Transportation of liquid hydrogen requires specialized double-walled, vacuum-insulated tanks to minimize heat transfer and boil-off. Despite advanced insulation technologies, a typical boil-off rate of 0.3-0.5% per day remains unavoidable, necessitating venting systems or re-liquefaction capabilities for longer transport durations [17].

#### 2.2.1.2 Economic viability

The economics of liquid hydrogen transportation are significantly influenced by the high energy requirements for liquefaction. A U.S. Department of Energy study estimated that liquefaction consumes approximately 30-40% of the hydrogen's energy content, with energy requirements ranging from 10-13 kWh/kg of hydrogen [16].

Liquefaction plant capital costs scale with capacity, ranging from approximately $50 million for a 6,000 kg/day facility to $800 million for a 200,000 kg/day operation. Once liquefied, transportation costs by specialized trucks range from 1-2 USD/kg for distances up to 500 km, while shipping costs for distances between 1,000-5,000+ km often exceed 2 USD/kg [17].

When combined with liquefaction costs of $1.70-1.81 per kg (depending on scale) and the energy losses associated with the process, liquid hydrogen represents a relatively expensive transportation option. However, for long-distance, high-volume transport where pipelines are not feasible, it often remains the most practical approach despite these costs [16].

#### 2.2.1.3 Technological readiness

Cryogenic hydrogen technology is well-established, with commercial-scale liquefaction plants operating worldwide. Significant technological developments continue to emerge, particularly in the maritime shipping sector. Kawasaki Heavy Industries has developed specialized cargo containment systems for liquid hydrogen tankers, receiving approval from classification society ClassNK in 2023 for vessels designed to carry 160,000 m³ of liquid hydrogen (40,000 m³ per containment unit) [15].

Research efforts are focused on improving liquefaction efficiency and reducing boil-off rates during transportation and storage. Advanced insulation materials, active refrigeration systems, and optimized tank designs represent key areas of ongoing development [16].

#### 2.2.1.4 Scalability assessment

Liquid hydrogen offers substantially improved volumetric density compared to compressed gas, making it more scalable for large-volume transportation. Studies indicate that the same 42,000-liter trailer that carries 627 kg of compressed hydrogen (200 bar) can transport approximately 2,980 kg in liquid form, representing a nearly 5-fold increase in capacity [17]. However, the intensive energy requirements, specialized infrastructure needs, and handling complexities associated with cryogenic temperatures present significant barriers to rapid scaling. The development of larger-scale maritime shipping capabilities, exemplified by Kawasaki's projects, will be critical to enabling international liquid hydrogen trade at the volumes projected for future hydrogen economies [16].

### 2.2.2 Ammonia as a hydrogen carrier

#### 2.2.2.1 Technical process and properties

Ammonia ($NH_3$) represents one of the most promising hydrogen carrier molecules, containing 17.6% hydrogen by weight. The production of ammonia via the Haber-Bosch process, initially commercialized in the early 20th century, combines nitrogen from the air with hydrogen under high pressure (150-300 bar) and moderate temperature (400-500°C) in the presence of an iron catalyst [10].

Ammonia can be transported as a liquid at modest pressure (8-10 bar) at ambient temperature or refrigerated to -33°C at atmospheric pressure. Upon reaching its destination, ammonia can be converted back to hydrogen through catalytic decomposition (cracking) at temperatures of 400-700°C, typically yielding hydrogen with 99.5-99.9% purity after additional purification steps [14].

The established ammonia production and transportation infrastructure represents a significant advantage, with approximately 239.4 million metric tons produced globally in 2022, supported by extensive international shipping, storage, and handling capabilities [10].

### 2.2.2.2 Economic viability

Ammonia offers compelling economics for long-distance hydrogen transportation when existing infrastructure can be leveraged. A comparative analysis of transportation costs between Rotterdam and Australia (approximately 10,850 nautical miles) found that ammonia offered the lowest intermediate storage and shipping costs at \$0.56/kg of hydrogen, excluding conversion and reconversion expenses [10].

