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Modern technologies and prospects for hydrogen transportation: challenges, solutions and role in the development of hydrogen energy

Abstract

Hydrogen energy is considered a key element of the global strategy to reduce anthropogenic greenhouse gas emissions and transition to a low-carbon development model. Hydrogen is positioned as a versatile energy carrier, capable of partially or completely replacing traditional hydrocarbon resources in the transport sector, industry, and the electric power industry. However, one of the main factors hindering the large-scale implementation of hydrogen technologies remains the problem of its efficient and safe transportation. Unlike traditional fuels, hydrogen has a low volumetric energy density under normal conditions, requiring the use of specialized storage and delivery technologies that directly impact the economic efficiency and safety of the emerging infrastructure. This article presents a comprehensive analysis of key hydrogen transportation methods, including its movement in a gaseous state under high pressure, in liquefied form at cryogenic temperatures, and as part of chemical compounds such as ammonia, methanol, and liquid organic hydrogen carriers (LOHC). A comparative analysis of these approaches is conducted, taking into account their technological features, energy intensity, safety indicators, and commercialization potential. Environmental aspects and potential risks associated with hydrogen leaks and losses, which can have an indirect impact on climate processes, are also considered. The final section analyzes promising areas for the development of hydrogen logistics, including the formation of international transport corridors, the integration of storage systems with renewable energy sources, and the improvement of regulatory frameworks. Thus, addressing hydrogen transportation challenges is a key factor in the development of a global hydrogen market and the implementation of sustainable energy development.

Keywords: *hydrogen energy, hydrogen transportation, liquid hydrogen, hydrogen pipeline, cryogenic technologies, ammonia, hydrogen logistics, energy transition, sustainable development*

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Hidrogen nəqli üçün müasir texnologiyalar və perspektivlər: çətinliklər, həllər və hidrogen enerjisinin inkişafında rol

Xülasə

Hidrogen enerjisi antropogen istixana qazı tullantılarının azaldılması və aşağı karbonlu inkişaf modelinə keçid üzrə qlobal strategiyanın əsas elementi hesab olunur. Hidrogen nəqliyyat sektorunda, sənayedə və elektrik enerjisi sənayesində ənənəvi karbohidrogen ehtiyatlarını qismən və ya tamamilə əvəz edə bilən çox yönlü enerji daşıyıcısı kimi mövqe tutur. Lakin hidrogen texnologiyalarının genişmiqyaslı tətbiqinə mane olan əsas amillərdən biri onun səmərəli və təhlükəsiz daşınması problemidir. Ənənəvi yanacaqlardan fərqli olaraq, hidrogen normal şəraitdə aşağı həcmli enerji sıxlığına malikdir və bu da inkişaf etməkdə olan infrastrukturun iqtisadi səmərəliliyinə və təhlükəsizliyinə birbaşa təsir edən ixtisaslaşdırılmış saxlama və çatdırılma texnologiyalarının istifadəsini tələb edir. Bu məqalədə hidrogenin yüksək təzyiq altında qaz halında, kriogen temperaturda mayeləşdirilmiş formada və ammoniyak, metanol və maye üzvi hidrogen daşıyıcıları (LOHC) kimi kimyəvi birləşmələrin bir hissəsi kimi hərəkəti də daxil olmaqla, əsas hidrogen daşınma üsullarının hərtərəfli təhlili təqdim olunur. Bu yanaşmaların texnoloji xüsusiyyətləri, enerji intensivliyi, təhlükəsizlik göstəriciləri və kommertiya potensialı nəzərə alınmaqla müqayisəli təhlili aparılır. İqlim proseslərinə dolayı təsir göstərə biləcək hidrogen sızmaları və itkiləri ilə əlaqəli ekoloji aspektlər və potensial risklər də nəzərə alınır. Son bölmədə beynəlxalq nəqliyyat dəhlizlərinin formalaşdırılması, saxlama sistemlərinin bərpa olunan enerji mənbələri ilə inteqrasiyası və tənzimləyici çərçivə işlərinin təkmilləşdirilməsi daxil olmaqla, hidrogen logistikasının inkişafı üçün perspektivli sahələr təhlil edilir. Beləliklə, hidrogen nəqli ilə bağlı problemlərin həlli qlobal hidrogen bazarının inkişafında və davamlı enerji inkişafının həyata keçirilməsində əsas amildir.

