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HYDROGEN PRODUCTION AND DISTRIBUTION: LOGISTICAL CHALLENGES

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Abstract

Hydrogen, as an energy carrier, has gained attention as a potential transitional solution to address environmental challenges in transportation. This review examines the logistical challenges of integrating hydrogen as a vehicle fuel, with a focus on its production, transportation, storage, and distribution. While hydrogen offers excellent energy characteristics, its specific properties require tailored solutions across every stage of the supply chain. The study identifies technological, regulatory, and organizational challenges, emphasizing the necessity of innovation, harmonized regulations, and specialized training. Technological advancements, such as improved materials and processes, have the potential to reduce logistical difficulties. Aligning international regulations can ensure safer and more efficient operations. Comprehensive training programs further enhance safety and reliability. Key findings suggest that although hydrogen remains more expensive and energy-intensive than fossil fuels, strategic solutions, such as producing hydrogen using surplus renewable energy, could significantly improve its sustainability. Additionally, optimizing traffic systems and adopting shared transportation practices could complement hydrogen's environmental benefits. Ultimately, this study highlights the potential of hydrogen as a sustainable transportation solution, contingent upon the implementation of innovative and collaborative strategies. Ultimately, this study highlights the potential of hydrogen as a sustainable transportation solution, contingent upon the implementation of innovative and collaborative strategies. It lays the groundwork for further research and practical applications that contribute to the advancement of hydrogen-powered logistics.

***Keywords**: Hydrogen logistics. Hydrogen-powered vehicles. Sustainable hydrogen transportation. Environmental impact of hydrogen. Technological advancements in hydrogen systems. Regulatory harmonization for hydrogen supply chains. Hydrogen supply chain optimization.*

1 Introduction

The topic of using hydrogen as a fuel has become relevant again, as it always does when existing conditions cannot solve problems due to overly ambitious environmental demands or crises in the supply of fossil fuels.

In 1807, François Isaac de Rivaz constructed the first internal combustion engine that used hydrogen fuel. However, this engine was not suitable for widespread use. The first commercial, single-cylinder, two-stroke engine, the Hippomobile, was invented in 1860 by Etienne Lenoir of France. Around 350-400 Lenoir gas motors were sold. During World War II, junior military technician Boris Shelishch developed the 1941 GAZ-AA, which utilized the oxygen-hydrogen mixture derived from the deflated barrage balloons, commonly referred to as spent hydrogen (Gusev & Dyadyuchenko, 2002). He converted 200 GAZ-AA trucks to run on hydrogen. (Universitesi, n.d.)

The prototypes of hydrogen-powered vehicle engines made in the 1970s coincided with the first oil crisis of 1973-74. A similar but less intense situation occurred during the second oil crisis (1979-80), which arose due to reduced oil production during the Iranian Revolution and the Iran-Iraq War (Graefe, 2013). However, with the end of the crisis, due to favorable oil prices and technical obstacles, hydrogen did not find widespread application in practice and was sidelined until later decades. At the end of the last century, the most developed countries began to focus on reducing CO_2 emissions and seeking more environmentally friendly solutions, so hydrogen again gained importance in transportation.

1.1 Types of Hydrogen Powertrains

Currently, there are two main types of hydrogen powertrains used in vehicles (Cekerevac, Dvorak, & Cekerevac, 2025):

- *Hydrogen Internal Combustion Engine (HICE):* These engines utilize hydrogen in the combustion process, like gasoline and CNG engines. Advantages include zero CO_2 emissions and quick refueling.
- *Fuel Cell (FC):* These vehicles use fuel cells that convert hydrogen into electricity through an electrochemical reaction. Advantages include high efficiency, zero harmful gas emissions, and a more extended range compared to battery electric vehicles (Le-Boucher, 2022)

Both types have advantages and challenges, but both can contribute to reducing harmful gas emissions at the point of use and transitioning to more sustainable energy sources.