However, when including all process steps—initial hydrogen production, conversion to ammonia, transportation, reconversion to hydrogen, and final purification—total costs for distances above 5,000 km often exceed \$2 USD/kg of hydrogen. The conversion and reconversion processes represent approximately 50-60% of this total cost [14].

Industry projections indicate potential for significant cost reductions through scale economies, technological improvements in catalysts, and integrated system designs. The International Renewable Energy Agency (IRENA) forecasts potential ammonia transport cost reductions to below \$1 USD/kg for long-distance transportation by 2030, driven primarily by improved conversion efficiency and larger shipment volumes [10].

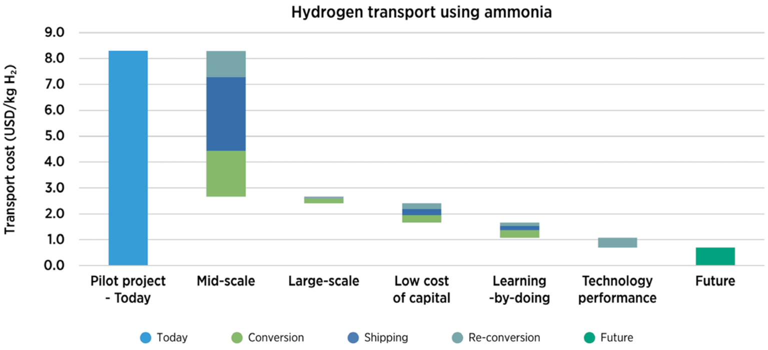


**Figure 5. Factors contributing to the reduction of ammonia transport cost.**

### 2.2.2.3 Technological readiness

The ammonia production, transportation, and storage technologies are mature and commercially established worldwide. Maritime shipping capacity continues to expand, with companies like Maersk ordering new 93,000 m³ ammonia tankers capable of carrying the equivalent of 11,160,000 kg of hydrogen (delivery expected by 2026) [14].

The technological development focus has shifted to optimizing the ammonia cracking process for hydrogen recovery. Current systems typically operate at 400-700 °C with various catalyst formulations based on ruthenium, nickel, or iron. Advanced membrane technologies are being developed to improve hydrogen separation and purification efficiency after the cracking process [10].

### 2.2.2.4 Scalability assessment

Ammonia's established global production and distribution infrastructure provides a significant advantage for rapid scaling of hydrogen transportation. The existing ammonia industry, valued at approximately \$205.3 billion, offers immediately available transportation pathways that can be leveraged without the massive infrastructure investments required for new hydrogen-specific systems [14].

However, ammonia's toxicity presents a notable challenge for expanded use, particularly in densely populated areas. Exposure to high concentrations can cause severe respiratory damage, blindness, or death, necessitating robust safety systems and careful facility siting. Despite these challenges, the combination of existing infrastructure and high hydrogen density makes ammonia one of the most promising carriers for the global hydrogen trade system envisioned for the coming decades [10].

### 2.2.3 Liquid Organic Hydrogen Carriers (LOHCs)

#### 2.2.3.1 Technical process and materials

Liquid Organic Hydrogen Carriers (LOHCs) represent an emerging class of hydrogen transportation methods that utilize reversible hydrogenation of organic compounds. These carrier molecules, typically aromatic hydrocarbons such as toluene, benzyltoluene, or methylcyclohexane, can absorb and release hydrogen through catalytic reactions [7].

The hydrogenation process typically occurs at moderate temperatures (150-200 °C) and pressures (25-50 bar) in the presence of suitable catalysts, often platinum or nickel-based. The resulting hydrogenated carrier is a stable liquid that can be transported using conventional infrastructure. At the destination, dehydrogenation occurs at elevated temperatures (250-320 °C) and lower pressures (1-3 bar), releasing the stored hydrogen for purification and use [3].

LOHCs offer impressive volumetric hydrogen densities—benzyltoluene-based systems can achieve 54-56 kg of hydrogen per $m^3$, compared to 14.94 kg/$m^3$ for 200 bar compressed gas and 70.96 kg/$m^3$ for liquid hydrogen [3].

