MEST Journal – FBIM Transactions
DOI 10.12709/mest.13.13.SP.03

Review article
MEST Journal
MESTE WORLD

LOGISTICAL CHALLENGES IN HYDROGEN SUPPLY CHAIN FOR AUTOMOTIVE APPLICATIONS

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JEL Category: **G32, R41, Q42**

Abstract

This paper explores the environmental aspects and logistical challenges of hydrogen-powered vehicles. While electric cars are currently considered the optimal solution for reducing urban pollution, their ecological impact is shifted to areas where electricity is produced, and batteries are manufactured. Hydrogen, as an energy carrier, presents a promising alternative if made in an environmentally friendly manner. The paper discusses the requirements concerning hydrogen production, transport, storage, distribution, and vehicle refueling. It highlights the technological and organizational challenges in the hydrogen supply chain, emphasizing that they are solvable. The analysis shows that hydrogen can be a viable transitional solution until a more sustainable vehicle propulsion method is developed. However, it remains more expensive per unit of energy than fossil fuels, and its production is energy intensive. The paper also addresses the importance of regulatory harmonization, technological advancements, and training for safe hydrogen use. Finally, it underscores the need for better traffic and transport organizations to reduce environmental pollution effectively. Enhancing public transport and embracing a sharing economy can reduce vehicle production, traffic, and energy use, benefiting the environment.

Keywords: *Hydrogen Supply Chain. Hydrogen-Powered Vehicles. Environmental Impact. Logistical Challenges. Regulatory Harmonization*

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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. The first prototypes of hydrogen-powered vehicle engines were made in the 1970s, coinciding with the first oil crisis of 1973-74 when the Organization of the Petroleum Exporting Countries (OPEC) reduced oil production and imposed an oil embargo on countries supporting Israel during the Yom Kippur War. Oil prices skyrocketed, leading to a recession in many industrialized countries. It increased efforts in developing alternative vehicle propulsion solutions based on methanol, ethanol, and hydrogen. 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.

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. In 1933, the Norsk Hydro Power Company converted a small truck to run on hydrogen gas. During WWII, junior military technician Boris Shelishch created the 1941 GAZ-AA, which used the oxygen-hydrogen mixture from the lowered barrage balloons, so-called spent hydrogen (Gusev & Dyadyuchenko, 2002). He converted 200 GAZ-AA trucks to run on that fuel. (Universitesi, n.d.)

1.1 Types of Hydrogen Powertrains

Currently, there are two main types of hydrogen powertrains used in vehicles:

- *Hydrogen Internal Combustion Engine Vehicles (HICEV):* These engines use hydrogen in the combustion process in the same way gasoline and CNG engines do. Advantages include zero CO_2 emissions and quick refueling.
- *Fuel Cell Electric Vehicles (FCEV):* 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 contribute to reducing harmful gas emissions at the point of use and transitioning to more sustainable energy sources.

1.2 Hydrogen: A Unique Element

Hydrogen, the most abundant element in the universe, makes up about 75% of the visible mass of the cosmos. It is a fundamental building block of stars and plays a crucial role in nuclear fusion processes that produce energy in stars. It burns readily in the air and has wide flammability limits, ranging from 4% to 75% concentration (AIChE, 2023). The stoichiometric air-to-fuel ratio (AFR) of hydrogen is approximately 34:1. Additionally, hydrogen has a lower ignition energy compared to gasoline or natural gas, meaning it can ignite more easily (Delp, 2004). When it burns, it produces water vapor as the main byproduct, making it a more environmentally friendly fuel (Lacoma, 2017).

Hydrogen is a unique element with properties that make it difficult to classify in the Mendeleev periodic table. According to its electronic configuration, having only one electron, it belongs to group 1 along with alkali metals (ns^1) such as lithium and sodium. Regarding physical properties, hydrogen is a gas at room temperature, while alkali metals are solid. Regarding reactivity, it can form bonds with almost all elements, like halogens ($ns^2\ np^5$) (group 17), making it akin to fluorine and chlorine. In the periodic table, it is often in group 1 (Alkali metals) due to its electronic configuration, but it differs from other group elements in many physical and chemical properties. Hydrogen can also be in group 17 (Halogens) due to its ability to form diatomic molecules (H_2) and reactivity like halogens. Because of its unique properties, some periodic tables place it at the top, outside any specific group. This discussion highlights its uniqueness and shows that it does not fit perfectly into any periodic table group. (BYJU'S, 2022)

It may not have found its place in the periodic table, but it is on its way to finding its place as an energy carrier in Spark Ignition engines (SI) or fuel cells. Using solar, biological, or electrical sources in hydrogen production requires more energy to produce it than it releases during combustion, making it more akin to a battery for energy storage (Čekerevac, 2024; McCarthy, 1995). If we overlook this fact, then hydrogen can be called a fuel.