1.2 Hydrogen from a Logistics Perspective

The following characteristics of hydrogen are particularly significant for logistics (Cekerevac, Dvorak, & Cekerevac, 2025):

- It is very light, and when used as fuel, its small molecules have a higher potential for leakage. (Čekerevac, 2024) They can easily pass through many materials that would otherwise be impermeable to larger molecules. Therefore, special sealing of pipelines and tanks is required
- Hydrogen-air mixtures have a wide flammability range.
- Hydrogen burns with a colorless flame. That makes it difficult for firefighters to handle in case of a fire.
- High flame speed, 2-3 m/s, and even more.
- High autoignition temperature. (Stępień, 2021).
- It has a low density. It is approximately 14.4 times lighter than air and tends to rise when it leaks.
- Because of its lower volumetric heating value, hydrogen must be stored in tanks under very high pressures (20 to 70 MPa) to ensure the necessary vehicle range. Consequently, it must be transported under very high pressure. When transported in tanker trucks, it is usually compressed to a pressure of at least 20 MPa. This facilitates efficient storage and transportation of large quantities of hydrogen.
- Producing hydrogen requires more energy than it can release at the point of use, making it more of an energy carrier than a fuel.

1.3 Significance of Study

This study focuses on the current state of hydrogen and the significant logistical challenges connected with using it as a transportation fuel. Hydrogen has distinctive properties that make it both promising and complex to handle. Its ability to reduce harmful emissions positions it as a compelling transitional energy solution. In the ongoing search for sustainable energy sources, hydrogen continues to gain recognition for its potential to bridge current practices with future innovations. However, hydrogen production, transportation, storage, and utilization remain insufficiently explored, leaving significant gaps in our understanding of their practical implementation.

This review emphasizes the necessity of a holistic approach to hydrogen logistics, encompassing technological innovations, regulatory harmonization, and organizational improvements. The study identifies unresolved issues and suggests practical solutions. In doing so, it advances scientific discourse on clean energy adoption and promotes environmentally responsible practices. Additionally, it highlights the importance of training and education to ensure safe and efficient hydrogen management across its supply chain.

Through this exploration, the study establishes itself as a valuable resource for policymakers, industry professionals, and researchers seeking to optimize hydrogen utilization in transportation while minimizing ecological impacts and overcoming logistical hurdles.

2 METHODOLOGY

Although the authors question the current viability of hydrogen as a fuel for vehicle propulsion, this study seeks to answer the following question: How can logistical challenges related to production, transportation, storage, and distribution of hydrogen be overcome to enable its more sustainable use while minimizing environmental impact?

This review paper employs research methods that involve identifying, selecting, analyzing, and synthesizing relevant literature. To ensure comprehensive coverage, the authors conducted searches across academic platforms such as Google Scholar, SpringerLink, MDPI, and KOBSON, as well as specialized websites focused on hydrogen logistics. The search was further enriched by incorporating the authors' prior research on alternative fuels and logistics.

AI tools, including Copilot, DeepSeek, and ChatGPT, were utilized to optimize literature searches. Keywords such as Hydrogen Supply Chain, Hydrogen-Powered Vehicles, Environmental Impact, Logistical Challenges, and Regulatory Harmonization guided the process. While most of the analyzed literature was in English, additional sources in other languages were incorporated for broader perspectives.

Selection criteria ensured relevance and quality by prioritizing peer-reviewed papers and works published within the last five years, with a few pivotal exceptions. Out of 58 sources reviewed, 39 met the inclusion criteria, and 24 were cited directly in the paper.

The authors conducted a critical evaluation of the literature, emphasizing methodological validity and contextual relevance. Information was organized through thematic analysis, identifying key patterns and forming a conceptual framework addressing:

- Logistical challenges in hydrogen production.
- Logistical obstacles in hydrogen transport from production to refueling stations.
- General logistical issues related to hydrogen-powered vehicles.

This thematic approach enabled the integration of findings and the formulation of conclusions. The role of AI tools in suggesting additional insights further refined the analytical process, while the inclusion of multidisciplinary sources enriched the study’s depth and applicability.