#### 2.2.3.2 Economic viability

The economic profile of LOHC systems is heavily influenced by the energy requirements for hydrogenation and dehydrogenation processes, as well as the capital costs for the specialized catalytic reactors. Current estimates place the total cost for long-distance transportation (>5,000 km) between $2-3 USD/kg of hydrogen, with the dehydrogenation process typically representing the largest cost component [7].

A key economic advantage of Liquid Organic Hydrogen Carriers (LOHCs) is their compatibility with existing liquid fuel infrastructure. Minimal modifications are required to adapt conventional tanker trucks, vessels, and storage facilities designed for petroleum products, potentially saving billions in infrastructure development costs compared to hydrogen-specific systems [7].

The carrier molecules themselves represent a recurring cost, though their cyclical nature (being reused after dehydrogenation) mitigates this expense over multiple transportation cycles. Degradation rates of 0.1-0.5% per cycle necessitate periodic replenishment, adding marginally to operational costs [3].

#### 2.2.3.3 Technological readiness

While LOHC technology was initially proposed in 1975, commercial development has accelerated significantly in the past decade. Companies including Hydrogenious (using dibenzyltoluene), Chiyoda Corporation (using methylcyclohexane in their SPERA Hydrogen system), and OCOchem (using formic acid) have developed commercial-scale systems with varying technical approaches [3].

Current technological development focuses on improving catalyst efficiency and longevity, reducing energy requirements for dehydrogenation, and optimizing system integration. The technology has progressed from laboratory demonstration to small commercial deployments, with several systems now operating at multi-ton capacities [7].

#### 2.2.3.4 Scalability assessment

LOHCs offer several advantages for scalability in the emerging hydrogen economy. Their compatibility with existing petroleum transport infrastructure provides an immediate pathway to expansion without requiring specialized cryogenic equipment or high-pressure systems. Additionally, many LOHC materials exhibit favorable safety characteristics—dibenzyltoluene, for instance, has a high flash point of 112.5 °C and remains non-explosive even when loaded with hydrogen. The ambient temperature and pressure transportation conditions eliminate boil-off losses associated with cryogenic systems and reduce safety concerns compared to high-pressure gas or toxic ammonia. These characteristics position LOHCs as potentially ideal carriers for hydrogen distribution in populated areas or for end-user delivery applications [7]. However, the energy intensity of the dehydrogenation process and the required reactor infrastructure at distribution points represent significant barriers to rapid scaling. Current estimates suggest that 30-40% of the hydrogen's energy content is consumed in the release process, highlighting the need for continued efficiency improvements to achieve economic viability at a global scale [3].

### 2.3 Comparative Matrix of Transportation Methods

#### 2.3.1 Cost comparison across distance ranges

The economic viability of hydrogen transportation methods substantially varies significantly with distance, as illustrated in Table 1. Nevertheless, studies indicate that for short distances (<100 km), predominantly pipelines offer the lowest cost option when infrastructure exists, while compressed hydrogen provides flexibility despite higher costs. As distances increase beyond 500 km, liquid carriers like ammonia and LOHCs become increasingly competitive, particularly for international shipping beyond 5,000 km.

**Table 1. Approximate Hydrogen Transportation Costs by Method and Distance (USD/kg)**

| Transportation Method | <100 km | 100-500 km | 500-1000 km | 1000-5000 km | >5000 km |
|---|---|---|---|---|---|
| Pipeline (existing) | 0.1-0.2 | 0.2-0.3 | 0.3-0.5 | 0.5-1.0 | 1.0-2.0 |
| Pipeline (new) | 0.3-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | >3.0 |
| Compressed Gas (200 bar) | 0.1-1.0 | 1.0-2.0 | 2.0-3.0 | >3.0 | Impractical |
| Liquid Hydrogen | 1.0-1.5 | 1.5-2.0 | 2.0-2.5 | 2.5-3.0 | >3.0 |
| Ammonia | 1.5-2.0 | 1.5-2.0 | 1.5-2.0 | 1.0-2.0 | 1.0-2.0 |
| LOHCs | 1.5-2.0 | 1.5-2.0 | 1.5-2.0 | 1.5-2.5 | 2.0-3.0 |

Note: Costs exclude production, conversion, and reconversion expenses where applicable. Actual costs vary based on scale, specific routes, and market conditions. Data synthesized from multiple sources [7, 10, 11].