1.3 Hydrogen by Colors

The actual contribution to environmental protection largely depends on the method of hydrogen production. Accordingly, hydrogen is classified by colors that indicate different production methods and their environmental impacts (Brown & Roberts, 2021):

1. *Green Hydrogen* is produced by water electrolysis using renewable energy sources (solar, wind). It ensures zero CO_2 emissions. Now, it accounts for about 0.1% of hydrogen production (IAE, 2019), but this can increase as renewable energy costs continue to decrease (Marchant, 2021).
2. *Pink Hydrogen* is produced through water electrolysis powered by nuclear energy, resulting in zero CO_2 emissions during its use. However, it relies on this power source.
3. *Blue Hydrogen*, produced by natural gas reforming with carbon capture and storage (CCS), ensures low CO_2 emissions due to production technology.
4. *Gray Hydrogen:* It is produced by natural gas reforming without carbon capture. Its use results in high CO_2 emissions.
5. *Turquoise Hydrogen*, produced by methane pyrolysis, in use results in low CO_2 emissions but depends on the energy source for pyrolysis.
6. *Black* and *Brown Hydrogen* are produced by gasification of black (bituminous) or brown coal, which results in the highest emissions of CO_2 and other pollutants.

These colors help distinguish different hydrogen production methods and their environmental impacts.

1.4 Hydrogen from a Logistics Perspective

The following hydrogen characteristics are particularly significant for logistics:

- 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, which 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, hydrogen requires transportation under very high pressure. When transported in tanker trucks, the pressure is at least 20 MPa. That allows for efficient storage and transport of large hydrogen quantities.

2 HYDROGEN SUPPLY CHAIN FROM PRODUCTION TO VEHICLE

Providing hydrogen for road vehicle propulsion is very complex and challenging. It is an expensive fuel that needs to be produced and delivered in large quantities. Each phase in the logistics chain involves many demanding operations associated with numerous risks. In this section, we will analyze the challenges of hydrogen supply for vehicle propulsion, breaking them down by stages in the production and distribution chain for a detailed examination.

2.1 Hydrogen Production

Hydrogen production belongs to the group of process manufacturing and includes industrial methods that use chemical reactions and physical processes to convert raw materials into finished products. Whether it involves electrolysis, methane reforming, methane pyrolysis, or biomass gasification, they are costly facilities that require significant investments. The size of the investment in production capacities can significantly impact the supply chains for hydrogen-powered vehicles. This impact can be both positive and negative, depending on various factors. The main positive influencing factors in this case are:

- *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:

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

Hydrogen production incurs high production costs. The costs largely depend on the desired hydrogen type. Although fuel cells can use all hydrogen types, green is the most desirable. Internal combustion engines are less demanding in terms of hydrogen purity. If the reason for hydrogen use is environmental, then the most desirable is one with the least negative environmental impact. 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, between 0.95 and 1.9 EUR. Turquoise hydrogen 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). Figure 1 shows European hydrogen production in 2020. One can see that 95% of the 11.5 Mtpa of hydrogen production capacity in Europe is from fossil fuels (UNECE, 2024).

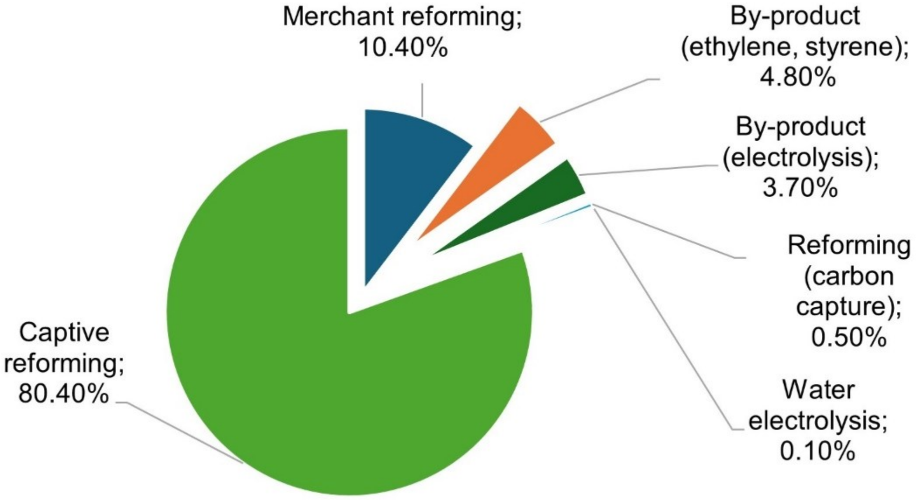

Figure 1 Production capacity by process in 2020

Source: (UNECE, 2024)

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

Processes like electrolysis and methane reforming are highly energy-intensive, thus highlighting the importance of energy efficiency in these operations. Energy efficiency is crucial in assessing the sustainability and cost-effectiveness of hydrogen production processes, such as electrolysis and methane reforming. This criterion refers to the ratio between the energy input into the process and the energy obtained in hydrogen.

- 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.

In both processes, the goal is to maximize energy output relative to the input, thereby reducing costs and environmental impact. Improving energy efficiency requires further technological innovations, process optimization, and renewable energy sources. In this way, hydrogen can become a more sustainable and economical energy source for the future.

The production of gray and blue hydrogen generates significant carbon dioxide emissions, presenting a major environmental concern. When using hydrogen, the focus is on the product's carbon footprint (PCF), so it must have minimal impurities. No CO_2 emissions must occur during hydrogen production. To achieve this, continuous improvement of production processes is necessary, regardless of the color of the hydrogen.

Given the rapidly growing demand for hydrogen, scalability must be considered when designing production processes. The processes must be created and implemented to allow production capacities to match demand. The challenges in scaling hydrogen production lie primarily in proper production planning and investment in production according to needs. These are expensive and complex facilities, so both overly large and insufficient capacities are unfavorable.

