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HYDROGEN HAZARDS, RISKS, AND PROTECTION: AN IN-DEPTH REVIEW

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Abstract

This paper delves into the significance of hydrogen as a clean energy source, focusing on its properties, production, storage, and distribution. The study highlights the general risks associated with hydrogen usage in various sectors, including hydrogen stations, vehicles, and industrial applications. It presents a comprehensive analysis of hydrogen hazards with safety measures, protocols, and regulations at international, national, and occupational levels. A key section of the paper examines several known hydrogen-related incidents, such as explosions and fires at various facilities and locations worldwide, from the BP Texas City Refinery explosion in 2005 to more recent incidents. Each case study provides an in-depth analysis and extracts valuable lessons learned to improve safety standards and protection measures. The paper explores the future of hydrogen and risk management, emphasizing the development of new technologies and innovative solutions for safer hydrogen use. That includes hydrogen fuel cells coupling with renewable energy sources like wind and solar power to ensure a reliable energy supply and enhance grid stability. By integrating hydrogen as an energy storage medium, the study addresses the intermittent nature of renewable energy sources, ultimately contributing to a more stable and flexible energy system. In conclusion, this paper underscores the importance of continued research and development to mitigate risks, enhance protection measures, and ensure the safe adoption of hydrogen as a sustainable energy solution.

Keywords: *Hydrogen Safety. Risk Management. Clean Energy. Fuel Cells. Renewable Integration. Incident Analysis.*

1 INTRODUCTION

Hydrogen finds extensive applications in industry, and recently, people have increasingly explored its use for heating buildings and as fuel for motor vehicles. Due to its properties, it has long been the

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focus of environmentalists seeking alternatives to fossil fuels. High expectations are from its application to address CO_2 emissions issues. From time to time, for various reasons, its use as a fuel becomes popular, but then, because of technical difficulties and application costs, it falls into the background. Recently, this idea has gained momentum again, making it a topic of general interest for designers, manufacturers, logisticians, safety experts, and others, including the general public. This paper focuses on the hazards and risks associated with hydrogen supply chains. Therefore, we will discuss the properties and hydrogen applications to the extent necessary to understand the specifics that may affect the magnitude of hazards and risks. We will not debate the justification of expectations that hydrogen use will eliminate environmental risks, but we will only highlight the risks that could hurt the environment.

1.1 Properties of Hydrogen

Hydrogen is an element with properties that make it unique in the periodic table. Given its current popularity, its properties are detailed in the available literature (e.g., (Brown A. , 2019; Jolly, 2024; Čekerevac, Dvorak, & Prigoda, 2025), etc.). For better clarity, we will list only some of its physical and chemical properties related to the main challenges in a tabular form in Table 1.

Table 1 Hydrogen and methane basic characteristics[1]

Characteristic	**Hydrogen**	**Methane (CH_4)**
Chemical formula	H_2	CH_4
Molecular Weight	2 Da (2 g/mol)	16 Da (16 g/mol)
Flammability Limit	4% - 75%	5% – 15%
Adiabatic Flame Temperature in the air at 1 atmosphere	2,127°C (≈2,400 K) (Princeton, n.d.)	≈1,957 °C (≈2230 K)
Flame Speed at standard pressure and temperature	~ 2-3 m/s	~0.4 m/s
Liquid density	70. 8 kg/m^3 (at boiling point –252,9 °C)	422 kg/m^3 (at boiling point, –62 °C)
Lower Heating Value by Weight	120-142 MJ/kg[2]	≈50 MJ/kg
Volumetric Lower Heating Value	10.8-12.6 MJ/m^3	≈35.8 MJ/m^3
Boiling point (at .1MPa)	~ 20.3 K (–252.9 °C)	111.6 K (–161.6 °C)

Source: Authors, based on (Čekerevac Z. , 2024)

Hydrogen is very light, and its small molecules have a higher potential for leakage. Because of its low density, it tends to concentrate near the ceiling in enclosed spaces, while outside, it quickly rises. Regarding reactivity, it can form bonds with almost all elements. Hydrogen has a very low ignition energy and a wide flammability range (4-75%). That means it can easily ignite, and depending on the conditions, it can burn or explode even in small concentrations. If the hydrogen concentration in a mixture is between 18.3% and 59% by volume, there is a high risk of explosion. Even small amounts of hydrogen in confined spaces can lead to explosive reactions. The ignition energy of hydrogen, the minimum energy required to initiate ignition, is approximately 0.017mJ. Hydrogen self-ignites in the air at about 560°C (~833K), and in the presence of a spark, flame, or hot surfaces, it can ignite at significantly lower temperatures. (Xing, 2021). The flame temperature during the stoichiometric combustion of hydrogen in air is slightly lower than the adiabatic temperature due to nitrogen and other components in the air that absorb part of the heat, reaching about 1930°C (2203K). Additionally, hydrogen has a high burning velocity (2-3 m/s), which can lead to rapid and intense fires (Perelli & Genna, 2022). Hydrogen burns with an invisible flame, which can impact firefighter safety during a fire (Čekerevac Z. , 2024).

In conclusion, although hydrogen is not considered a direct greenhouse gas, it can indirectly contribute to climate change. When hydrogen enters the atmosphere, it can affect the concentrations of other greenhouse gases such

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[1] Standard conditions here refer to a temperature of 15°C (approximately 288 K) and a pressure of 101.325 kPa. (HandWiki, 2022)

[2] For comparison, 1 kg of hydrogen equals 3.3 kg of gasoline (based on the lower heating value) (Enapter, 2024).

as methane (CH_4), ozone (O_3), and water vapor (H_2O). Here are a few examples:

- *Methane*: Hydrogen can affect tropospheric chemistry by increasing methane concentration, as it can interfere with the reactions that break down methane.
- *Ozone*: Hydrogen can contribute to the formation of greenhouse gas ozone in the troposphere.
- *Water vapor*: Hydrogen can also contribute to increased concentrations of water vapor, another significant greenhouse gas.

All of this results in the indirect warming of the atmosphere, contributing to climate change.

1.2 Importance of Studying Hazards and Risks

Although people claim that hydrogen is crucial in reducing carbon dioxide emissions and combating climate change, to avoid negative environmental impacts, careful management of its production and use is necessary. For example, producing hydrogen from fossil fuels can lead to CO_2 emissions, while hydrogen leakage into the atmosphere can contribute to global warming (Calabrese, et al., 2024).

The planned widespread use of hydrogen introduces new safety risks that require careful consideration and strict risk management. Given the specific properties of hydrogen, the diversity of its applications, the methods of hydrogen production, transportation, and storage, there are various potential hazards and risks. Producing, transporting, and storing hydrogen is not easy. We will examine the specifics that affect dangers and risks.

1.2.1 Hydrogen Production

Producers can generate hydrogen in several ways, from water electrolysis to coal gasification. One of the popular ways to facilitate differentiation among the produced hydrogen types is color labeling. There is still no universal standard for that system, so various labels appear in literature and industry. Brown and Roberts (2021) provided one such classification:

1. *Green* hydrogen comes from water electrolysis using renewable energy sources (solar, wind), resulting in zero CO_2 emissions. It accounts for about 0.1% of hydrogen production (IAE, 2019), but will increase as renewable energy costs decrease (Marchant, 2021).
2. *Pink is* produced by electrolysis of water using nuclear energy. Its combustion results in zero CO_2 emissions. However, it relies on this power source.
3. *Blue* hydrogen comes from reforming natural gas with carbon capture and storage (CCS). It ensures low CO_2 emissions due to the production technology.
4. *Gray* is produced by natural gas reforming without carbon capture. Its use results in high CO_2 emissions.
5. *Turquoise* is produced by methane pyrolysis, yielding solid carbon instead of CO_2. Its use results in low CO_2 emissions, but the total CO_2 emission depends on the energy source for pyrolysis.
6. *Black* and *Brown* are produced by black (bituminous coal) or brown coal gasification, respectively. Its production results in the highest CO_2 emissions and other pollutants.
7. *White* typically refers to natural, geological hydrogen generated within the Earth’s crust through water-rock reactions and sourced directly from the Earth (Anderson, 2024).
8. *Gold* can refer to natural, geological hydrogen found in the Earth's crust, obtained through microbiological processes.