### 2.3.2 Technology readiness level summary

The technological maturity of transportation methods significantly impacts implementation timelines and risk profiles. Table 2 summarizes the current technology readiness levels and key development focuses for each method.

**Table 2. Technology Readiness Assessment of Hydrogen Transportation Methods**

| Transportation Method | Readiness Level | Commercial Deployment Status | Key Development Focus Areas |
|---|---|---|---|
| Pipeline | High | Established industrial networks (limited) | Materials for hydrogen service, Permeation reduction, Blending limits |
| Compressed Gas | High | Widely deployed commercially | Higher pressure systems, Composite materials, Weight reduction |
| Liquid Hydrogen | Medium-High | Industrial scale, Limited shipping | Liquefaction efficiency, Boil-off reduction, Maritime transport |
| Ammonia | High | Global production and shipping | Cracking efficiency, Catalyst longevity, Purification systems |
| LOHCs | Medium | Early commercial demonstration | Dehydrogenation efficiency, Catalyst development, System integration |

Note: Assessment based on consolidated information from [3, 7, 17].

### 2.3.3 Scalability potential evaluation

The potential for rapid deployment at a global scale varies substantially between transportation methods, influenced by factors including existing infrastructure compatibility, energy efficiency, safety characteristics, and technical complexity. Table 3 evaluates these factors across the primary transportation methods.

**Table 3. Scalability Factors for Hydrogen Transportation Methods**

| Transportation Method | Infrastructure Compatibility | Energy Efficiency | Safety Profile | Volumetric Density (kg $H_2/m^3$) | Scalability Potential |
|---|---|---|---|---|---|
| Pipeline | Limited (new) / High (retrofitted) | Very High | Medium | Variable (pressure dependent) | High (regional) |
| Compressed Gas | Medium | High | Medium-Low | 15-40 (pressure dependent) | Low(long-distance) |
| Liquid Hydrogen | Low | Low-Medium | Medium | 71 | Medium |
| Ammonia | High | Medium | Low (toxic) | 121 (17.6% by weight) | High (global) |
| LOHCs | Very High | Low-Medium | High | 54-56 (dibenzyltoluene) | High (integrated) |

Note: Evaluation synthesized from [3, 10, 16].

### 2.3.4 Optimal application scenarios

Each hydrogen transportation method offers distinct advantages in specific contexts, with optimal applications determined by factors including distance, volume, infrastructure availability, and end-use requirements. Table 4 outlines the scenarios where each method demonstrates the maximum comparative advantage.

**Table 4. Optimal Application Scenarios for Hydrogen Transportation Methods**

| Transportation Method | Optimal Distance Range | Preferred Volume Scale | Ideal Application Scenario |
|---|---|---|---|
| Pipeline | <1,000 km (regional) | Very high | Industrial clusters, Regional hydrogen backbones |
| Compressed Gas | <500 km | Low to medium | Distribution from hubs, Small-scale supply |
| Liquid Hydrogen | 500-10,000+ km | Medium to high | International shipping without existing infrastructure |
| Ammonia | 1,000-10,000+ km | Very high | Intercontinental energy trade, Fertilizer industry integration |
| LOHCs | 500-10,000+ km | Medium to high | Consumer distribution, Integration with liquid fuels |

Note: Scenario recommendations based on [3, 10, 11].

The optimal transportation strategy for specific hydrogen projects will often involve combinations of these methods in integrated supply chains, with different carriers utilized at various stages from production to end-use. However, as the global hydrogen economy develops, continued technological advancement and infrastructure investment will likely shift these comparative advantages, potentially enabling more cost-effective and efficient transportation across all distance ranges.