2.2 Transport to Storage

In addition to reducing hydrogen production costs, it is necessary to provide appropriate infrastructure for its transport, storage, and distribution. Given the properties of the substance, hydrogen transport and storage have several specificities:

- Hydrogen has a low *energy density*, making it difficult to transport large quantities. For more economic transportation, it must either be compressed to high pressures or converted into a liquid state.
- Hydrogen is highly flammable, requiring *special safety measures* during transport.
- There is currently a lack of developed *infrastructure* for hydrogen transport, whether by pipeline or specialized vehicles.
- *Transport costs* are high due to the need for specialized vehicles and equipment.

Hydrogen transportation can utilize land transport (tank trailers or pipelines) or maritime transport, depending on the locations of production facilities and storage. The method of transport depends on the quantity to be transported, available transport infrastructure, distance, and storage size. For large consumers or storage facilities, pipeline transport is suitable. Although it involves high investments, it is cost-effective for large quantities

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[1] author's note

of transported hydrogen. One advantage is that there is no need to invest always in entirely new infrastructure, as existing natural gas pipelines can be repurposed when conditions allow. Another one is that hydrogen loses pressure much less over long distances than natural gas, allowing it to be transported at lower pressures. An input pressure of 2 to 3 MPa is sufficient (Wlodek, Laciak, Kurowska, & et al., 2016). However, compared to natural gas, hydrogen pipeline transport is less energy-efficient due to hydrogen's lower heating value.

From a risk assessment perspective, the main risk of transporting hydrogen in metal pipes is potential material failure due to hydrogen migration. Hydrogen can penetrate metal pipe walls and cause hydrogen embrittlement. There are two main mechanisms contributing to pipe material degradation:

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

Research in Juelich, Germany (Cerniauskas, Junco, Grube, & et al., 2020), showed that X70 steel, widely used as pipe material in Europe, has no problems with HAZ and reduced FCP degradation compared to other pipe steels, such as X60. Researchers also analyzed the costs of various options for repurposing existing pipes for pure hydrogen transport. They concluded that a mixture with 0.015% oxygen in the transported hydrogen is proven effective in limiting hydrogen embrittlement in metal materials (Holbrook, Cialone, Collings, & et al., 2012) and is the most cost-effective option for repurposing existing small-diameter pipes (<250 mm). Using existing pipes without modifications may be cheaper than building new ones for pipelines with larger diameters. Integrating specialized hydrogen delivery pipes within existing natural gas pipes (pipe-in-pipe approach) is expected to be the most expensive option. For hydrogen pipeline transport, whether repurposing or building new pipelines, to meet fuel cell requirements, it must be further purified. For example, using pressure swing adsorption (PSA) purification technology, a maximum purity of 99.9999% can be achieved (Mahler AGS, 2022).

For transporting large quantities of hydrogen, maritime transport is also cost-effective and indispensable for intercontinental transport. The simplest method is transporting compressed hydrogen. Hydrogen is easiest to compress from 2 to 25 MPa and then pumped into ship tanks. The main drawback of this approach is the low density of hydrogen in the tank. Despite this, this method can be competitive over a few thousand kilometers. (GEV, 2021)

- Liquid hydrogen (LH_2) transportation has become increasingly attractive due to its high volumetric density and the ability to integrate technologies from other cryogenic systems, such as liquefied natural gas (LNG) shipping. By the end of January 2024, Europe had 57 large LNG terminals operational (Statista, 2024), which can be upgraded for LH_2. The advantages of LH_2 transportation include locating energy-intensive liquefaction plants on the exporter's side, where energy is cheap. For storage and regasification on the importer's side, minimal energy is needed. The main challenge is boil-off loss, as re-liquefaction on board is currently unavailable. The best way to use evaporated hydrogen is as fuel to power the ship. The HySTRA project between Australia and Japan successfully transports LH_2, with the first ship, Suiso Frontier (Koide, 2021). It departed Japan in December 2021 and returned in February 2022 carrying about 75 tons of LH_2.
- Shipping hydrogen as ammonia is more convenient than compressed gas (CGH2) or liquid hydrogen (LH2) due to less stringent storage requirements. Ammonia shipping is well-established, with 17.5 million tons transported annually using 170 ships. The infrastructure for ammonia is mature, with 38 exports and 88 import terminals (Jacobsen, 2020). However, ammonia synthesis is energy-intensive, and cracking ammonia to release hydrogen requires significant energy, making this method less attractive.
- Liquid Organic Hydrogen Carriers (LOHCs) offer another alternative, with easier handling and higher hydrogen density than CGH_2. LOHCs can be transported using existing infrastructure, but dehydrogenation is energy intensive. Despite their potential, no large-scale LOHC shipping systems exist yet.

For small hydrogen quantities, transporting compressed hydrogen in pressure vessels is simplest. Multiple Type III or Type IV pressure vessels can be secured in containers and transported by truck for larger quantities. Hydrogen pressure typically is maintained between 20 and 50 MPa, allowing a single truck to carry 200–1000 kg of hydrogen. Gas container modules can transport 240–1115 kg of hydrogen at 50 MPa (Hexagon, 2019). Gas tube trailers used for natural gas are also suitable for hydrogen, with Type III vessels commonly used and horizontally bundled. In the USA, hydrogen pressure is regulated at 25 MPa, which results in a capacity of ~380 kg per trailer. Replacing Type III with Type IV vessels increases capacity to 560–900 kg. However, CGH_2 trailers are only suitable for short-distance transportation (100–200 km) for small hydrogen needs, for example, in hydrogen distribution to low-capacity refueling stations. Alternatively, hydrogen can be transported in liquid form (LH_2), which is suitable for medium distances (>130 km). LH_2 has a higher volumetric storage density than compressed hydrogen (CGH_2), allowing one LH_2 trailer to transport much higher amounts. For example, a 13.7-m-long cryogenic tank can carry 4000 kg of hydrogen at 20 K (Yang, Hunger, Berrettoni, Sprecher, & Wang, 2023). A key challenge is boil-off, but cryogenic tanks can hold 1.2 MPa, higher than stationary tanks. During delivery, vented hydrogen is recycled back to the liquefaction plant. Not all transported hydrogen is deliverable. Some must stay in the tank to maintain cryogenic temperatures. Typically, 10% of the liquid hydrogen remains in the tank.