White and gold hydrogen can be said to leave the smallest carbon footprint. In the literature, some works equate gold and white hydrogen (e.g., (Hub team, 2023; Le, 2024), etc.). Due to variations in use and definition, it is significant to check the context in which one uses these terms. The number of colors is not limited, and the discovery of new methods for hydrogen production will lead to labeling with other colors.

Besides the common risks associated with storage and transport, each method of hydrogen production has its specific risks. For example, electrolysis requires high voltages and can produce explosive mixtures of hydrogen and oxygen. (Perelli & Genna, 2022). Natural gas reforming involves high temperatures and pressures, which can lead to leaks and explosions (Calabrese, et al., 2024). The methane pyrolysis process requires high temperatures (between 600 and 1200°C), which can present technical challenges and increase costs. Additionally, methane pyrolysis produces solid carbon as a byproduct. Managing and storing this carbon can be challenging, especially in large quantities. Although methane pyrolysis does not release direct CO_2 emissions, the process is energy-intensive and may require significant energy to maintain high temperatures. (Fromm, 2024) The production of "black" and "brown" hydrogen through coal gasification carries several key safety risks, such as the creation of explosive atmospheres, the release of carbon dioxide (CO_2) within the production facility, high temperatures and pressures, and toxicological risks due to the potential release of carbon monoxide (CO) and sulfur dioxide (SO_2). (EIGA, 2022)

Not all hydrogen production methods are economically viable or environmentally friendly, nor do they yield the same quality of hydrogen.

1.2.2 Hydrogen Storage

Storing hydrogen presents a significant challenge for its widespread use. The method of storage affects the transportation method and future use of hydrogen. There are two main types of hydrogen storage systems: physical and material.

Physical Storage Systems

Physical systems change the state of hydrogen by increasing pressure (compressed gaseous hydrogen storage, CGH_2), lowering temperature (liquid hydrogen storage, LH_2), or combining both (cryocompressed hydrogen storage, CcH_2). The other group uses materials that bind hydrogen, increasing storage density and safety.

The oldest and most straightforward method of storing compressed hydrogen is using tanks that can withstand high pressure. These tanks can be made of steel, aluminum, or composite materials. Typical operating pressures range from 15 to 95 MPa. Underground hydrogen storage (UHS) is a promising method for the long-term storage of excess hydrogen. It can utilize salt caverns, aquifers, and depleted gas fields. (Kuterbekov, et al., 2024) Salt caverns are ideal due to their tightness and resistance to chemical reactions, but they are small and rarely available. Depleted gas fields offer larger volumes but may reduce hydrogen purity due to residual natural gas. Aquifers are another option but pose risks of leakage and chemical reactions.

Liquid hydrogen storage (LH_2) involves storing hydrogen at extremely low temperatures, below 20 K, in cryogenic tanks that are usually vacuum insulated to minimize losses due to evaporation. Storing hydrogen in liquid form is more complex but allows the storing of larger amounts of hydrogen.

Cryo-compressed hydrogen storage (CcH_2) combines the advantages of compressed and cryogenic storage, keeping hydrogen at very low temperatures and high pressures, up to 35 MPa. That increases the density and efficiency of storage, making it suitable for applications requiring high energy and long range, such as in the automotive industry.

Material Storage

Material storage systems use materials that absorb and release hydrogen, improving storage efficiency and safety. Three main types are metal hydrides, chemical hydrogen storage, and sorbent materials.

- *Metal hydrides* form bonds between metals and hydrogen, offering high storage density but requiring high temperatures to release hydrogen.
- *Chemical hydrogen storage* uses compounds that release hydrogen through chemical reactions, providing high energy density but often requiring complex regeneration processes.
- *Sorbent materials* use physical adsorption to store hydrogen at lower pressures and temperatures, making them safer and more practical.

Challenges of Hydrogen Storage

Hydrogen storage presents a unique challenge due to its physical properties, facing several significant issues: high storage costs, energy losses, leakage, and long-term stability. Hydrogen can be stored as a gas under high pressure or liquid at extremely low temperatures.

Both methods carry risks. High-pressure storage can lead to leaks and explosions, while liquid storage can cause cryogenic burns and other problems related to extremely low temperatures. These factors necessitate specialized equipment and strict safety protocols (Calabrese, et al., 2024). The high costs of equipment, energy-intensive compression and cooling processes, risk of leakage due to small hydrogen molecules, and reactions with storage container materials are key problems. Solving these challenges requires continuous research and innovation in material science, engineering, and energy management to improve hydrogen storage technologies' efficiency, safety, and cost-effectiveness.

1.2.3 Transport and Distribution of Hydrogen

In addition to reducing hydrogen production costs, it is necessary to ensure adequate infrastructure for its transport and distribution. These activities can be risky due to the potential for leaks and explosions. Hydrogen can be transported via pipelines, trucks, or ships, each with specific risks. For example, pipelines can corrode and leak, while truck transport can lead to accidents and explosions (Calabrese, et al., 2024). Given the characteristics of hydrogen, its transport and distribution involve several specific factors:

- Hydrogen has low energy density, which requires transporting large quantities. It is compressed to high pressures or converted to a liquid state for more economical transport.
- Hydrogen is highly flammable, necessitating special safety measures during transport.
- Transport costs are high due to the need for specialized vehicles and equipment.
- There is currently a lack of developed infrastructure for hydrogen transport, whether by pipelines or specialized vehicles.

Hydrogen can be transported by land (tanks or pipelines) or sea. The choice of transport method depends on the quantity of being transported, available 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 of transported hydrogen. One advantage is that existing natural gas pipelines can be repurposed when conditions permit, and hydrogen loses much less pressure over long distances than natural gas. That allows for transport at lower pressures, with an input pressure of 2 to 3 MPa sufficient. From a risk assessment perspective, the main risk of hydrogen transport in metal pipelines is the potential for material failure due to hydrogen's impact. There are two main mechanisms contributing to pipeline material degradation:

- Heat-affected Zone (HAZ) degradation
- Fatigue Crack Propagation (FCP) in the base material of the pipeline.

Research in Juelich, Germany (Cerniauskas, Junco, Grube, & et al., 2020), showed that X70 steel, widely used as a pipeline material in Europe, does not have issues with HAZ and has reduced FCP degradation compared to other steels, such as X60. Researchers also analyzed the costs of different options for repurposing existing pipelines for pure hydrogen transport. They concluded that a mixture with 0.015% oxygen in the transported hydrogen is effective in limiting hydrogen embrittlement in metal materials (Holbrook, Cialone, Collings, & et al., 2012) and the most cost-effective option for repurposing existing small-diameter pipelines (<250 mm). Using existing pipelines without modifications can be cheaper than building new ones for larger-diameter pipelines. Additional purification is necessary to meet fuel cell requirements for hydrogen transport via pipelines. For example, a maximum purity of 99.9999% can be achieved using pressure swing adsorption (PSA) purification technology.

For transporting large quantities of hydrogen, especially for intercontinental transport, maritime transport appears cost-effective and necessary. The simplest method is compressing hydrogen to 2 to 25 MPa and pumping it into ship tanks. The main drawback of this approach is the low density of hydrogen in the tank. However, this method can be competitive over several thousand kilometers. Liquid hydrogen (LH_2) transport is becoming increasingly attractive as it allows for high volumetric density and the integration of technologies from other cryogenic systems, such as LNG transport. By the end of January 2024, Europe had 57 large LNG terminals that could be modified for LH_2. The advantages of LH_2 transport include locating energy concentration facilities on the producer's side, where energy is cheap. Storage and regasification on the importer's side require minimal energy.

Transporting hydrogen within ammonia is more favorable than the previous two methods due to less stringent storage requirements. Ammonia transport is well-established. The infrastructure for ammonia is mature, with 38 export terminals and 88 import terminals. (Jacobsen, 2020). However, ammonia synthesis is energy-intensive, and the decomposition of ammonia to release hydrogen requires significant energy, making this method less attractive.