3 HYDROGEN SUPPLY CHAIN FROM PRODUCTION TO HYDROGEN STATIONS

The use of hydrogen as a fuel for road vehicles presents significant complexities and challenges. Due to its high production and distribution costs, supplying hydrogen in large quantities requires extensive logistical coordination. Each stage of the supply chain involves intricate processes and inherent risks (Cekerevac, Dvorak, & Cekerevac, 2025). In this section, we will analyze the key challenges associated with hydrogen as a vehicle fuel, examining each phase of its production and distribution in greater detail.

3.1 Hydrogen Production

In August 2022, Sinopec (China Petroleum & Chemical Corporation) launched the world's largest green hydrogen plant under the Kuqa Project, located in Xinjiang, northwest China (Fig. 1). The facility was designed to produce 20,000 tons of green hydrogen annually, powered by a 300 MW solar plant, with an estimated production cost of $2.67 per kilogram. This initiative aimed to replace fossil-based hydrogen at Sinopec Tahe refinery, reducing CO_2 emissions by 485,000 tons annually (BGEN, 2022). [1]

However, the project faced major technical issues (Dokso, Sinopec's Kuqa Green Hydrogen Project Faces Prolonged Challenges, 2024A): electrolyzers supplied by Cockerill Jingli, Longi, and Peric malfunctioned at below 50% of capacity, limiting operations to just 20% of the planned output. Sinopec admitted these problems would delay full capacity until late 2025. In 2024, Sinopec initiated an auction for its Inner Mongolia green hydrogen venture, which includes a 400 km H_2 pipeline to Beijing, starting at $10 million (Yihe, 2024; Collins, 2024). Despite uncertainties, Sinopec remains committed to hydrogen, establishing a $690 million venture capital fund for hydrogen supply chain investments (Reuters, 2025).

Fig. 1 Hydrogen storage tanks at Sinopec's Kuqa project, Xinjiang. (Photo: Sinopec)

Fig. 2 The Kintore Hydrogen Hub will be located in Scotland Source: Statera Energy

The United Kingdom is also prepared to invest in hydrogen infrastructure. Table 1 presents the top five upcoming green hydrogen projects ranked by electrolyzer capacity.

Table 1 Top Upcoming Green Hydrogen Projects in the UK Source: (Blackridge, 2025)

Project	**Electrolyzer Capacity**	**Developer**	**Expected Year of Commissiong**
Kintore Green Hydrogen Plant	3000 MW	Department for Energy Security & Net Zero and Worley	2030*
Eastington Humber Hydrogen Hub	1000 MW	Equinor and Centrica	2029
Stanlow Hydrogen Project	350 MW	Essar Oil UK & Progressive Energy	2027
Dolphyn Green Hydrogen Project Phase 3	100-300 MW	ERM	2028
HyGreen Teesside	80 MW	BP p.l.c	2025

* Kintore Green Hydrogen Plant (Fig. 2) is a planned project in Scotland that will produce green hydrogen using renewable energy sources. The project, under development by Statera Energy, is expected to have a total electrolyzer capacity of 3 GW, positioning it as one of the largest hydrogen production facilities in Europe. In its initial phase, the plant will operate with a 500 MW electrolyzer capacity.

[1] The car Hyundai NEXO consumes approximately 1.03 kg per 100 km. (Radovanović, 2025).

Currently, the project faces local opposition due to concerns about cultural and historical heritage and its environmental impact. Despite these objections, Aberdeenshire Council has recommended its approval. The final investment decision (FID) is expected in the year 2025. Construction is scheduled to begin in 2026, with full operational deployment planned for the early 2030s (Boyle, 2025).

Russia has ambitious plans for hydrogen production and is actively developing several large-scale projects across the country. According to Neftegaz (Minpromtorg RF, 2021), Rosatom has planned four pilot hydrogen production facilities in Kaliningrad, Murmansk, and Sakhalin, scheduled to begin operations between 2024 and 2025. In Murmansk, a project aimed at exporting hydrogen to Europe seeks to produce 150 tons annually. On Sakhalin, two hydrogen plants are under development, including one in collaboration with Air Liquide, utilizing wind-powered water electrolysis.