2.3 Storage

Hydrogen storage presents a significant challenge for the widespread use of hydrogen. The way hydrogen is stored affects its transport method and future use. Yang and colleagues in (A Review of Hydrogen Storage and Transport Technologies, 2023) have already discussed technical solutions for hydrogen storage, so we will not delve into the details here. We will only note that there are generally two types of hydrogen storage systems: physical and material-based. Physical systems change the state of hydrogen by increasing pressure (compressed gaseous hydrogen storage, CGH_2), lowering temperature (liquid hydrogen storage, LH_2), or a combination of both (Cryo-Compressed Hydrogen storage, CcH_2). The second group of storage systems uses materials that bind to hydrogen, increasing the density and safety of storage. Most technologies in this group are still in the research and demonstration phase. A graphical representation of hydrogen storage technologies is in Figure 2.

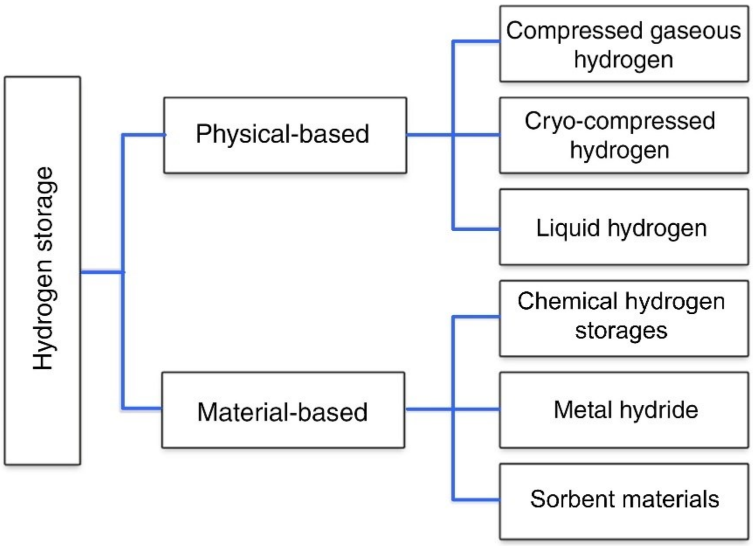

Fig. 2 Overview of hydrogen storage technologies
Source: Authors based on (Yang, Hunger, Berrettoni, Sprecher, & Wang, 2023)

2.3.1 Physical-based Hydrogen Storages

Tanks that can withstand high storage pressures are the oldest and most basic method for storing compressed hydrogen. Their manufacturing materials can consist of steel, aluminum, or advanced composites. Typical operating pressures range from 15 to 95 MPa, depending on the purpose, size, and materials used for tank construction. For storing surplus hydrogen, especially for medium- and long-term needs, underground hydrogen storage (UHS) is a promising method. It utilizes salt caverns, aquifers, and depleted gas reservoirs. Salt caverns are ideal due to their tightness, favorable mechanical properties, and resistance to chemical reactions, but they are small and not widely available. Depleted gas reservoirs offer larger volumes and well-known geological characteristics but may reduce hydrogen purity due to residual natural gas. The aquifers, with their large volumes, are another option but pose risks of leakage, biochemical reactions, and hydrogen-mineral interactions. Currently, there are no documented cases of pure hydrogen storage in aquifers. Zivar, Kumar, & Foroozesh (2021) summarized existing UHS cases and their applications. NASA has led advancements in LH2 storage, using large-scale tanks for space missions. The largest active LH_2 tanks, constructed in the 1960s, are still in use at the Kennedy Space Center. Future developments can result in even larger tanks capable of storing thousands of tons.

Liquid hydrogen storage (LH_2) is significantly more complex but enables much larger storage capacities, requiring temperatures below -253°C. This method is advantageous for its high energy density, making it suitable for applications requiring compact storage solutions. LH_2 cryogenic tanks are vacuum-insulated to minimize evaporation losses. These tanks can be cylindrical or spherical. Spherical tanks accommodate immense volumes. The insulation and redundant pressure relief devices are crucial for maintaining safety and preventing over-pressurization (H2Tools, 2024).

Cryo-compressed hydrogen storage (CcH_2) combines the benefits of compressed and cryogenic storage, keeping hydrogen at very low temperatures and high pressures, up to 35 MPa. This approach enhances storage density and efficiency, making it suitable for applications requiring high energy and long-range capabilities, such as in the automotive industry (H2Tools, 2024). The CcH_2 system uses cryogenic pressure vessels designed to withstand the combined stresses of high pressure and low temperature. These vessels are often made from advanced composite materials to ensure durability and safety. One of the key advantages of CcH_2 is its ability to reduce boil-off losses, a common issue in liquid hydrogen storage, by maintaining hydrogen in a supercritical state (Toenshoff, 2015).