For small quantities of hydrogen, transporting compressed hydrogen in pressure vessels is the simplest method. Multiple Type III or Type IV pressure vessels, fixed in containers and transported by truck, can be used for larger quantities. The hydrogen pressure is typically between 20 and 50 MPa, allowing a single truck to carry 200-1000 kg of hydrogen. However, CGH_2 trucks are suitable only for short transport distances (100-200 km) for small hydrogen needs, such as distributing hydrogen to small-capacity refueling stations. The alternative for medium distances (>130 km) is transporting hydrogen in liquid form (LH_2). LH_2 has a higher volumetric storage density, allowing a single LH_2 truck to transport much larger quantities, e.g., a 13.7-meter cryogenic tank can carry 4000 kg of hydrogen at 20 K (Yang, Hunger, Berrettoni, Sprecher, & Wang, 2023). The main challenge is evaporation, but cryogenic tanks can maintain a pressure of 1.2 MPa, higher than stationary tanks. During delivery, evaporated hydrogen is recovered and redirected back to the reliquefaction facility. Not all transported hydrogen is deliverable. Some must remain in the tank to maintain cryogenic temperature. Typically, 10% of the liquid hydrogen stays in the tank.

The characteristics of hydrogen and its transportation are sources of potential hazards and risks. It should be pointed out that the energy of 1000 kg of hydrogen transported by a single truck is equivalent to approximately 28,686 kg of TNT. Such transport requires the fulfillment of all safety requirements.

2 GENERAL RISKS AT THE HYDROGEN USAGE SITE

Due to its unique physical and chemical properties, hydrogen is still widely used today in many areas, including:

- Industrial use
- Energy storage and use as fuel for fuel cells and hydrogen vehicle engines
- Experimental applications, including research and development of new technologies and methods for using hydrogen in various sectors, including those where it is already applied.

Hydrogen as fuel or as a participant in processes in the process industry carries risks. Hydrogen fuel cells, used in vehicles, can be sensitive to leaks and explosions. Tanks and pipelines are also critical system elements. Just as there are challenges in storing hydrogen at the producer's site, storing hydrogen at hydrogen stations at the point of delivery to the end user and the end user's site carries its hazards and risks. Industrial use of hydrogen requires strict safety measures to prevent accidents. (Perelli & Genna, 2022).

2.1 Hydrogen Stations

Hydrogen storage at a hydrogen station depends on the type of hydrogen delivered to the station, and storage at the end user, for example, in a vehicle, depends on the kind of hydrogen supplied at the station. Hydrogen station storage is like storage at the producer's site but on a much smaller scale. Here, we will focus on hydrogen storage in vehicles. There are two main types of tanks:

- *Compressed Hydrogen Tanks (CGH_2):* These tanks store hydrogen at a pressure of 70 MPa. They are made from composite materials like carbon fiber, making them lightweight and extremely strong. They are designed to withstand high pressures and have multilayer insulation materials to minimize heat loss.
- *Cryo-Compressed Hydrogen Tanks (CCH_2):* These tanks store hydrogen at lower temperatures and a pressure of 35 MPa. The advantage of this technology is greater storage capacity, allowing for a longer vehicle range. The tanks maintain a low temperature thanks to special insulation and tank design. Over time, hydrogen can gradually heat up due to external influences. Multilayer insulation and a vacuum layer can reduce heat transfer. Some systems use active cooling methods to maintain the low temperature of the hydrogen. An automatic safety valve can regulate the pressure. Some systems use passive cooling methods, such as phase change materials inside the tank, to further reduce hydrogen heating.

2.2 Vehicles

For hydrogen to be used in fuel cells, its pressure must be typically between 0.1 and 0.2 MPa. In internal combustion engines, pressure regulators reduce the hydrogen pressure to a level safe for injection into the combustion chamber. The pressure regulator in vehicles is not just one valve. It is a system that may include multiple valves and components for precise pressure control.

All system components must be in good condition for normal and safe operation. The main challenges are efficiency, reliability, and safety. Pressure regulators must be precise and reliable to ensure stable hydrogen pressure in all scenarios. That requires advanced materials and technologies capable of withstanding high pressures and preventing leaks. The safety factor is critically important. The average hydrogen tank in fuel cell vehicles can hold about 5-6 kg of hydrogen at 70 MPa, which allows the vehicle's range of approximately 480 kilometers. China Aerospace Science and Technology Corporation (CASC) has successfully developed China's first 100-kilogram liquid hydrogen (LH_2) system for installation in vehicles, representing a significant step forward in the transportation sector (Xinhua, 2024). An explosion of only 5 kg of hydrogen can release 600 MJ of energy. Consequences can be catastrophic depending on the speed and duration of combustion. That highlights the importance of careful hydrogen handling and the implementation of appropriate safety measures. (Čekerevac, Dvorak, & Prigoda, 2025)

Another risk can be servicing vehicles with hydrogen. Refueling speed and necessary skills are important aspects from the driver's perspective. Refueling a hydrogen tank is slower than with conventional fuels but manageable. Ensuring a simple and efficient user experience when refueling vehicles is much more significant. That can be a challenge when introducing new technologies.

2.3 Industrial Application

Many authors have presented reviews of hydrogen uses, including Brown (2019) and Savitri (2022), and here only some of the main industrial uses of hydrogen will be presented:

1. One of the most widespread uses of hydrogen is in oil refineries. Hydrogen is crucial in the processes of hydrodesulfurization and hydrocracking. Hydrodesulfurization is a process for reducing sulfur dioxide emissions from fuels by removing sulfur from petroleum products. (Skala, Orlović, Marković, Terlecki-Baričević, & Jovanović, 2002) In hydrocracking, heavy petroleum intermediates are broken down into smaller molecules in the presence of hydrogen and a catalyst, producing lighter derivatives such as gasoline and diesel. (Ribeiro, 2020) These processes occur under high pressure and temperatures, which can be dangerous if equipment fails or there are management errors. The catalysts and chemical reactants used in these processes can be toxic and are effective only under certain conditions, requiring strict control and safety measures. If not used properly, they can hurt human health and the environment.
2. Hydrogen is a key component of ammonia production based on the Haber-Bosch process. This process involves the direct reaction of hydrogen and nitrogen under high pressure and temperature in the presence of a metal catalyst. Ammonia is used to produce fertilizers essential for the agricultural industry. Additionally, it is used in cleaning products, plastic production, the textile industry, as a refrigerant, etc. (HZG, 2023). Each of these applications carries specific hazards and risks.
3. In combination with carbon dioxide, hydrogen is used to produce methanol. Methanol is an important chemical used as a raw material for plastics, adhesives, solvents, fuels, and acetic acid production. The methanol production process involves the reaction of hydrogen and carbon dioxide under high pressure (5 to 10 MPa) and temperature (200°C to 300°C) in the presence of a catalyst. Acetic acid production also occurs at pressures of around 30 to 60 bar (about 3 to 6 MPa) and temperatures between 150°C and 200°C. And here, high pressures and temperatures pose significant risks.
4. Hydrogen is used to produce synthetic fuels through the Fischer-Tropsch synthesis. This process involves the reaction of hydrogen with carbon monoxide to produce liquid hydrocarbons that can serve as fuels. (NETL, 2024) Synthetic fuels are an alternative to

fossil fuels and can be used in transportation and industry. The process operates under high pressure and temperatures, which can be dangerous if equipment fails or there are management errors. It involves syngas (a mixture of carbon monoxide and hydrogen), which are explosive and flammable. The catalysts used in FTS, such as cobalt, nickel, iron, and palladium, can be toxic and require strict control. The process uses chemical reactants that can hurt human health and the environment if not used properly. The products of the process can include high concentrations of carbon and other harmful components that need to be adequately managed and decontaminated.