Açar sözlər: hidrogen enerjisi, hidrogen nəqli, maye hidrogen, hidrogen boru kəməri, kriogen texnologiyalar, ammoniyak, hidrogen logistikası, enerji keçidi, davamlı inkişaf

Introduction

The global energy transition to sustainable, low-carbon energy sources is one of the key strategic challenges of the 21st century. Rising greenhouse gas concentrations in the atmosphere, the gradual depletion of fossil fuel reserves, and increasing geopolitical instability in traditional energy markets are driving the search for alternative solutions that can ensure both energy security and environmental sustainability in the long term. In this context, hydrogen occupies a special place, being viewed as a versatile energy carrier with high potential for integration into various economic sectors—from electric power to transport and industry (Weissenburger et al., 2025). Interest in hydrogen is largely driven by its environmental characteristics. When used in fuel cells or during combustion, hydrogen does not emit carbon dioxide, and the end product of the reaction is water vapor. This makes it an important element of national and international decarbonization strategies and the achievement of "green transition" goals. Currently, a number of countries and regions, including the European Union, Japan, South Korea, and Australia, are implementing large-scale national programs aimed at developing the production, storage, and transportation of hydrogen. Despite significant advances in hydrogen production technologies, hydrogen transportation remains one of the most complex and unresolved issues (Halder et al., 2024). Unlike energy sources such as oil or natural gas, hydrogen has an extremely low energy density under standard conditions, requiring specialized methods for its storage, liquefaction, or conversion into a chemically bound form. These characteristics significantly complicate logistics and directly impact the economic viability of hydrogen projects. The challenges of hydrogen transportation are complex and encompass a wide range of issues, from engineering solutions and materials science to environmental risks and regulatory frameworks. The effectiveness of transport solutions directly impacts the development of hydrogen infrastructure, the cost of the final product, and the competitiveness of hydrogen in the global energy market. The purpose of this article is to comprehensively analyze current hydrogen transportation technologies and methods,

identify their key advantages and limitations, and determine promising areas for further development in this area. The study examines the physicochemical foundations of hydrogen storage, existing logistical approaches, safety and standardization issues, and the role of transportation in creating a sustainable hydrogen economy (Clark et al., 2025).

Research

2. Hydrogen Storage and Transportation Methods The efficiency of hydrogen use as an energy carrier is largely determined by the methods used for its storage and transportation. Gaseous hydrogen occupies a significant volume and has a high diffusion capacity, which places increased demands on materials and engineering solutions. Currently, three main approaches are most widely used: storing and transporting hydrogen in gaseous form, in liquefied form, and in chemical compounds. Each of these methods has its own advantages and limitations and is used depending on specific conditions and tasks (Hydrogen et al., 2023).

2.1. Gaseous Hydrogen The most common method for storing and transporting hydrogen is its compression to high pressure, typically in the range of 350 to 700 bar. This pressure significantly increases the energy density per unit volume. Specialized cylinders and tanks made of high-strength steels or composite materials are used for these purposes. The advantages of this approach include relative technological maturity, equipment availability, and the possibility of partial integration with the existing gas infrastructure (World Bank Group, 2025). At the same time, this method is characterized by significant energy consumption during the compression process, as well as increased requirements for system integrity due to the small size of hydrogen molecules. An additional challenge is the hydrogen embrittlement of metals, which requires the use of special alloys, protective coatings, and regular monitoring of equipment conditions (International Energy Agency (IEA), 2023).

2.2. Liquid Hydrogen When cooled to approximately -253°C , hydrogen liquefies, increasing its bulk density to approximately 800 times its normal density. This makes liquid hydrogen an attractive option for long-distance transportation, including sea transport. Storage is carried out in cryogenic tanks with highly efficient thermal insulation. The main advantage of this method is the high energy concentration at relatively moderate pressures (Xie et al., 2024). However, the hydrogen liquefaction process requires significant energy inputs, which can reach 30–40% of its energy content. Furthermore, long-term storage inevitably results in hydrogen loss due to evaporation, complicating system operation. Despite these limitations, liquid hydrogen technologies are actively used in the aerospace industry and are considered a promising solution for international hydrogen trade (IRENA, 2022).