2.3.2 Material-based Hydrogen Storages

Material-based hydrogen storage involves using materials that can absorb and release hydrogen, enhancing storage efficiency and safety. Three main types are metal hydrides, chemical hydrogen storage, and sorbent materials.

- Metal hydrides store molecular hydrogen by forming metal-hydrogen bonds. They offer high storage densities but require high temperatures for hydrogen release.
- Chemical hydrogen storage relies on compounds that release hydrogen through chemical reactions, offering high energy density but often requiring complex regeneration processes. Liquid organic hydrogen carriers (LOHC) fall within this storage category, leveraging chemical reactions to bind and release it—an essential characteristic of chemical hydrogen storage.
- Sorbent materials use physical adsorption to store hydrogen at lower pressures and temperatures, making them safer and more practical for various applications.

All research in material-based hydrogen storage aims to improve volumetric and gravimetric capacities, increase lifespan, and ease of use, with each group having its specific focus. For metal hydrides, the focus is on hydrogen adsorption/desorption kinetics and reaction thermodynamics of potential material candidates. For chemical hydrogen storage, the emphasis is on reducing the release of volatile impurities and efficient regeneration processes for the spent storage material. For sorbent materials, the focus is optimizing the pore size, increasing pore volume and surface area, and investigating the effects of material densification. (Energy.gov, n.d.)

2.3.3 Challenges in Hydrogen Storage

Hydrogen storage presents several significant challenges requiring resolution to become a viable option for widespread use. Here are some of the primary issues:

- High storage costs,
- Energy loss,

- Leakage, and
- Long-term stability.

Storing hydrogen in liquid or gaseous form requires advanced and expensive equipment and technology. Liquid hydrogen storage necessitates cryogenic tanks that can maintain extremely low temperatures, while gaseous hydrogen storage requires high-pressure vessels. Both storage systems involve substantial initial investments and ongoing maintenance costs, making them economically challenging for large-scale adoption.

The processes involved in compressing and cooling for storage consume considerable energy. For instance, compressing a gas to high pressures or cooling it to cryogenic temperatures requires sophisticated machinery and significant energy input. This energy consumption reduces overall efficiency as an energy carrier, as a portion of the energy produced must be used to store it.

Hydrogen molecules are minuscule and can easily permeate through many materials, leading to potential leakage. This results in the loss of stored hydrogen and poses safety risks, as it is highly flammable. Ensuring the integrity of storage containers and preventing leaks is a critical challenge that requires the development of advanced materials and sealing technologies.

Maintaining the long-term stability of stored hydrogen is another significant challenge. Over time, it can react with the materials of the storage container, leading to degradation and potential contamination. In addition, physical and chemical properties can change under prolonged storage conditions, affecting its purity and usability. Developing hydrogen storage systems that can preserve stability over extended periods is essential for practical use.

Overcoming these challenges demands continuous research and innovation in materials science, engineering, and energy management. Enhancing efficiency, safety, and affordability in hydrogen storage will unlock its full potential as a clean and sustainable energy source.

2.4 Hydrogen Distribution

Transporting hydrogen from the producer to storage can be described as a demanding and costly endeavor with numerous risks. However, it is a part of the logistics process that, once well-defined, usually does not require adjustments. Distribution can be even more complex, involving a significantly larger and more diverse group of participants, a wider range of operational methods, and a stronger influence of the human factor. In addition to the requirement for trained personnel handling distribution, there are unavoidable demands:

- *Efficiency*: As with everything related to production, storage, and transportation, the retrieval and distribution of hydrogen from storage can be energy intensive. Hydrogen liquefaction is extremely energy-intensive, and maintaining the low temperature of the tanks is also energy-demanding.
- *Safety*: The properties of hydrogen require rigorous safety measures to prevent incidents during retrieval.
- *Technical complexity*: The complexity of the equipment and procedures for safely retrieving hydrogen requires highly trained personnel to operate the facilities.
- *Investments*: Robust infrastructure must be ensured at all levels, and distribution requires significant infrastructure investments. As the network of hydrogen fueling stations expands, problems become more pronounced. It is also important to note whether hydrogen is used as fuel in internal combustion engines or fuel cells. Pure green hydrogen is more suitable for fuel cells, while internal combustion engines can tolerate less pure hydrogen.
- *Market demand*: Hydrogen is currently an expensive fuel, and the fact that hydrogen fueling stations are scarce makes its use in vehicles difficult. However, the development of hydrogen-powered cars promotes the use of hydrogen. Considering economies of scale, a significant reduction in production costs can be expected, making hydrogen more attractive to consumers. Statistics show that global hydrogen consumption in 2022 was 95Mt and is growing at 3% annually. The adoption of hydrogen as a fuel for passenger vehicles will lead to a significant increase in demand. The green hydrogen market was valued at $6.26 billion in 2023 and is expected to reach $165.84 billion by 2033 (Washington, 2024) The problem of transporting hydrogen containers becomes more significant,

especially when they need to be transported over long distances.

If we isolate and consider only the part of distribution related to road transport of hydrogen, we will notice:

- High transport costs due to the need for specialized vehicles and equipment.
- Hydrogen loss can occur due to leakage during transport, regardless of the storage and transport method chosen.
- Different regulations and standards in various regions can complicate transport.
- Need for logistical coordination. There are numerous challenges in coordinating between different means of transport and infrastructure.