5. In semiconductor manufacturing, hydrogen is used as a reducing agent and for surface cleaning. Hydrogen helps remove oxides and other impurities from semiconductor surfaces. That is crucial for producing high-quality electronic components. Additionally, hydrogen is used in processes such as deoxidation and disinfection to reduce the presence of microorganisms and oxides on semiconductor surfaces. (Ramm, Beck, Zueger, Dommann, & Pixley, 1993) The use of hydrogen in semiconductor manufacturing poses several hazards and potential risks, including chemical hazards and infrastructural challenges related to transport, storage, and use. Hydrogen can react with certain chemicals, producing toxic or beneficial reactions that may harm to human health. The "grey" hydrogen use contributes to environmental risks, and there is a risk of fire and explosion if hydrogen is used or stored improperly.
6. In the glass industry, hydrogen is used to create a reductive environment during glass production. This atmosphere helps prevent the oxidation of metals and other materials in the glass, which can improve the quality of the final glass products. The reductive atmosphere can also help control the color of the glass and prevent unwanted reactions that could affect the purity and the glass's aesthetic appearance (Sharma & Aslam, 2023). The use of hydrogen in the glass industry to create reducing atmospheres can lead to several risks due to the characteristics of hydrogen:
    - Explosiveness,
    - Flammability,
    - Invisible flame,
    - The low viscosity of hydrogen can lead to gas loss and potential explosions,
    - Hydrogen reactivity can cause reactions with some chemical substances, creating toxic materials harmful to human health.
7. In transportation, hydrogen is used as fuel in internal combustion engines and fuel cells. Fuel cells produce electricity through the electrochemical reaction between hydrogen and oxygen. (Čekerevac Z. , 2024) Besides vehicles, they are also used in stationary power systems and portable devices. Fuel cells are often used in micro-combined heat and power (CHP) systems, which simultaneously produce electricity and heat, making these systems energy-efficient and environmentally friendly. That further reduces fossil fuel consumption and CO_2 emissions. In addition to efficiency, these systems enable decentralized energy production and can reduce the need for extensive electrical grids and improve energy security. They are especially suitable for sparsely populated areas. In addition to hazards and risks like those mentioned previously, this application is characterized by the process taking place under conditions of platform movement. An additional risk can be the danger of collision or vehicle rollover. Therefore, the safety requirements are even more pronounced.
8. In the metallurgical industry, hydrogen is a reductant for extracting metals from their oxides. For example, hydrogen is a key element in hydrothermal extraction processes to produce tungsten and molybdenum. Tungsten and molybdenum are essential for manufacturing alloys and other industrial products. (CORDIS - EU, 2024) This process requires extreme conditions for efficient metal extraction from their oxides. High pressures and temperatures facilitate reactions that would otherwise be slower or impossible (Goryany, Hinnemann, & Myronova, 2017). Accordingly, there are associated hazards and risks.
9. In the food industry, hydrogen is extensively used for leak detection, sterilization, disinfection, and fat hydrogenation. Hydrogen, either alone or mixed with nitrogen, is used to detect tiny leaks in food packaging as it quickly disperses through small cracks, allowing for

easy identification of leak points (Qanbar & Hong, 2024). Due to its antioxidant properties, it is used in sterilization and disinfection processes to reduce the presence of microorganisms in production facilities and medicine (McEvoy & Rowan, 2019). Hydrogen is used to hydrogenate unsaturated fats and oils, resulting in the formation of saturated fats. This process is used to produce margarine and other hydrogenated products. Hydrogenation takes place in heated tanks with a catalyst, which improves the stability and shelf life of products like margarine and oil (Spiekermann & Seidensticker, 2024).

10. Hydrogen is used in processes such as hydroformylation[3] to produce liquid carbons, which are used as additives in food products. (Franke, Selent, & Boerner, 2012; InfoCons, 2023) The hydroformylation process occurs in heated tanks in the presence of catalysts, typically cobalt or rhodium. During hydroformylation, the tanks are usually heated between 110 °C and 180 °C, allowing optimal catalyst activity and reaction efficiency. However, this also poses risks to workers if appropriate safety measures are not taken.

3 HYDROGEN HAZARDS AND SOLUTIONS

3.1 Risk Analysis and Safety Measures

It is essential to conduct detailed risk analyses to ensure safety in all stages of hydrogen production, storage, transport, and use. That includes identifying potential hazards, assessing the likelihood and consequences of accidents, and implementing preventive and protective measures. For example, a Hazard and Operability (HAZOP) analysis can help identify hazardous scenarios and evaluate the effectiveness of existing safety barriers. (Perelli & Genna, 2022)

Based on the considerations discussed in sections 1 and 2, we identified the following:

1. *Physical hazards of hydrogen, including*:
   - *High Pressure:* The high pressure of hydrogen during storage and transport in its gaseous state poses risks of explosion or tank rupture, which can cause serious injuries or damage.
   - *Low Temperature:* Hydrogen stored in its liquid form (LH_2) brings a risk of contact with materials at extremely low temperatures, which can cause severe burns or frostbite on the skin.
   - *Leaks:* Hydrogen is a very light gas and can easily pass through many materials, leading to potential leaks. Hydrogen leaks can be dangerous because the gas can accumulate in confined spaces, increasing the risk of ignition and explosion.
   - *High Diffusivity:* Hydrogen has high diffusivity. It spreads quickly through various materials and spaces. That can increase the risk of hydrogen accumulation in confined spaces, where it may ignite.

   Understanding these physical hazards is crucial for the safe handling and storage of hydrogen.

2. Chemical Reaction Hazards of Hydrogen (reactions with other materials, corrosion) Include:
   - *Explosiveness:* Hydrogen is highly explosive when mixed with air or oxygen within flammability limits. In the presence of an ignition source, such as a spark or flame, a powerful explosion can occur.
   - *Flammability:* Hydrogen is very flammable and can easily ignite in the presence of a heat source. When it burns, it produces a high-energy flame.
   - *Reactivity:* Hydrogen can react with various chemical substances, such as halogens (chlorine, fluorine, bromine) and oxidizers. That can lead to explosive reactions. It can also react with metals to form metal hydrides, which can be very reactive.
   - *Permeability:* Hydrogen can penetrate through many materials, including metals, leading to chemical reactions that degrade the materials, known as hydrogen embrittlement. That can cause cracking and failures in metal structures

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[3] Hydroformylation, also known as the Oxo process, is a catalytic reaction that involves the reaction of carbon monoxide (CO) and hydrogen (H_2) with olefins (alkenes) to form aldehyde isomers (MT, 2023)

and tanks. One specific form of hydrogen permeability is high-temperature hydrogen attack (HTHA). HTHA occurs when hydrogen at temperatures above 205°C reacts with carbon in steel, forming methane and causing material degradation that weakens the structure. (Ali, Ul-Hamid, Alhems, & Saeed, 2020)

Understanding these chemical hazards is crucial for safe handling, storage, and transportation.

3.2 Safety Protocols and Precautionary Measures

Hazards and risks exist at every stage of hydrogen production, storage, transport, and usage. In the field of hazard and risk protection related to hydrogen, there are several defined standards, regulations, guidelines, and best practice examples.

There are international and national standards and regulations that address safety issues related to hydrogen. The standards define requirements for the design, construction, operation, and maintenance of hydrogen production, storage, and transport facilities. Adherence to these standards is crucial for minimizing risks and ensuring safety (Calabrese, et al., 2024). Here, we will present some key standards and regulations related to hydrogen, including those for workplace safety, environmental protection, and hydrogen facilities.

3.2.1 International Standards

1. *ISO/TS 19880-1:2020* (ISO/TC 197, 2020) is a safety standard that defines the minimum requirements for the design, installation, commissioning, operation, inspection, and maintenance of public and private fueling stations delivering gaseous hydrogen to light road vehicles (e.g., fuel cell electric vehicles). It does not apply to cryogenic hydrogen delivery or hydrogen for metal hydride applications. Manufacturers may take additional safety measures using risk management methodologies. The document also includes requirements for refueling medium and heavy road vehicles (e.g., buses, trucks), and many general requirements apply to stations for other hydrogen applications.
2. *ISO 14687* (ISO/TC 197, 2019) standard specifies the minimum requirements for the quality of hydrogen distributed as fuel for road vehicles and stationary applications. This standard helps ensure the quality of hydrogen used in fuel cells.
3. *ISO 16110-1:2007* (ISO/TC 197, 2007) defines safety and performance requirements for hydrogen production systems. It applies to standalone or factory-matched hydrogen generation systems with a capacity of less than 400 m³/h at 0°C and 101.325 kPa. These systems convert input fuel into hydrogen-rich gas suitable for various devices (e.g., fuel cell systems). The standard applies to hydrogen generators using natural gas, petroleum-derived fuels, alcohols, esters, ethers, aldehydes, ketones, Fischer-Tropsch liquids, and hydrogen gas mixtures. It is intended for stationary hydrogen generators for commercial, industrial, and residential use. The aim is to cover all significant hazards, except those related to environmental compatibility.
4. *ISO 17268:2020* (ISO/TC 197, 2020B) defines the design, safety features, and operational characteristics of gaseous hydrogen land vehicle (GHLV) refueling connectors, specifying how refueling connectors should look and function to ensure compatibility and safety. Where applicable, GHLV refueling connectors include the following components:
    - Receptacle and protective cap (mounted on the vehicle),
    - Nozzle, and
    - Communication hardware.