The Russian government has approved the Hydrogen Energy Development Concept, aiming to establish the country as a leading exporter of hydrogen by 2035 (Pravitel'stvo RF, 2020). Additionally, Sakhalin Island hosts Russia's first green hydrogen project, which is expected to become operational by June 2024 (Dokso, 2024B).

These initiatives are part of a broader strategy to build a hydrogen economy; however, they face significant challenges, including technical obstacles and geopolitical factors.

The European Union has a significant number of active and planned hydrogen production facilities. The EU has set ambitious targets for hydrogen infrastructure development, aiming to achieve 10 million tons of domestically produced renewable hydrogen and 10 million tons of imports by 2030 (H2 Inframap, 2022). According to the latest update, the EU has over 160 planned or operational hydrogen production projects (GIE, 2023). Portugal is emerging as one of Europe’s leaders in green hydrogen infrastructure development. The country has an ambitious national strategy that promotes hydrogen production, storage, and consumption as a key component of the energy transition.

Hydrogen production falls under process manufacturing, relying on industrial methods that utilize chemical reactions and physical processes to transform raw materials into usable products. Techniques such as electrolysis, methane reforming, methane pyrolysis, and biomass gasification require large-scale facilities with high investment costs. The scale of these investments plays a critical role in shaping the supply chains for hydrogen-powered vehicles, exerting both positive and negative effects depending on various conditions. The key positive influencing factors include (Cekerevac, Dvorak, & Cekerevac, 2025):

- *Economies of* scale. Larger investments can lead to higher production capacities and lower production costs per unit.
- *Infrastructure.* Development of the necessary infrastructure for the production, storage, and distribution of hydrogen, which can improve the efficiency and reliability of supply.

The main negative impacts are (Cekerevac, Dvorak, & Cekerevac, 2025):

- *Capital* costs.
- *Technological risks,* because of the introduction of new technologies.
- *Regulatory challenges,* because a production needs to comply with laws and regulations and obtain various permits.

Hydrogen production is notably associated with significant production costs. The costs largely depend on the type of hydrogen. While fuel cells can accommodate all varieties, green hydrogen is considered the most desirable option. Internal combustion engines are less demanding in terms of hydrogen purity. If the motivation for utilizing hydrogen is environmentally, then the most favorable option is one that poses the least negative impact on the environment. The production of green hydrogen through electrolysis is expensive due to the high cost of renewable energy and ranges from 2.8 to 5.6 EUR per kilogram. One kilogram of hydrogen is equivalent to 3.3 kg of gasoline. The production cost of an energy-equivalent amount of petrol in Austria, e.g., would be around 1.8 EUR (GPP, 2024). The price of pink- is like green hydrogen but can vary depending on the cost of nuclear energy. A kilogram of blue hydrogen is between 1.4 and 2.8 EUR per kilogram. The most common type, gray hydrogen, has the lowest price, 0.95 to 1.9 EUR. Turquoise hydrogen's price is still developing, but it is expected to be competitive with blue hydrogen. The current production costs of turquoise hydrogen are 1.5 to 2.5 times higher than in the case of gray hydrogen. (BASF, 2024) Black and brown hydrogen are the cheapest but the most harmful to the environment. According to available data, the average production cost of black hydrogen is around 1.5 to 2 EUR/kg (UNECE, 2024). The price of brown hydrogen is similar but may be slightly higher because lignite is less energy-efficient than coal (UNECE, 2024).

Hydrogen production in 2024 remained consistent with 2023 levels, reaching 97 Mt, of which less than 1% was low-emissions hydrogen. (IAE, 2024) According to the same source, "based on announced projects, low-emissions hydrogen (production[2]) could reach 49 Mtpa by 2030", and hydrogen prices for renewable, low-carbon, and gray hydrogen will equalize till 2050.