Hydrogen fueling stations for refueling motor vehicles with hydrogen represent key infrastructure for the development and expansion of hydrogen-powered cars. By the end of 2023, there were 1,063 active hydrogen stations worldwide (Starks, 2024), and this number is expected to grow significantly in the coming years. In Europe, Germany has the largest number of stations, with 91 active by the end of 2023 (Statista, 2023). In the United States, there are 59 open public stations (mostly in California), with an additional 50 in various stages of planning or construction. In addition, there are private fueling stations for private fleets (EERE, Hydrogen Fueling Stations, 2024). However, the largest number of operational hydrogen stations is in China, with 400, and plans to build another 1,200 stations by the end of 2025 (Polly, 2024).

Hydrogen stations enable quick and efficient refueling of vehicles, just like how gas stations serve cars with fossil fuels. If we analyze hydrogen stations, we can highlight some of their specificities and differences compared to conventional gas stations:

- Storage method
- Refueling technology
- Safety aspects
- Environmental aspects

Hydrogen stations use different technologies for hydrogen storage. CGH_2 (Compressed Gaseous Hydrogen) is the most used technology, where hydrogen is stored and distributed at a pressure of 700 bars. This technology allows quick vehicle refueling, usually in less than 5 minutes, comparable to refueling gasoline vehicles. CcH_2 (Cryo-Compressed Hydrogen) technology uses cryogenic cooling to store hydrogen at lower temperatures and a pressure of 350 bars. The advantage of this technology is a higher storage capacity, allowing for a longer vehicle range. It is not uncommon for both technologies to be available within the same hydrogen station.

To ensure reliable tank refueling, hydrogen stations are equipped with compressors and dispensers, regardless of whether hydrogen production is on-site or delivered (off-site)[2] Compressors are necessary to increase the hydrogen pressure to the level required for efficient vehicle refueling. High pressure is crucial for quick and efficient vehicle refueling and is usually 70 MPa. Compressors are designed to operate safely in a hydrogen environment, with specialized materials and constructions that minimize the risk of leaks and explosions. Compressed hydrogen dispensers are like CNG dispensers but differ in operating pressure and materials. These differences affect the design and construction of the dispensers. The dispenser has a nozzle that connects to the vehicle's tank. When the nozzle is properly connected, the refueling process begins. The dispenser then controls the pressure and flow of hydrogen to ensure safe and efficient refueling. Dispensers are equipped with safety systems that include leak detectors, automatic shut-off valves, and fire suppression systems. The user interface of the dispenser allows drivers to monitor the refueling process. This can feature screens with information on pressure, the amount of hydrogen refueled, and costs (see Figure 3). Finally, but very importantly, dispensers use standardized protocols for communication with the vehicle to ensure compatibility and safety.

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[2] Both methods have their advantages and challenges. On-site production can be more efficient and environmentally friendly, but it requires significant initial investments in equipment and infrastructure. Hydrogen delivery is more flexible and can be easier to implement in the early stages of developing a network of hydrogen stations.

Figure 3 Visualization of a Hydrogen Station
Source: Made with Designer. Powered by DALL·E 3.

The construction of dispensers ensures that the refueling process is quick, efficient, and safe for users.

Hydrogen is a highly flammable gas, so stations feature advanced safety systems, including leak detectors, automatic shut-off valves, and fire suppression systems. Stations are designed to minimize the risk of explosions and leaks, with special materials and constructions that prevent accidents. The safety aspect is closely related to the environmental aspect.

2.5 Vehicle Tank Refueling

The way hydrogen is stored in a vehicle heavily depends on the type of hydrogen refueled at the hydrogen station. There are two main types of tanks:

- Compressed Gas Tanks (CGH2): These tanks store hydrogen at a pressure of 70 MPa. They are made from composite materials such as carbon fiber, making them lightweight and extremely strong. They are designed to withstand high pressures and have multi-layer insulation materials to minimize heat loss.
- Cryo-Compressed Hydrogen (CcH_2) Tanks: These tanks store hydrogen at lower temperatures and a pressure of 35 MPa. The advantage of this technology is a higher storage capacity, allowing for a longer vehicle range. When a vehicle is refueled with cryo-compressed hydrogen, the low temperature is maintained in the vehicle's tank thanks to special insulation and tank design. These tanks are designed to minimize heat loss and keep hydrogen at low temperatures for extended periods. However, over time hydrogen may gradually warm up due to external influences and heat gains. To control this, the tanks have multiple insulation layers and a vacuum layer that reduces heat transfer. In addition, some systems use active cooling methods to maintain the low temperature of the hydrogen. If the vehicle is not used for an extended period, without active cooling, the temperature will gradually increase. The pressure can be managed by an automatic safety valve. This represents a safe energy loss and a potential risk to the environment where excess hydrogen is released. Some systems also use passive cooling methods, such as phase change materials within the tank, to further reduce hydrogen warming (Yang, Hunger, Berrettoni, Sprecher, & Wang, 2023).