   This document applies to refueling connectors with nominal working pressures or hydrogen service levels up to 70 MPa. It does not apply to refueling connectors that deliver hydrogen-natural gas blends.

3.2.2 National Standards and Regulations

In addition to implementing international standards, countries develop national regulations for protection against the hazards and risks related to hydrogen, including rules for the design, construction, and maintenance of hydrogen installations. For example:

- Serbia has enacted its Law on Flammable and Combustible Liquids and Flammable

Gases (54/2015), which regulates the use and storage of flammable gases, including hydrogen.

- In the United States, the American Society for Testing and Materials (ASTM) has adopted ASTM *D7606* (ASTM, 2024). This standard specifies the quality of hydrogen for fuel cells in road vehicles. It describes the procedure for sampling high-pressure hydrogen at fueling stations operating at 35 or 70 MPa using a Hydrogen Quality Sampling Apparatus (HQSA). It does not include the analysis of the collected sample; for that, applicable ASTM standards listed in another part of the practice apply. The standard is not intended for the sampling and measuring of particles in high-pressure hydrogen. For these procedures, ASTM D7650 and D7651 are used. The standard does not address all safety aspects of its use; users are responsible for implementing appropriate safety, health, and environmental protection practices. The principles of standardization established by the World Trade Organization (WTO) guided the development of this standard.
- The *AIAA G-095* Guide to Safety of Hydrogen and Hydrogen Systems is a comprehensive resource that provides safety guidelines for the design, construction, and operation of hydrogen systems. It covers various aspects such as system design, material selection, operations, storage, transportation, and emergency procedures. The guide aims to help designers, builders, and users of hydrogen systems avoid or resolve hydrogen hazards. It includes pertinent research summaries and a quick-reference format for easy access to supporting data. The guide emphasizes the importance of safety systems and controls, usage, personnel training, hazard management, design, facilities, detection, storage, transportation, and emergency procedures. It also provides additional information regarding codes, standards, and regulations, a sample safety data sheet, and an extensive bibliography. (AIAA G-095, 2017)
- The *NFPA 2*: *Hydrogen Technologies Code* is a national standard developed by the National Fire Protection Association (NFPA) in the United States. It is not an international standard, but it is widely recognized and used as a reference for hydrogen safety globally. The code provides comprehensive safety guidelines for hydrogen generation, installation, storage, piping, use, and handling in compressed gas (GH_2) and cryogenic liquid (LH_2) forms. The code aims to ensure safety in hydrogen technologies, addressing stationary, portable, and vehicular applications. It was first published in 2011 and is updated every four years. (Umel, 2020)

  The latest version of the *NFPA 2:2023 Hydrogen Technologies Code* includes several updates and revisions to enhance safety measures for hydrogen systems. Some of the key changes are (NFPA 2-2023):

  1. *Updated Safety Guidelines*.
  2. *New Requirements for Storage and Piping*: Enhanced requirements for hydrogen storage and piping to improve safety and reduce risks.
  3. *Improved Emergency Procedures*: Updated emergency procedures to ensure better preparedness and response in case of hydrogen-related incidents.
  4. *Additional Information on Codes and Standards*: Expanded information on relevant codes, standards, and regulations to help users comply with industry best practices.
  5. *Revised Material Selection Criteria*. Updated criteria for material selection to ensure compatibility and safety in hydrogen systems.

These changes aim to provide more comprehensive safeguards and improve the overall safety of hydrogen technologies.

- The *EN 17124:2022* standard, developed by the European Committee for Standardization (CEN), specifies the quality characteristics of hydrogen fuel dispensed at hydrogen refueling stations for use in proton exchange membrane (PEM) fuel cell vehicle systems. The primary focus of the standard is to ensure that hydrogen fuel meets the required purity levels to prevent any harm to the fuel cell systems. It also outlines the quality assurance considerations necessary to ensure the uniformity of hydrogen fuel and aims to provide a consistent and reliable framework for hydrogen fuel quality in Europe. Different aspects of quality assurance are grouped into specific clauses, Clause 5.1 to 5.32 (EN 17124:2022):

- *Clause 5.1 General Requirements*: A quality assurance plan must be created for the entire supply chain to ensure the hydrogen quality meets the requirements listed in Clause 4. This plan can be developed using one of two approaches: a prescriptive approach or a risk assessment approach. Impurities can be introduced at several points along the supply chain. Annex B details these potential sources. When a contaminant is classified as potentially present, it must be considered in the quality assurance methodology.
- *Clause 5.2 Prescriptive Approach*: A prescriptive approach can be applied to well-defined supply chains. However, the standard does not explicitly define the prescriptive approach.
- *Clause 5.3 Risk Assessment*: Risk assessment involves identifying the likelihood and severity of impurities exceeding threshold values specified in Table 1 of EN 17124:2022. That entails answering three fundamental questions (EN 17124:2022):
  - What might go wrong? (Identifying events that could cause impurities to exceed threshold values)
  - What is the likelihood of occurrence? (Probability of impurities exceeding threshold values)
  - What are the consequences for the fuel cell car? (Severity of the impact)

An effective risk assessment requires robust data sets to ensure high-quality outputs. Revealing assumptions and uncertainties can enhance confidence in the results. Overall, the EN 17124:2022 standard provides a framework for maintaining hydrogen fuel quality through comprehensive quality assurance methodology, ensuring PEM fuel cell vehicles operate safely and efficiently. (EN 17124:2022, 2022)

- **Japan** developed its Basic Hydrogen Strategy with a strong emphasis on safety and risk management for hydrogen technologies. The strategy follows the S+3E principles: Safety, Energy Security, Economic Efficiency, and Environmental Sustainability. Here are some key points on how it addresses safety and risks. The strategy includes comprehensive safety guidelines for the entire hydrogen supply chain, from production to end-use. That involves setting up robust safety regulations and ensuring all stakeholders follow these guidelines. The strategy emphasizes the importance of conducting thorough risk assessments to identify potential hazards and implement measures to mitigate them. That includes evaluating the probability and severity of incidents related to hydrogen. Japan focuses on developing advanced technologies to enhance the safety of hydrogen systems. That includes research and development efforts to improve detection, prevention, and response to hydrogen-related incidents. The strategy promotes collaboration between the public and private sectors to establish a rational safety regulation system. That ensures that safety measures are consistently applied and updated based on the latest scientific data and technological advancements. The strategy supports the establishment of third-party certification and inspection bodies to ensure compliance with safety standards and provide an additional layer of oversight. (METI, 2023)

  By addressing these aspects, the Basic Hydrogen Strategy aims to create a safe and secure environment for the widespread use of hydrogen as a clean energy source in Japan.

3.2.3 Occupational Safety and Environmental Protection Regulations

*The **ATEX** Directive 2014/34/EU* (2014) regulates equipment and working conditions in explosive atmospheres, including hydrogen. It outlines essential health and safety requirements and conformity assessment procedures that must be met before products can be placed on the EU market. This directive is aligned with the new legislative framework policy and has been applicable since April 20, 2016.