**Table 5. Hydrogen Transportation Methods of Their Advantages and Disadvantages**

| Method | Advantages | Disadvantages |
|---|---|---|
| Compressed Gaseous Hydrogen Tanks | Established technology.<br>Suitable for short distances.<br>Lower initial capital expenditure. | Expensive for long-distance transport.<br>Limited capacity per tank.<br>Energy-intensive compression. |
| Pipelines | Most economically viable for short distances.<br>Offers consistent transportation. | High initial investment.<br>Limited to specific areas.<br>Challenges with leakage and containment.<br>Environmental concerns. |
| Cryogenic Transportation | High density for large-scale transport. | High costs due to liquefaction.<br>Technological challenges with storage and efficiency.<br>Specialized handling and infrastructure. |
| Ammonia as a Carrier | Established infrastructure for production and shipping.<br>Potential for low-cost long-distance transport. | Additional costs for cracking and purification.<br>Safety and environmental concerns.<br>Cost competitiveness. |
| Liquid Organic Hydrogen Carriers (LOHCs) | High storage capacity per volume.<br>Compatible with existing infrastructure for oil.<br>Safer handling<br>Evolving rapidly. | Costly hydrogenation and dehydrogenation.<br>Requires purification.<br>Technological challenges.<br>Limited availability and industry maturity. |

## 3. Current Challenges in Hydrogen Transportation

Despite hydrogen's potential as a sustainable energy carrier, significant challenges impede the development of efficient and economical transportation systems. This section examines the technical limitations, infrastructure development barriers, and policy considerations that currently constrain the hydrogen transportation landscape.

### 3.1 Technical Limitations

### 3.1.1 Material compatibility and hydrogen embrittlement

One of the foremost technical challenges in hydrogen transportation is the phenomenon of hydrogen embrittlement, where hydrogen atoms penetrate metal structures, causing increased brittleness and potential structural failure, as research indicates [3]. Furthermore, evidence suggests that materials used for containment vessels, pipelines, and storage tanks must withstand the unique properties of hydrogen, including its small molecular size and high diffusivity, as research indicates. According to Zeng and Liu [13], standard carbon steel pipelines used for natural gas transportation are susceptible to hydrogen embrittlement, necessitating either dedicated hydrogen-compatible materials or protective coatings for retrofitted infrastructure, according to the literature.

#### 3.1.2 Energy requirements for phase transformation

The conversion of hydrogen into transportable forms demands substantial energy input. Liquefaction of hydrogen to -253°C requires approximately 30-40% of hydrogen's energy content, representing a significant efficiency loss [16]. Similarly, the processes of hydrogenation and dehydrogenation in LOHC systems consume between 25-35% of the energy content of the transported hydrogen [9]. This energy intensity diminishes the overall efficiency of hydrogen as an energy vector.

#### 3.1.3 Boil-Off and leakage challenges

Hydrogen's physical properties create containment difficulties across transportation methods. Cryogenic liquid hydrogen systems face boil-off rates of 0.3-3% per day, depending on tank design and insulation quality [16]. For compressed gas transportation, hydrogen's small molecular size leads to higher leakage rates compared to natural gas, with potential leakage increasing by 5-10% for even modest hydrogen blends in existing pipelines [6]. These losses compound the economic and environmental challenges of hydrogen transport.

#### 3.1.4 Carrier conversion inefficiencies

Chemical carriers like ammonia and LOHCs present their own technical hurdles. The reconversion process from ammonia to hydrogen typically achieves only 80-85% recovery rates, while LOHC dehydrogenation efficiency ranges from 85-95% under optimal conditions [10]. The round-trip efficiency of these transport pathways, which accounts for the energy consumed during conversion and reconversion processes, dictates the overall energy loss. These energy loss percentages, derived from efficiency data in recent techno-economic analyses, are presented in Table 6.