To use hydrogen in fuel cells, it is necessary to reduce its pressure to an optimal value, usually one to two bars (0.1-0.2 MPa). In internal combustion engines, pressure regulators reduce the hydrogen pressure to a level safe for injection into the combustion chamber (HTW, 2024). The hydrogen pressure regulator in vehicles is usually not just one valve but a system that may include multiple valves and components for precise pressure control. Pressure regulation works as follows:

- Primary Pressure Regulator: This valve reduces the hydrogen pressure from the tank (usually 70 MPa) to an intermediate pressure suitable for further use. The primary regulator is designed to withstand high pressures and ensure stable output pressure.
- Secondary Pressure Regulator: After the primary regulator, the secondary regulator further reduces the pressure to the level required for fuel cells or internal combustion engines. This regulator ensures precise pressure control to maintain system efficiency and safety.
- Safety Valves: The system includes safety valves that automatically release excess hydrogen if the pressure exceeds a certain threshold.

The schematic of hydrogen supply to vehicle engines or fuel cells is shown in Figure 4.

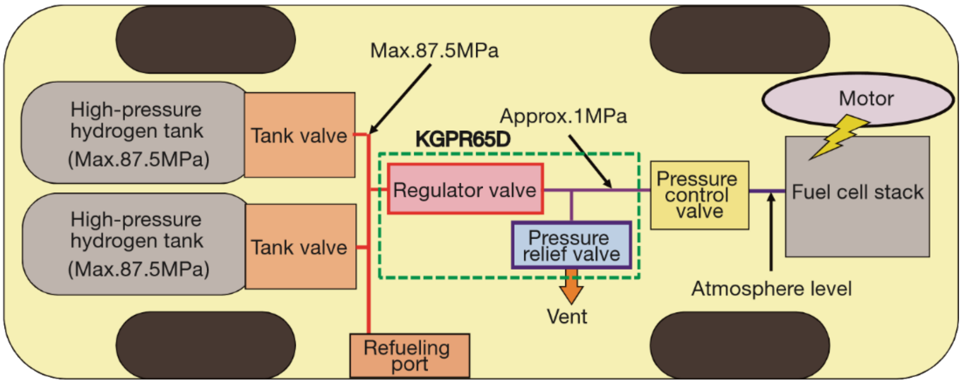

Fig. 4 System configuration of fuel cell vehicle

Source: (Kawasaki, 2020)

In hydrogen vehicle fuel systems, the main challenges are efficiency, reliability, and safety. Pressure regulators must be highly accurate and reliable to ensure stable hydrogen pressure in all scenarios. This requires advanced materials and technologies that can withstand high pressures and prevent leaks. The safety factor is critically important. An average hydrogen tank in fuel cell vehicles can hold about 5-6 kilograms of hydrogen at 70 MPa. This amount of hydrogen allows the car to have a range of approximately 480 kilometers (EERE, Hydrogen Storage, 2017). In the unfortunate event of an explosion, 5 kg of hydrogen would release 600 MJ, equivalent to approximately 143 kg of TNT. The consequences would be catastrophic. This comparison highlights the importance of careful handling of hydrogen and the implementation of appropriate safety measures. Any accident in the early stages of hydrogen application could have unforeseeable consequences for the entire hydrogen-based automotive industry. Safety valves and multi-layer pressure regulation systems are crucial for preventing accidents and ensuring user safety.

From the driver's perspective, as the end user, besides the aspect of cost, the speed at which the tank can be refueled and the skill required are important. Refueling a hydrogen tank can be slower compared to conventional fuels. Ensuring a simple and efficient user experience when refueling vehicles can be a significant challenge when introducing new technologies.

3 OTHER LOGISTICAL CHALLENGES OF HYDROGEN-POWERED VEHICLES

In addition to these hydrogen-specific requirements, general aspects such as the following should be considered when defining the supply chain:

- Regulatory challenges
- Environmental impact
- Technological advancements
- Training and
- Education

Regulatory challenges related to hydrogen-powered vehicles include different regulations and standards in various countries, which can complicate international hydrogen transportation. The lack of regulation harmonization can lead to discrepancies in safety standards, storage and transport procedures, and infrastructure requirements (magility, 2022). For example, while some countries have strict regulations for hydrogen storage and transport, others may have less stringent standards, making it difficult to align operations globally. Additionally, different approaches to the classification and preferences for hydrogen sources can further complicate the situation (Barnes & Yafimava, 2021).

The transport and storage of hydrogen can have a significant environmental impact. Potential risks include hydrogen leakage, which can lead to emissions affecting the ozone layer (Osman, et al., 2022). Although hydrogen is a clean energy source at the point of use, its transport and storage processes can involve greenhouse gas emissions, especially if fossil fuels are used for hydrogen production. Additionally, hydrogen leakage can contribute to ozone formation in the troposphere, negatively affecting air quality (Wei, Sacchi, Tukker, Suhd, & Steubing, 2024).

Technological advancements are crucial for more efficient hydrogen transport and storage. Innovations in nanotechnology, such as advanced materials for hydrogen storage and transport, can significantly improve efficiency and safety. The development of new methods for producing green hydrogen, such as electrolysis, and the use of renewable energy sources, can reduce the ecological footprint of the hydrogen economy. Additionally, advancements in leak detection and pressure control technologies can increase the safety and reliability of the systems.

Training and education are essential for the safe use of hydrogen. All employees working with hydrogen must be adequately trained in safety procedures, hydrogen properties, and proper equipment handling. Specialized training includes understanding the safety requirements for working with hydrogen under high pressure and handling cryogenic liquids. Additionally, training in emergency procedures and first aid is necessary to minimize damage in case of an accident. Continuous education and periodic training, especially when introducing new equipment, are important to keep staff well-trained and up-to-date with the latest technologies and safety practices.