The Seveso III Directive (2012/18/EU) focuses on controlling the risks of major accidents involving hazardous substances such as hydrogen. This directive establishes rules aimed at preventing major accidents involving dangerous substances and minimizing their impact on human health and the environment. It seeks to ensure a high level of protection consistently across the European Union. The directive applies to certain establishments but excludes military facilities, hazards from ionizing radiation, transportation of dangerous substances (and related temporary storage) outside the covered establishments, pipeline transport, mining, quarrying activities, offshore exploration, and certain gas storage and waste disposal sites. However, it does include onshore underground gas storage and specific chemical and thermal processing operations involving dangerous substances. (EU, 2012)

U.S. regulations include:

- ***Occupational Safety and Health Administration*** *(OSHA)* ***standards***: Regulations related to the safety of workers handling hydrogen, including proper storage and usage.
- ***Environmental Protection Agency*** *(EPA)* ***regulations***: Rules concerning hydrogen emissions and their environmental impact.

  The P-28 guidance (CGA, 2022) document outlines compliance with OSHA's Process Safety Management (PSM) and EPA's Risk Management Program (RMP) for U.S. industrial gas facilities using bulk liquid hydrogen. It helps tank owners/operators meet these regulations and the CGA H-5 standard for Bulk Hydrogen Supply Systems. CGA H-5 (2020, 09) standard outlines the basic criteria for locating, selecting, installing, starting, maintaining, and removing bulk hydrogen supply systems. It covers both liquid and gaseous hydrogen supply systems. It references NFPA 55 for minimum distances between hydrogen systems and exposures. Further details are found in CGA P-29 (2022, 02 01), which guides the application of OSHA PSM and EPA RMP to the compressed gas industry.

The ***International Energy Agency*** (IEA) has defined guidelines and standards for the safe storage, transport, and use of hydrogen (IAE, 2006).

3.2.4 The Additional Standards and Recommendations

ISO/TR 15916 (2015) offers guidelines for using and storing hydrogen in gaseous and liquid forms, including hydrides. It highlights key safety concerns, hazards, and risks, and details hydrogen properties relevant to safety. Other International Standards outline specific safety requirements for various hydrogen applications.

ISO 26142 (2010) specifies performance requirements and test methods for hydrogen detection devices used in stationary settings to measure and monitor hydrogen levels. It addresses safety operations like nitrogen purging, ventilation, or system shut off based on hydrogen concentration but excludes overall safety system and installation requirements. It covers precision, response time, stability, measuring range, selectivity, and poisoning, and is intended for certification goals.

Safety Data Sheet: Each hydrogen installation must have a detailed safety sheet that defines hazards, precautions, and first aid measures. This document is mandatory for all work related to hydrogen.

Explosion Protection: There are specific regulations for hydrogen explosion protection, including technical normative standards and preventive measures.

Although ISO standards like ISO/TR 15916 and ISO 26142 are indeed international standards, they can still be included in the Additional Standards and Recommendations section. This is because they provide specific guidelines and recommendations that complement the broader global and national standards. Including them in this section allows us to emphasize their role in providing additional safety protocols and precautionary measures, which is important for a comprehensive review of hydrogen hazards and risks.

The implementation of these standards and regulations ensures that the use of hydrogen is safe, efficient, and environmentally friendly and is key to ensuring the safety and sustainability of hydrogen use.

4 INCIDENTS AND CASE STUDIES

4.1 Analysis of Known Hydrogen-Related Incidents

4.1.1 Explosion in the BP Texas City Refinery in Texas (2005)

On March 23, 2005, the BP Texas City Refinery, the third largest in the United States, experienced a catastrophic disaster, marking one of the most severe industrial accidents in U.S. history. During the startup of an isomerization unit, an overfilled raffinate splitter tower caused pressure relief devices to open, leading to a flammable liquid geyser from an unflared blowdown stack, which triggered massive explosions and fires. This resulted in 15 fatalities and injuries to 180 individuals. The community was deeply affected, with financial losses exceeding $1.5 billion. Fatalities occurred in or near office trailers close to the blowdown drum, while a shelter-in-place order required 43,000 people to stay indoors. The damage extended to houses up to 1.2 km from the refinery. The incident highlighted significant safety failures and underscored the importance of stringent safety protocols in industrial operations. Overall, this tragedy emphasized the critical need for robust safety management systems and comprehensive risk assessments to prevent similar occurrences in the future. It serves as a somber reminder of the devastating consequences that can arise from lapses in industrial safety measures. (CSB, 2007)

4.1.2 Hydrogen Storage Fire in Emeryville, California (2012)

The incident at the AC Transit Facility in Emeryville, CA, on May 4, 2012, began around 7:45 AM when a pressure relief valve failed, releasing approximately 300 kg of hydrogen. Within the first minute, about 30 kilograms of hydrogen was released, igniting a loud explosion. This caused a jet flame from the vent system, igniting paint and dust on the canopy of a manual dispenser, producing yellow flames and smoke. Emergency services were immediately contacted. An AC Transit employee activated an emergency stop, isolating the incident to high-pressure storage tubes, preventing further hydrogen release. The building was evacuated. Low-pressure alarms indicated that most of the hydrogen had vented. Despite this, the Emeryville Fire Department (EFD) personnel used security cameras for remote site observation and observed escalating conditions and erroneous multiple release points. By 10:00 AM, EFD, Linde, and AC Transit personnel confirmed the vent stack fire using thermal imaging. The situation was stabilized, and by 10:12 AM, personnel closed the isolation valve on the leaking vent stack. The incident was terminated at 10:58 AM. (Harris, Marchi, Levin, & Butler, 2012, Jun)

This hydrogen release could have been avoided with better planning and communication. Although the valve was the immediate cause, the incident revealed the need to improve the overall approach to safety and risk management in such projects. The damage from the hydrogen release, explosion, and fire, including infrastructure and equipment damage at the site, was significant. The exact amount of damage is not available in accessible sources. There were no injuries or fatalities resulting from the Emeryville hydrogen explosion (Harris, Marchi, Levin, & Butler, 2012, Jun). This incident underscored the importance of robust safety measures and effective communication in hydrogen projects, offering valuable lessons for improving safety standards and risk management practices in the industry.

4.1.3 Fire at a Hydrogen Storage Facility in Santa Clara, California (2019)

An explosion during the filling of hydrogen distribution trailers occurred at a hydrogen production and storage facility of a chemical plant in Santa Clara (California, USA) on June 1, 2019, (Pena, 2019). The explosion passed without any fatalities or injuries on-site. (HIAD, 2019) Firefighters arriving at the scene saw several burning tankers, likely containing liquid hydrogen (2-4 tons) or gaseous hydrogen (200-500 kg) (ARIA-53903, 2019). Nearby businesses and homes were evacuated as a precaution. The fire was extinguished in just over an hour without further explosions. Firefighters used thermal imaging and took air samples to ensure hydrogen no longer posed a threat. The hydrogen filling station was destroyed, and the operator took its tanker fleet off the road for inspection. The accident affected nine out of eleven hydrogen fueling stations in the area, impacting 1,000 fuel-cell car owners for several weeks. Employees reported hydrogen had begun leaking a few minutes before the explosion while it was being transferred to a distribution trailer (ARIA-53903, 2019). This incident highlighted the importance of proper safety protocols and communication during hydrogen transfer operations.

4.1.4 The Explosion at the Gangwon Technopark in Gangneung (2019)

On May 23, 2019, a significant explosion occurred at the Gangwon Technopark in Gangneung, South Korea. The hydrogen storage tank at a new-energy research center burst, resulting in devastating consequences. Tragically, the incident claimed the lives of two businessmen on-site and injured six others. (HIAD, 2019) An engineer was demonstrating the system, feeding hydrogen from the tanks to fuel cell (FC) units for generation when the explosion happened.

The blast, equivalent to about 50 kg of TNT, caused extensive damage to the 5,100 m^2 building, shattering windows, destroying walls, and scattering debris, damaging neighboring structures also. Firefighters used thermal imaging and took air samples to ensure no further hydrogen threat. The accident impacted nine out of eleven hydrogen fueling stations in the area, affecting 1,000 fuel-cell car owners for several weeks.

Investigations revealed that oxygen permeation into the hydrogen storage tank caused a pressure spike that led to the catastrophic explosion. The highly flammable hydrogen combined with oxygen created an explosive mixture. (Kim & Kim, 2019)

This incident prompted a thorough review of safety protocols and regulations for hydrogen storage and handling in South Korea. Authorities and industry experts emphasized the need for improved safety standards, regular inspections, and enhanced training for personnel involved in hydrogen-related projects. The Gangwon Technopark explosion is a stark reminder of the potential dangers of hydrogen technology, despite its promising applications in clean energy. It underscores the necessity for ongoing research and development to mitigate risks and ensure the safe deployment of hydrogen systems.