2.3. Chemically bound hydrogen An alternative approach involves transporting hydrogen in a chemically bound form—as part of compounds such as ammonia, metal hydrides, or liquid organic hydrogen carriers (LOHCs). In this case, hydrogen is stored as stable molecules. This allows for its transportation and storage under near-normal conditions. The advantages of this method include a high level of safety, minimal risk of leaks, and the ability to utilize existing chemical transport infrastructure. However, releasing hydrogen from its bound state requires additional energy inputs and, in some cases, is accompanied by the formation of byproducts. Despite this, chemical carriers are considered one of the most promising solutions for large-scale hydrogen transportation, especially where safety and logistical reliability are paramount (Kurtz, 2019).

3. Safety and Environmental Aspects of Hydrogen Transportation. The development of hydrogen energy transport technologies is impossible without comprehensive consideration of safety issues. Despite the environmental benefits of hydrogen, its physical and chemical properties pose increased risks during storage and transportation. Hydrogen's high permeability contributes to leaks and material degradation, while the formation of explosive mixtures with air and low flame visibility require special protective measures. To minimize risks, modern engineering solutions are being actively implemented, including multilayer composite tank and pipeline structures, as well as automated leak monitoring and detection systems (Schmidt et al., 2020). International standards and regulations covering requirements for equipment, operation, and personnel training play a significant

role. An effective safety system involves not only technical measures but also the development of organizational and management mechanisms, including specialist training and the development of emergency response scenarios. The environmental aspects of hydrogen transportation also require careful analysis (Sujan et al., 2024). Although the end use of hydrogen does not result in direct greenhouse gas emissions, its production, storage, and transportation processes involve additional energy consumption and potential leaks. Hydrogen release into the atmosphere can have an indirect impact on climate change, making it crucial to minimize losses and improve the energy efficiency of the entire supply chain (Yang et al., 2023). The development of hydrogen transport infrastructure is largely driven by advances in new materials and technologies. Promising areas include the development of composite materials and specialized alloys for pipelines and tanks, as well as the use of nanomaterials and membrane technologies aimed at reducing hydrogen losses and increasing operational reliability (Timalsina et al., 2025). International initiatives to develop hydrogen transport corridors facilitate the integration of production and consumer centers at the interregional and intercontinental levels, ensuring the sustainability of supply chains and reducing operating costs. The development of multimodal transport systems combining pipelines, land, and sea transport is particularly important, increasing supply flexibility and economic efficiency. In parallel, research is underway into chemical hydrogen carriers, including ammonia and LOHC, as solutions for safe long-distance transportation (Ueckerdt et al., 2021). The integration of these technologies with renewable energy sources creates the preconditions for the large-scale implementation of "green" hydrogen and the development of a global low-carbon economy. In this context, innovations in materials science, transport technologies, and logistics solutions are becoming key elements in the development of a safe, efficient and sustainable hydrogen infrastructure necessary for a successful energy transition (Züttel et al., 2010).

Conclusion

The analysis confirms that hydrogen transportation represents one of the most significant and complex challenges on the path to creating a fully-fledged hydrogen energy system. While hydrogen production is rapidly developing, aspects of its storage, transportation, and logistics have a decisive impact on the economic viability, safety, and scale of implementation of hydrogen technologies. The specific physical and chemical properties of hydrogen, particularly its low volumetric energy density, require the development of specialized infrastructure that is fundamentally different from conventional energy transportation systems. The hydrogen delivery methods examined—high-pressure gas, liquefied gas, and chemical carriers—exhibit varying degrees of maturity and applicability. Each has its own strengths and limitations related to energy consumption, material requirements, safety, and environmental impact. This underscores the lack of a one-size-fits-all solution and the need for a flexible, context-specific approach to selecting logistics schemes, taking into account factors such as distance, supply volumes, and regional specifics. Improving materials and engineering solutions is a cornerstone of developing hydrogen transport infrastructure. The development of alloys resistant to hydrogen embrittlement, the use of composite materials, and the implementation of leak monitoring systems all contribute to increased reliability and safety. At the same time, growing awareness of the environmental risks associated with hydrogen loss necessitates integrating energy efficiency and sustainability principles throughout the entire supply chain. In the future, key areas for the development of hydrogen logistics will be the establishment of international transport corridors, the development of multimodal shipping systems, and the close integration of transport infrastructure with renewable energy sources. These steps will enable the scalability of green hydrogen production and create a global market that can significantly contribute to the decarbonization of the global energy sector. Overall, the successful development of hydrogen energy is unthinkable without a systemic solution to transportation challenges, based on technological innovation, economic feasibility, and strict safety standards. Further research and practical projects in this area will play a decisive role in the transition to a sustainable, low-carbon energy system and the formation of a new architecture for global energy supply.

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