Hydrogen production methods such as electrolysis and methane reforming demand substantial energy input, making energy efficiency a critical consideration. Assessing the sustainability and economic viability of these processes depends on their ability to optimize energy usage. Energy efficiency is determined by the ratio between the energy supplied to the system and the energy extracted from hydrogen, influencing both environmental impact and cost-effectiveness. The key figures for energy efficiency are (Cekerevac, Dvorak, & Cekerevac, 2025):

- Electrolysis efficiency depends on the efficiency of the electrolyzer, which typically ranges between 60% and 80%. That means that 60% to 80% of the input electrical energy is converted into the chemical energy of hydrogen, while the rest is lost as heat. Improving electrolyzer efficiency and using renewable energy sources can significantly reduce energy costs and carbon dioxide emissions.
- Methane reforming (SMR) is currently the most common industrial process for hydrogen production. The SMR process energy efficiency is usually between 65% and 75%. Although this process is more energy-efficient than electrolysis, it generates a significant amount of carbon dioxide. Adding carbon capture and storage (CCS) technologies can reduce emissions but further increase energy costs.

Both methods aim to optimize energy output about input, minimizing costs and environmental impact. Enhancing energy efficiency depends on technological advancements, process refinement, and the integration of renewable energy sources. These improvements can make hydrogen a more viable and sustainable energy option; however, carbon dioxide emissions remain a major challenge in gray and blue hydrogen production.

In hydrogen utilization, minimizing the product's carbon footprint (PCF) is a primary consideration. High purity levels are essential, and production must be entirely free of CO2 emissions. Achieving this requires ongoing advancements in production technologies, ensuring improved efficiency and sustainability, regardless of the hydrogen type.

As hydrogen demand continues to grow, scalability must be a key factor in designing production processes. Facilities should be planned and implemented in a way that ensures production capacity aligns with market needs. The primary challenge in scaling hydrogen production lies in effective planning and investment that reflects demand fluctuations. Given the high costs and complexity of these facilities, both excessive capacity and insufficient manufacturing can lead to inefficiencies and financial strain.

[2] author's note

3.2 Transport to Storage

To ensure efficient hydrogen utilization, reducing production costs must be accompanied by the development of appropriate transport, storage, and distribution infrastructure. Due to its unique properties, hydrogen requires specialized handling:

- Its low energy density makes large-scale transport challenging, requiring high-pressure compression or liquefaction to improve cost efficiency.
- As a highly flammable substance, it demands strict safety protocols throughout the transport process.
- The existing infrastructure for hydrogen transport is still underdeveloped, whether via pipelines or specialized vehicles.
- Transport remains expensive, given the need for specialized equipment and vehicles.

Hydrogen can be transported by land (tank trailers or pipelines) or sea, depending on production and storage locations. The choice of transport method depends on volume, available infrastructure, distance, and storage capacity. For large-scale consumers or storage facilities, pipelines offer an efficient solution. While they require significant investment, they provide cost-effective long-distance transport. One advantage is the potential repurpose of existing natural gas pipelines, reducing the need for entirely new infrastructure. Additionally, hydrogen maintains pressure more effectively over long distances than natural gas, allowing transport at lower pressures, typically around 2 to 3 MPa (Wlodek, Laciak, Kurowska, & et al., 2016). Due to hydrogen's lower heating value, compared to natural gas, hydrogen pipeline transport is less energy-efficient.

From a risk assessment standpoint, the primary concern in transporting hydrogen through metal pipelines is the potential for material failure due to hydrogen migration. Hydrogen can permeate the pipe walls, leading to hydrogen embrittlement, which weakens the material over time. Two key mechanisms contribute to the degradation of pipeline materials (Cekerevac, Dvorak, & Cekerevac, 2025):

- Degradation of heat-affected zones (HAZ)
- Growth of fatigue cracks (FCP) in the base pipe material (Holbrook, Cialone, Collings, & et al., 2012).

Research conducted in Juelich, Germany has demonstrated that X70 steel, commonly used for pipelines in Europe, exhibits greater resistance to heat-affected zone (HAZ) degradation and fatigue crack propagation (FCP) compared to X60 steel (Cerniauskas, Junco, Grube, & et al., 2020), In evaluating the feasibility of repurposing existing pipelines for pure hydrogen transport, researchers found that introducing 0.015% oxygen into the hydrogen stream effectively limits hydrogen embrittlement in metal pipes, making it the most cost-efficient solution for repurposing small-diameter pipelines (<250 mm) (Holbrook, Cialone, Collings, & et al., 2012).