Following the explosion, South Korea's government and industry stakeholders collaborated to strengthen safety measures and prevent similar incidents in the future. The lessons from this tragic event continue to inform safety practices and regulations in the hydrogen industry worldwide.

4.1.5 Explosion at Hydrogen Refueling Station in Kjørbo (2019)

On June 10, 2019, an explosion followed by a fire occurred at a hydrogen fueling station outside Oslo in Kjorbo, Norway, where it was produced on-site by an electrolyzer. Emergency services arrived seven minutes after the explosion and set up a 500-meter cordon. They closed the motorway and nearby roads to traffic. Firefighters brought the fire under control two and a half hours after the explosion.

There were no fatalities and on-site injuries, but the blast caused the airbags of nearby vehicles to deploy, slightly injuring three people. The nation's hydrogen supply was interrupted, and makers of fuel-cell vehicles put deliveries of new ones on hold. All the operator's hydrogen fueling stations, regardless of the used technology, were temporarily closed. That included 10 stations and lasted as long as the investigation in Europe, the USA, and South Korea. (HIAD, 2019).

After 17 days of investigation, the operator determined that a leak in the high-pressure hydrogen storage unit (cylinders containing the gas compressed at two hundred bar) caused the incident. The bolts on the ring between the coupling flange and one of the cylinders had not been torqued adequately, allowing hydrogen to leak out and form a highly explosive mixture with air. The investigation did not determine the source of the ignition. According to reports, the most likely causes are auto-ignition or moving gravel under the unit. (Nel, 2019) The operator scheduled inspections at stations featuring the same assembly systems (four in Norway, three in Iceland, and three in Germany). It updated its assembly procedures and improved the quality of its verifications (double checks). It looked into ways to improve the detection of hydrogen leaks and avoid the presence of ignition sources at its sites (flat surfaces free of gravel, better ventilation).

4.1.6 The Hydrogen Explosion at the Sinopec Facility in Kuqa, Xinjiang (2021)

On March 31, 2021, a hydrogen explosion occurred at the Sinopec hydrogen production facility in Kuqa, Xinjiang, China. It was caused by safety issues related to the electrolyzers used in the facility. The explosion resulted in significant damage to the facility and surrounding infrastructure. The electrolyzers, supplied by three different Chinese manufacturers—Cockerill Jingli, Longi, and Peric—each had their technical issues, but all shared a common problem related to their flexibility (Collins, 2023). When operating at less than 30% of their maximum capacity, the machines stopped releasing hydrogen. That led to a hydrogen concentration in oxygen, creating an explosive mixture (Collins, 2023).

The explosion caused extensive damage to the facility and nearby buildings, highlighting the potential dangers associated with hydrogen production. The incident prompted a thorough review of China's safety protocols and regulations for hydrogen storage and handling. Authorities and industry experts emphasized the need for improved safety standards, regular inspections, and enhanced training for personnel involved in hydrogen-related projects.

The Sinopec facility, the world's largest green hydrogen project at the time, had been operating at less than a third of its installed capacity due to various factors, including missing safety features in the system design and lower-than-promised efficiencies. The explosion underscored the necessity for ongoing research and development to mitigate risks and ensure the safe deployment of hydrogen systems.

4.1.7 Fire on Board Suiso Frontier (2022)

The Suiso Frontier is a prototype ship designed to evaluate the technical aspects of transporting liquefied hydrogen (LH_2) by sea. It departed from Kobe, Japan, on December 25, 2021, carrying 55 tons of LH_2 and arrived at the Port of Hastings, Victoria, on January 20, 2022, to load additional cargo before returning to Kobe. On January 24, after loading LH_2 at Hastings, the ship remained berthed. The incident occurred on the evening of January 25 when the gas control equipment malfunctioned. A worker observed a yellow gas flame briefly emitting from the gas combustion unit's vent stack. Fortunately, no subsequent fires, explosions, injuries, or damage were reported. The Suiso Frontier returned to Kobe on February 25, 2022, successfully delivering the world's first cargo of liquefied hydrogen.

The Australian Transport Safety Bureau (ATSB) investigation revealed that the fire was caused by the failure of an incorrectly fitted electrical solenoid valve in the ship's gas combustion unit. This valve was not compatible with the ship's alternating current (AC) supply, leading to its malfunction. As a result, the air fan discharge damper closed, causing the temperature within the gas combustion unit to rise significantly. This eventually led to the discharge of a flame from the unit's vent stack. The ATSB found that these direct current solenoid valves were incompatible with the 230 V AC supply from the gas combustion unit's control system and were not designed for the conditions they were subjected to during roughly 400 hours of service before the incident. Also, the ATSB found that the gas combustion unit's control system was not equipped to detect valve failure or the damper's closure. In response to the incident, the manufacturer, Saacke, installed limit switches on each air fan discharge damper to monitor their position and updated the system's control logic to stop the unit if a fault is detected. (Habibic, 2023)

The investigation underscored the importance of equipping automated shipboard operating systems with safety controls to prevent hazardous outcomes from malfunctions. It highlighted the need for stringent manufacturer quality controls to ensure correct system components are specified and installed.

4.1.8 The Hydrogen Truck Explosion in Ohio (2023)

On the sixth of February 2023, a truck carrying 420 kg of hydrogen exploded after a crash in Delaware County, Ohio. The incident occurred around 2:30 p.m. at the intersection of Route 23 and Orange Point Drive. A Toyota Corolla collided with the truck, causing the hydrogen tanks in the trailer to ignite and catch fire (WSYX, 2023). The explosion sent flames up to ten meters into the air and caused significant damage to nearby traffic signals and utility lines.

Three people, including the occupants of the truck and the driver of the Toyota, were transported to the hospital with minor injuries. The explosion highlighted the potential dangers of transporting hydrogen and the importance of stringent safety measures.

4.1.9 Explosion at a Chemical Processing Plant in Northwest Queensland (2023)

On September 17, 2023, a significant hydrogen explosion and fire occurred at a chemical processing plant in Northwest Queensland, Australia, injuring three workers and damaging plant equipment. The incident happened during the recommissioning of equipment after routine maintenance. The pressurized hydrogen gas escaped because the butterfly valve failed (Fasching, 2023; Bond, 2023).

The direct cause was the failure of a butterfly valve under a hydrogen header pressure of approximately 2000 kPa (Fasching, 2023). Three workers were injured, including two involved in the recommissioning process and a store worker located about 40 meters from the incident site. Although the injured workers did not require hospitalization, the incident had the potential for more severe consequences. Investigations suggested that the bearing bush bolts of the butterfly valve may not have been correctly installed during the overhaul, leading to the separation of the valve bearing bush.

This incident highlights several significant safety considerations (Fasching, 2023):

- The critical importance of quality checks for correct assembly of high-pressure valves after maintenance overhauls.
- The need for effective systems and processes to ensure quality assurance in valve overhaul and testing.
- The necessity of complying with original equipment manufacturer (OEM) specifications for equipment maintenance involved in hydrogen usage.

The incident serves as a reminder of the potential dangers associated with hydrogen gas and the importance of rigorous safety protocols in chemical processing plants, particularly during maintenance and recommissioning procedures (Bond, 2023).

4.1.10 Explosion at the Bargi Hydroelectric Power Plant (2024)

On April 9, 2024, a deadly explosion occurred underwater at the Bargi hydroelectric power plant, owned by Enel Green Power, near Bologna, Italy. The plant is the largest of its kind in the Emilia Romagna region, with a capacity of 330 megawatts. The explosion, approximately 30 meters below the surface of Lake Suviana, resulted in three deaths, five injuries, and four missing persons, but the dam itself was not damaged, and there was no interruption to the local power supply (Bloomberg, 2024; Gozzi, 2024).

The explosion happened during efficiency improvement works and testing of generation units, with the exact cause initially unclear. Preliminary investigations suggested fire broke out when a turbine exploded on the eighth floor below the surface. Enel Green Power had outsourced this work to Siemens Energy, ABB, and Voith. Search and rescue operations involving divers were complicated by flooding and the risk of further structural collapses (Akella, 2024).