**Table 6. Conversion Efficiencies of Hydrogen Transportation Methods**

| Transportation Method | Conversion Process | Typical Efficiency (%) | Energy Loss (% of $H_2$ LHV) |
|---|---|---|---|
| Compressed Gas | Compression (200-700 bar) | 87-92% | 8-13% |
| Liquid Hydrogen | Liquefaction (-253°C) | 60-70% | 30-40% |
| Ammonia | Synthesis & Cracking | 80-85% | 15-20% |
| LOHCs | Hydrogenation & Dehydrogenation | 65-75% | 25-35% |
| Blended Pipeline | Blending & Separation | 90-95% | 5-10% |

Source: Compiled from [9, 10].

### 3.2 Infrastructure Development Barriers

#### 3.2.1 High capital investment requirements

The development of hydrogen transportation infrastructure demands enormous capital investment. New hydrogen pipeline construction costs range from $0.3-4.5 million per kilometer, depending on diameter and location [13]. Similarly, establishing liquefaction plants requires investments of $50-800 million for capacities ranging from 6,000-200,000 kg/day [1]. This substantial financial burden creates a significant barrier to entry for potential investors and slows infrastructure development.

#### 3.2.2 Geographic constraints and network planning

The global hydrogen economy faces geographical challenges in aligning production centers with consumption hubs. As illustrated in Figure 2 from IRENA's report, potential trade routes span distances up to 23,957 kilometers, necessitating complex logistical planning and multimodal transportation solutions [12]. The optimization of transportation networks must balance regional resource availability, technological capabilities, and demand patterns to minimize costs and maximize efficiency.

### 3.2.3 Technological maturity disparities

The varying technological readiness levels across transportation methods create development imbalances. While compressed gas and pipeline transportation represent mature technologies, cryogenic shipping and LOHC systems remain in earlier development stages [5]. This disparity complicates infrastructure planning and investment decisions, as stakeholders must weigh near-term feasibility against long-term optimal solutions.

### 3.2.4 Existing infrastructure compatibility

The potential to leverage existing natural gas infrastructure for hydrogen transportation offers significant cost advantages but presents compatibility challenges. Current blending limits in natural gas pipelines typically restrict hydrogen content to 5-20% by volume, depending on pipeline specifications and regional regulations [11]. Retrofitting these systems for higher hydrogen concentrations or pure hydrogen service requires substantial modifications to address material compatibility, compression requirements, and safety concerns.

## 3.3 Policy and Regulatory Considerations

### 3.3.1 Standardization and safety protocols

The absence of globally harmonized standards for hydrogen transportation impedes international trade development. Safety protocols, equipment specifications, and quality standards vary significantly across regions, creating compliance complexities for cross-border transportation [14]. Standardization efforts must address the unique properties of hydrogen while ensuring compatibility with existing regulatory frameworks for hazardous materials transportation.

### 3.3.2 Market development mechanisms

Current policy frameworks often lack adequate mechanisms to stimulate hydrogen transportation infrastructure development. According to Razi and Dincer [4], effective market development requires targeted incentives that address the high capital costs and extended payback periods characteristic of hydrogen infrastructure investments. Government support through grants, tax incentives, and public-private partnerships represents essential components of a conducive policy environment.

### 3.3.3 Environmental impact assessment

The environmental implications of hydrogen transportation require careful regulatory consideration. Hydrogen leakage during transportation contributes to indirect greenhouse warming potential, with recent research suggesting a GWP100 of 11.6 ± 2.8 relative to $CO_2$ [6]. Regulatory frameworks must incorporate these environmental impacts when assessing transportation options and establishing permitting requirements.

### 3.3.4 International coordination challenges

The development of global hydrogen supply chains necessitates unprecedented international coordination. Bilateral agreements, as depicted in Figure 6, demonstrate early efforts to establish hydrogen trade relationships, but comprehensive frameworks for international hydrogen markets remain underdeveloped [18].