For larger pipeline diameters, utilizing existing infrastructure without modifications may prove more economical than constructing new pipelines. However, pipe-in-pipe integration, where hydrogen delivery pipes are placed inside natural gas pipelines, is expected to be the most expensive approach. Regardless of whether pipelines are repurposed or newly built, hydrogen must undergo further purification to meet fuel cell requirements. Technologies such as pressure swing adsorption (PSA) can achieve purity levels of 99.9999% (Mahler AGS, 2022).

For large-scale hydrogen transport, maritime shipping offers a cost-effective and essential solution for intercontinental distribution. The simplest approach involves transporting compressed hydrogen, which is efficiently compressed between 2 and 25 MPa before being stored in ship tanks [27]. However, one challenge of this method is hydrogen's low density, which limits storage capacity. Despite this limitation, compressed hydrogen transport remains competitive for distances exceeding several thousand kilometers. (GEV, 2021)

Liquid hydrogen (LH_2) transportation - is becoming increasingly attractive due to its high volumetric density and compatibility with technologies derived from other cryogenic systems, like liquefied natural gas (LNG) shipping. By the end of January 2024, Europe operated 57 large LNG terminals (Statista, 2024), which can be upgraded for LH_2 applications. - One advantage of LH_2 transportation is the ability to locate energy-intensive liquefaction plants on the exporter's side, where energy costs are lower, while the storage and regasification processes on the importer's side require minimal energy input. The primary challenge remains boil-off loss, as onboard re-liquefaction is not currently available; the optimal solution for managing evaporated hydrogen is to use it as fuel for the ship. Additionally, the HySTRA project between Australia and Japan has demonstrated a successful LH2 transport system, with the first ship, Suiso Frontier, launched in May 2024 and capable of carrying 75 tons of LH_2 at 20K (Koide, 2021).

Shipping hydrogen as ammonia is more convenient than using compressed hydrogen (CGH2) or liquid hydrogen (LH2) because it requires less stringent storage conditions. Ammonia transport is well established—approximately 17.5 million tons are shipped annually using 170 vessels, supported by a mature infrastructure of 38 export and 88 import terminals (Jacobsen, 2020). However, ammonia synthesis is highly energy intensive, and releasing hydrogen from ammonia (through cracking) demands significant energy, which makes this option less attractive.

Liquid Organic Hydrogen Carriers (LOHCs) present another alternative, offering easier handling and a higher hydrogen density than CGH_2. Although LOHCs benefit from the use of existing transport infrastructure, the dehydrogenation process is energy-intensive, and, to date, no large-scale LOHC shipping systems have been implemented.

For smaller volumes of hydrogen, transporting compressed hydrogen in pressure vessels is the simplest method. Containers equipped with multiple Type III or Type IV pressure vessels can be securely fastened and trucked to accommodate larger quantities. Typically, hydrogen is stored at pressures ranging from 20 to 50 MPa, allowing a single truck to carry between 200 and 1000 kg of hydrogen. Gas container modules can transport between 240 and 1115 kg at 50 MPa (Hexagon, 2019). Additionally, gas tube trailers—commonly used for natural gas—are suitable for hydrogen transport when equipped with Type III vessels bundled horizontally. In the USA, hydrogen is regulated at 25 MPa, which results in a capacity of approximately 380 kg per trailer; upgrading from Type III to Type IV vessels increases the capacity to between 560 and 900 kg. It is important to note that CGH2 trailers are typically suitable only for short-distance transport (100–200 km) to meet small-scale needs, such as distributing hydrogen to low-capacity refueling stations.