4 CONCLUSIONS

Many authors, including the authors of this paper, have explored the environmental aspects of motor vehicle propulsion over the past fifty years and considered possible solutions. Various fuels and technological solutions have been tested. However, it has been shown that there is no magic wand that will provide vehicle propulsion without negatively impacting the environment. Currently, the optimal solution is the use of electric vehicles. Introducing electric vehicles can reduce pollution in cities, and the negative environmental impact is shifted from cities to locations where electricity is produced, lithium is mined, and electric batteries are manufactured. Recycling can reduce the environmental impact, but it is often carried out under compulsion due to the lack of economic benefits. Electric vehicles could be the problem solution only if electricity and batteries are provided in an environmentally friendly manner. Until that happens, we cannot say that electric vehicles are the best solution to the problem of environmental pollution.

This is why hydrogen has come back into the focus of researchers. Hydrogen is an energy carrier with significant potential for transporting people and goods. If it can be produced in an environmentally friendly way, it can be considered a good transitional solution until a new vehicle propulsion solution is found. Hydrogen has excellent energy characteristics, but the entire process from hydrogen production to its use in vehicles is associated with a series of logistical challenges. The specific properties of hydrogen dictate the need for specific solutions in production, transport, storage, distribution, vehicle tank storage, and transformation into vehicle propulsion energy. Based on the analyses conducted in sections 2 and 3, it can be concluded that all technological and organizational challenges in the hydrogen supply chain are solvable and that the use of hydrogen for vehicle propulsion is becoming more widespread with a high growth trend.

However, it should be noted that hydrogen, per unit of released energy, is more expensive than the comparative price of fossil fuels. Additionally, hydrogen production is still more energy-intensive than the energy hydrogen releases at the point of use. If hydrogen is produced by electrolysis, then the justification for transforming electrical energy into hydrogen energy and back into electrical can be raised. This could stem from eliminating the need for large batteries. It would be particularly favorable if hydrogen is produced using surplus electricity generated in an environmentally friendly way. Otherwise, these surpluses would be irretrievably lost. It is easy to conclude that the environmental aspect of using hydrogen for vehicle propulsion largely depends on how electricity is generated.

Regulatory challenges related to hydrogen-powered vehicles include different regulations and standards in various countries, which can complicate international transportation. The lack of harmonization of regulation can lead to discrepancies in safety standards, storage and transport procedures, and infrastructure requirements.

Technological advancements are crucial for more efficient hydrogen transport and storage. Innovations in nanotechnology, such as advanced materials for hydrogen storage and transport, can significantly improve efficiency and safety. The development of new methods for producing green hydrogen, such as electrolysis using renewable energy sources, can reduce the ecological footprint of the hydrogen economy. Additionally, advancements in leak detection and pressure control technologies can increase the safety and reliability of the systems.

Training and education are essential for the safe use of hydrogen. All employees working with hydrogen must be adequately trained in safety procedures, hydrogen properties, and proper equipment handling. Specialized training includes understanding the safety requirements for working with hydrogen under high pressure and handling cryogenic liquids. Additionally, training in emergency procedures and first aid is necessary to minimize damage in case of an accident. Continuous education and periodic training, especially when introducing new equipment, are important to keep staff well-trained and up-to-date with the latest technologies and safety practices.

Finally, we must emphasize that the simplest way to address the problem of environmental pollution is through better traffic and transport organization and increased vehicle utilization. Improving public urban transport and the sharing economy would contribute to reducing the production of motor vehicles, reducing traffic congestion, and decreasing the need for energy, garages, and parking spaces. Reducing the number of cars on the streets and in parking lots would simultaneously have a positive impact on the environment.

Conflict of Interest

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

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Received for publication: 04.11.2024
Revision received: 17.11.2024
Accepted for publication: 08.04.2025.

How to cite this article?

Style – **APA** *Sixth Edition:*

Cekerevac, Z., Dvorak, Z., & Cekerevac, D. (2025, April 15). Logistical Challenges in Hydrogen Supply Chain for Automotive Applications. *MEST Journal – SP FBIM Transactions, 13*(SP), 49-65. doi:10.12709/mest.13.13.SP.03

Style – **Chicago** *Sixteenth Edition:*

Cekerevac, Zoran, Zdenek Dvorak, and Damjan Cekerevac. "Logistical Challenges in Hydrogen Supply Chain for Automotive Applications." *MEST Journal – SP FBIM Transactions* (MESTE) 13, no. SP (April 2025): 49-65

Style – **GOST** *Name Sort:*

Cekerevac Zoran, Dvorak Zdenek and Cekerevac Damjan Logistical Challenges in Hydrogen Supply Chain for Automotive Applications [Journal] // MEST Journal – SP FBIM Transactions. - [s.l.] : MESTE, April 15, 2025. - SP : Vol. 13. - pp. 49-65.

Style – **Harvard** *Anglia:*

Cekerevac, Z., Dvorak, Z. & Cekerevac, D., 2025. Logistical Challenges in Hydrogen Supply Chain for Automotive Applications. *MEST Journal – SP FBIM Transactions,* 15 April, 13(SP), pp. 49-65

Style – **ISO 690** *Numerical Reference:*

Logistical Challenges in Hydrogen Supply Chain for Automotive Applications. **Cekerevac, Zoran, Dvorak, Zdenek and Cekerevac, Damjan.** SP, s.l. : MESTE, April 15, 2025, MEST Journal – SP FBIM Transactions, Vol. 13, pp. 49-65.