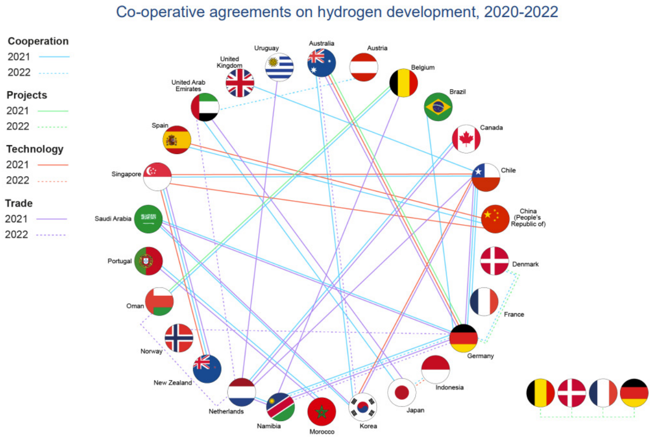


**Figure 6. Bilateral agreements on hydrogen development, 2020-2022 [18].**

Regulatory harmonization, trade standards, and cross-border infrastructure planning require multilateral cooperation to facilitate efficient global hydrogen movement. The challenges outlined in this section highlight the complexity of establishing effective hydrogen transportation systems. Technical limitations constrain efficiency and increase costs, while infrastructure development barriers impede rapid scaling. Policy and regulatory considerations further complicate the landscape, requiring coordinated efforts across stakeholders and jurisdictions. Addressing these challenges demands integrated approaches that combine technological innovation, strategic infrastructure investment, and supportive policy frameworks to realize hydrogen's potential in the global energy transition.

## 4. Conclusion

Our analysis indicates that each transportation method has specific advantages in specific situations, with no one solution applicable in all cases. Pipelines provide the lowest-cost transportation for short distances (<500 km), with transport prices for existing infrastructure starting from $0.1-0.2 USD/kg for routes under 100 km, as shown in Table 1. Compressed gaseous hydrogen, despite its low volumetric density, offers local distribution flexibility but becomes infeasible beyond 500 km.

Liquid hydrogen provides high energy density at the expense of an energy-consuming liquefaction process that utilizes 30-40% of the hydrogen's value. Chemical carriers—LOHCs and ammonia—are best suited for long-distance international transport. Ammonia can leverage established worldwide infrastructure and has competitive economics for distances longer than 5,000 km, though it faces challenges with conversion inefficiencies and toxicity. LOHCs provide good safety and compatibility with conventional fuel infrastructure but have energy-hungry dehydrogenation processes.

Persistent technical challenges in each method include material incompatibilities, energy requirements for phase transformation, and containment issues. These are further exacerbated by infrastructure expansion barriers like high capital requirements, geographical constraints, and regulatory obstacles.

### 4.1 Recommendations

First, stakeholders should develop integrated multi-modal transportation networks that leverage each method's strengths rather than viewing them as competing alternatives. Second, infrastructure investments should target high-utilization corridors while leveraging existing assets like natural gas pipelines and ammonia shipping routes. Research priorities should address critical technical limitations, particularly materials resistant to hydrogen embrittlement, efficient liquefaction processes, and enhanced catalysts for carrier conversion.

International cooperation must establish harmonized standards and regulations, such as those under development by the International Organization for Standardization's Technical Committee (ISO/TC 197) on hydrogen technologies, to reduce compliance complexity while ensuring safety. Moreover, policy support mechanisms should bridge the gap between technological feasibility and commercial viability through financial incentives, performance standards, and market-based mechanisms. Finally, comprehensive lifecycle assessment frameworks are needed to accurately evaluate sustainability impacts across transportation methods. The transition to global hydrogen transportation networks requires coordinated efforts spanning technological development, infrastructure investment, policy formulation, and international cooperation to enable the clean energy transition.

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## References

[1] Naseem K, Qin F, Khalid F, Suo G, Zahra T, Chen Z, et al. Essential parts of hydrogen economy: hydrogen production, storage, transportation and application. Renew Sustain Energy Rev. 2025;210:115196. doi:10.1016/j.rser.2024.115196.