Alternatively, hydrogen can be transported in liquid form (LH2), which is favorable for medium distances (over 130 km) due to its higher volumetric storage density compared to CGH2. For instance, a 13.7-meter-long cryogenic tank can carry up to 4000 kg of hydrogen at 20 K (Yang, Hunger, Berrettoni, Sprecher, & Wang, 2023). A key challenge in LH2 transport is boil-off; however, cryogenic tanks can sustain pressures up to 1.2 MPa—far exceeding those of stationary tanks. During delivery, vented hydrogen is recycled back to the liquefaction plant, and typically about 10% of the liquid hydrogen remains in the tank to maintain cryogenic temperatures.

4 OTHER CHALLENGES OF HYDROGEN LOGISTICS

In addition to hydrogen-specific requirements, broader aspects must be considered when defining the supply chain, including (Cekerevac, Dvorak, & Cekerevac, 2025):

1. Regulatory challenges
2. Environmental impact
3. Technological advancements
4. Training and

5. Education

Regulatory challenges associated with hydrogen-powered vehicles arise from the diverse regulations and standards across different countries, complicating international hydrogen transport. The lack of harmonized regulations can lead to discrepancies in safety standards, as well as differences in storage, transport procedures, and infrastructure requirements (magility, 2022). For instance, while some nations enforce strict guidelines for hydrogen storage and movement, others apply more lenient rules, making global operational alignment difficult. Furthermore, varying classifications and preferences for hydrogen sources add another layer of complexity (Barnes & Yafimava, 2021).

The transport and storage of hydrogen also have notable environmental implications. One significant risk is hydrogen leakage, which can result in emissions that adversely affect the ozone layer (Osman, et al., 2022). Although hydrogen serves as a clean energy source at the point of use, the processes involved in its production, transport, and storage—particularly when fossil fuels are used—may generate greenhouse gas emissions. Moreover, escaped hydrogen can facilitate ozone formation in the troposphere, further impacting air quality (Wei, Sacchi, Tukker, Suhd, & Steubing, 2024).

Technological advancements are key to optimizing hydrogen transport and storage. Innovations in nanotechnology, such as the development of advanced materials, can enhance both the efficiency and safety of these processes. Additionally, new methods for producing green hydrogen, such as electrolysis, and the increased reliance on renewable energy sources have the potential to lessen the environmental footprint of the hydrogen economy. Improvements in leak detection and pressure control technologies also contribute to safer and more reliable hydrogen systems.

Finally, comprehensive training and education are essential for the safe use of hydrogen. All personnel involved with hydrogen must receive proper training on safety procedures, the unique properties of hydrogen, and correct equipment handling techniques. Specialized training should encompass safety protocols for handling hydrogen under high pressure and working with cryogenic liquids, along with emergency procedures and first aid training to mitigate risks in the event of an accident. Continuous education and periodic retraining, especially when new equipment is introduced, are crucial to ensure that staff remain up-to-date with the latest technologies and safety practices.

5 CONCLUSIONS

Over the past fifty years, numerous authors, including the authors of this paper, have examined the environmental aspects of motor vehicle propulsion and explored potential solutions. Various fuels and technologies have been tested, yet no universal solution has been found that eliminates environmental impact entirely.

Currently, electric vehicles are widely regarded as the most viable alternative. While their adoption helps reduce pollution in urban areas, the environmental impact shifts elsewhere—to regions where electricity is generated, lithium is mined, and batteries are manufactured. Recycling can mitigate some of these effects, but its implementation is often driven by necessity rather than economic incentives. Electric vehicles can only be considered a true environmental solution if both electricity generation and battery production become sustainable. Until then, their role in reducing pollution remains partial rather than definitive.

This uncertainty has renewed interest in hydrogen as a fuel alternative. As an energy carrier, hydrogen holds immense potential for transporting people and goods, particularly if its production can be made environmentally friendly. In this scenario, hydrogen serves as a transitional solution until more advanced propulsion systems are developed.

Despite hydrogen's excellent energy properties, its adoption faces a series of logistical challenges. Its unique characteristics require specialized solutions across production, transport, storage, distribution, vehicle tank storage, and energy conversion. However, based on the analyses conducted in sections 3 and 4, it is evident that all technological and organizational hurdles in the hydrogen supply chain can be overcome. With its increasing use and rapid growth trend, hydrogen is becoming an increasingly viable option for vehicle propulsion.