[2] Liu M, Xiao P, Tao L. Blue hydrogen and green hydrogen production for heavy industries. SSRN Electron J. 2023. doi:10.2139/ssrn.4478002.

[3] Zarei-Jelyani M, Salahi F, Zarei-Jelyani F, Rahimpour MR. Introduction to hydrogen storage, transportation, and distribution technologies and challenges. In: Hydrogen transportation and storage. Boca Raton: CRC Press; 2024. p.3-14. doi:10.1201/9781003382553-2.

[4] Razi F, Dincer I. Renewable energy development and hydrogen economy in MENA region: a review. Renew Sustain Energy Rev. 2022;168:112763. doi:10.1016/j.rser.2022.112763.

[5] Yan X, Zheng W, Wei Y, Yan Z. Current status and economic analysis of green hydrogen energy industry chain. Processes. 2024;12:315. doi:10.3390/pr12020315.

[6] Xie Z, Jin Q, Lu W. A review on hydrogen storage and transportation: progresses and challenges [preprint]. 2024. doi:10.20944/preprints202406.0609.v1.

[7] Zendehboudi S, Ghorbani B. Hydrogen end-use and transportation. In: Hydrogen production, transportation, storage, and utilization. Amsterdam: Elsevier; 2025. p.331-415. doi:10.1016/b978-0-443-24042-3.00005-9.

[8] Ishaq M, Dincer I. Development of a novel renewable energy-based integrated system coupling biomass and H2S sources for clean hydrogen production. Renew Energy. 2024;237:121642. doi:10.1016/j.renene.2024.121642.

[9] Sophanna S. An in-depth comparison between the different methods of hydrogen transportation [Internet]. 2024 [cited 2025 Jun 19]. Available from: http://www.divigas.com/blog/transportation-of-hydrogen.

[10] Cui J, Aziz M. Techno-economic analysis of hydrogen transportation infrastructure using ammonia and methanol. Int J Hydrogen Energy. 2023;48:15737-47. doi:10.1016/j.ijhydene.2023.01.096.

[11] Dauletbay A. Transportation of hydrogen: hydrogen usage. In: Hydrogen technologies - advances, insights, and applications. London: IntechOpen; 2024. doi:10.5772/intechopen.1005066.

[12] Ogunsola OI, Ogunsola OM. Hydrogen delivery and transportation. In: Hydrogen technologies. Boca Raton: CRC Press; 2024. p.82-95. doi:10.1201/9781003348283-6.

[13] Zeng Y, Liu M. Pipelines for hydrogen transportation. In: Hydrogen transportation and storage. Boca Raton: CRC Press; 2024. p.173-99. doi:10.1201/9781003382553-11.

[14] Abdellatief TMM, Al-Asheh S, Alami AH. Transportation of green hydrogen and green ammonia. In: Comprehensive green materials. Amsterdam: Elsevier; 2025. p.570-81. doi:10.1016/b978-0-443-15738-7.00055-6.

[15] Jaiswal-Nagar D, Dixit V, Devasahayam S, editors. Section 4 - hydrogen transportation and distribution. In: Towards hydrogen infrastructure. Amsterdam: Elsevier; 2024. p.185-6. doi:10.1016/B978-0-323-95553-9.00084-4.

[16] Salahi F, Zarei-Jelyani F, Rahimpour MR. Cryogenic liquid tankers for hydrogen transportation. In: Hydrogen transportation and storage. Boca Raton: CRC Press; 2024. p.200-12. doi:10.1201/9781003382553-12.

[17] DelGatto VJ, Theodore L, Dupont RR, Ogwu MC. Hydrogen transportation and transmission. In: Hydrogen energy. Chichester: John Wiley & Sons Ltd.; 2025. p.213-28. doi:10.1002/9781394172290.ch13.

[18] International Energy Agency. Global hydrogen review 2022. Paris: IEA; 2022. Available from: https://www.iea.org/reports/global-hydrogen-review-2022.