Based on this study and the formulated research question, several key conclusions can be drawn. Technological advancements play a crucial role in addressing logistical challenges in hydrogen production, storage, and distribution. Innovations such as improved hydrogen production methods, enhanced storage materials, and advanced leak detection systems contribute to greater efficiency and sustainability.

Regulatory harmonization is essential for optimizing the hydrogen supply chain. The alignment of international regulations facilitates safer and more efficient transport, storage, and distribution, enabling broader adoption of hydrogen-powered vehicles. Streamlining regulatory frameworks supports market expansion and enhances industry-wide reliability.

Additionally, training and education significantly improve safety and operational efficiency in hydrogen handling. Comprehensive training programs help mitigate risks, enhance reliability, and ensure proper management throughout the hydrogen supply chain. Investing in specialized education and professional development strengthens technical expertise, reducing operational vulnerabilities.

While essential, hydrogen logistics cannot achieve full environmental potential in isolation. Maximizing its environmental benefits requires integrating hydrogen logistics with efficient traffic management, strengthened public transport networks, and broader adoption of sharing economy practices.

Recommendations for Future Research

To further advance the understanding and practical implementation of hydrogen logistics, future studies could focus on the following key areas:

- *Advancing Green Hydrogen Technologies.* To make green hydrogen more sustainable and accessible, future hydrogen producers should prioritize on energy-efficient and cost-effective production methods, such as enhanced electrolysis and renewable energy integration.
- *Optimizing Hydrogen Logistics.* Explore innovative solutions for improving hydrogen transport, storage, and distribution, including advanced materials, intelligent monitoring systems, and supply chain modeling.
- *Establishing Unified Regulations.* Develop harmonized international standards for safety, storage, and transportation to streamline hydrogen adoption and support global collaboration.
- *Assessing Environmental and Economic Impact.* Conduct life cycle assessments and evaluate the long-term economic feasibility of hydrogen compared to fossil fuels and other energy sources.
- *Strengthening Organizational and Human Factors.* Emphasize workforce training, leadership strategies, and cross-disciplinary collaboration to ensure safety and efficiency in hydrogen logistics.

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ПРОИЗВОДСТВО И РАСПРЕДЕЛЕНИЕ ВОДОРОДА: ЛОГИСТИЧЕСКИЕ ПРОБЛЕМЫ

Аннотация

Водород, как носитель энергии, привлек внимание как потенциальное переходное решение для экологических проблем в транспортной отрасли. В данном обзоре исследуются логистические сложности интеграции водорода в качестве топлива для транспортных средств, с акцентом на его производство, транспортировку, хранение и распределение. Несмотря на отличные энергетические характеристики водорода, его специфические свойства требуют адаптированных решений на каждом этапе цепочки поставок. В работе выделяются технологические, регулятивные и организационные проблемы, подчеркивая необходимость инноваций, унификации стандартов и специализированного обучения. Технологические достижения, включая улучшенные материалы и процессы, демонстрируют потенциал для сокращения логистических трудностей. Унификация международных стандартов способствует повышению безопасности и эффективности операций, а комплексные программы обучения увеличивают надежность и безопасность. Основные выводы указывают на то, что, хотя водород по-прежнему является более дорогостоящим и энергоёмким по сравнению с ископаемыми видами топлива, стратегические решения, такие как производство водорода с использованием избыточной возобновляемой энергии, могут значительно улучшить его устойчивость. Кроме того, оптимизация транспортных систем и внедрение практик совместного использования транспорта могут дополнить экологические преимущества водорода. В итоге данное исследование подчеркивает потенциал водорода для устойчивого транспорта при условии его внедрения с инновационными и совместными подходами, предлагая основу для дальнейших исследований и практического применения водородной логистики.

Ключевые слова: логистика водорода, транспортные средства на водороде, устойчивый транспорт на водороде, экологическое воздействие водорода, технологические достижения в водородных системах, унификация стандартов для цепочек поставок водорода, оптимизация цепочек поставок водорода.