This tragic event has raised concerns about workplace safety in Italy and led to planned strikes by major unions to address these issues (Akella, 2024). These incidents highlight the ongoing importance of safety measures, proper maintenance, and adherence to protocols in hydrogen-related facilities and operations.

In practice, there are also other examples. For example, as of January 2025, HydrogenPro company reported achieving over 365 consecutive days without any lost-time accidents, indicating improvements in safety practices in some areas of the hydrogen industry (HydrogenPro, 2024).

4.2 Lessons Learned from Hydrogen Incidents

Over the past few years, several significant hydrogen-related incidents have highlighted the need for improved safety protocols and risk management practices. Here are the key lessons learned:

1. *Importance of Safety Protocols*: Incidents such as at Gangwon Technopark (2019) and Sinopec (2021) emphasized the critical importance of adhering to stringent safety standards. Without proper safety measures, the risks associated with hydrogen storage

and transport can be catastrophic. These incidents confirmed the necessity for standardized safety protocols globally.

2. *Need for Thorough Inspections and Maintenance*: In both cases, technical issues and equipment deficiencies contributed to the accidents. Thorough inspections and regular maintenance of equipment are crucial to preventing such disasters. The Sinopec incident, for example, was exacerbated by the lack of flexibility in the electrolyzers. These shortcomings underscore the importance of continuous monitoring and maintenance.
3. *Education and Training of Personnel*: Training for personnel handling hydrogen must be comprehensive and ongoing. The incidents revealed gaps in knowledge and training, which contributed to the accidents. For instance, the Gangwon Technopark explosion occurred during a system demonstration, underscoring the need for adequately trained staff to handle such technology.
4. *Technological Improvement and Research*: Technological advancements and research are vital for reducing risks and enhancing safety. The incidents highlighted the need for further research and development of safer technologies for hydrogen storage and transport. Developing safety valves and sensors capable of detecting hydrogen leaks can significantly reduce the risk of explosions.
5. *Public-Private Collaboration*: Collaboration between government institutions and the private sector is essential for advancing safety standards. Following the incidents, governments and industrial partners worked together to strengthen safety measures and regulations. This collaboration enables quicker and more effective implementation of safety protocols.
6. *Awareness and Emergency Preparedness*: The incidents underscored the importance of awareness and preparedness for emergencies. For example, the Gangwon Technopark explosion required a swift response from firefighters who used thermal cameras and air sampling to ensure no further threats. Such preparedness can significantly mitigate the consequences of accidents.

These lessons have contributed to improving safety standards and practices in the hydrogen industry, reducing the risk of future incidents and making hydrogen a safer option for clean energy.

5 FUTURE OF HYDROGEN AND RISK MANAGEMENT

The future of hydrogen as a clean energy source looks promising, with significant advancements in technology and increased focus on safety and risk management. Here's an overview of the future of hydrogen and risk management, emphasizing new technologies for safer use and innovative solutions.

5.1 New Technologies Development for Safer Use of Hydrogen

5.1.1 Progress in Electrolysis Technologies

The progress in the development of electrolysis technologies is reflected, among other things, in the following (Kuterbekov, et al., 2024):

- Proton Exchange Membrane (PEM) electrolysis is becoming more efficient, with efficiencies reaching up to 80%.
- Advancements in PEM electrolyzers include enhanced materials and design innovations that increase efficiency and operational lifespan.

The statement about improved electrolysis technologies, particularly Proton Exchange Membrane (PEM) electrolysis, reflects recent advancements in this field. PEM electrolysis has reached high efficiency levels and an electrical efficiency of about 80% in working applications. Some sources suggest that efficiencies could reach 82-86% before 2030 (FCH, 2018).

Advancements in PEM electrolyzer technology include (Energy, n.d.):

- The efforts to decrease the total platinum group metal content from 3.0 mg/cm² to 0.5 mg/cm² by 2026 and ultimately to 0.125 mg/cm².
- The goal to achieve 3.0 A/cm² at 1.8 V/cell by 2026, and ultimately 3.0 A/cm² at 1.6 V/cell, compared to the current 2.0 A/cm² at 1.9 V/cell.

- A target to decrease the average degradation rate from 4.8 mV/kh to 2.3 mV/kh by 2026 and ultimately to 2.0 mV/kh[4].
- Extending the operational lifetime to double from 40,000 hours to 80,000 hours.
- Cost reduction from $1,000/kW to $250/kW by 2026 and ultimately to $150/kW.

These improvements in efficiency and design are driving the development of more cost-effective and reliable PEM electrolysis systems for hydrogen production.

5.1.2 Enhanced Safety Measures (SAAB, 2023)

Research focuses on preventing hydrogen leakage and improving containment methods during production, storage, and transportation. Researchers are developing advanced technologies to address the unique challenges posed by hydrogen's small molecule size and high diffusivity. These efforts include:

- Implementing layered gas detection systems that combine ultrasonic, traditional gas, and flame monitoring technologies for comprehensive leak detection (HydrogenTools, 2024).
- Improving materials and designs for storage tanks, pipelines, and other infrastructure to minimize the risk of hydrogen embrittlement and leakage (Swagelok, 2024).
- Utilizing high-quality stainless-steel components and optimizing tube fittings to reduce potential leak points in hydrogen systems (Swagelok, 2024).

Development of advanced technologies and stringent safety protocols to minimize hydrogen losses and ensure its role as a clean energy source. The industry is developing and implementing new technologies and strict safety protocols to reduce hydrogen losses (HydrogenTools, 2024; Swagelok, 2024):

- Developing robust leak prevention technologies, such as improved connectors, compressors, and storage vessels, aiming for nearly leak-proof systems.
- Implementing best practices adapted from other gas industries, considering hydrogen's unique properties.
- Establishing comprehensive safety management systems, including automatic shut-off and isolation of hydrogen sources, and audible and visual alarms activation in case of leaks.
- Integrating leak detection systems into control systems to ensure rapid response to potential leaks.

These measures aim to address the safety challenges associated with hydrogen while maximizing its potential as a clean energy source. SAAB and other industry leaders are working to ensure safe and efficient hydrogen use across the entire value chain by focusing on leak prevention, improved containment, and advanced safety protocols.

5.1.3 Integration with Renewable Energy

The integration of hydrogen applications with other forms of renewable energy generation can be done in two ways:

- by coupling and
- by full integration.

Coupling hydrogen fuel cells with wind or solar power systems ensures a reliable energy supply and improves grid stability. Hydrogen fuel cells can convert hydrogen into electricity when needed, complementing the variable output of wind and solar power.

This integration helps address the intermittent nature of renewable energy sources. Wind and solar power are inherently intermittent due to weather conditions and day/night cycles. By using hydrogen as an energy storage medium, this approach helps balance grid supply and demand. During times of high renewable energy production, excess energy can be used for electrolysis to produce hydrogen. It can be stored and later converted into electricity in fuel cells during low renewable generation periods. This strategy effectively decouples energy consumption from the immediate availability of renewable resources, providing a more consistent and reliable power

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[4] The abbreviation **mV/kh** stands for 'millivolts per kilogram of hydrogen'. Specifically, this term is usually used in the context of measuring the performance degradation of electrolyzers or fuel cells. Therefore, when discussing the reduction in degradation rate, it means a reduction in the amount of degradation for each kilogram of produced or consumed hydrogen.

supply. It enhances the overall stability and flexibility of renewable energy systems, making them more suitable for meeting continuous energy demands and supporting grid stability.

5.2 Innovative Solutions and Research

The hydrogen industry is experiencing a surge of innovation and research, driving rapid advancements in production methods, cost reduction, and market expansion. The hydrogen sector is poised for significant growth and transformation in the coming decades, from cutting-edge innovation centers to novel production techniques and regulatory improvements. Here are some examples of them.

1. Hydrogen Innovation Development Centers (Queisser, 2024):
    - ENOWA is setting up a Hydrogen Innovation Development Centre and the NEOM Green Hydrogen and e-Fuels Applied Research Institute.
    - These centers aim to bring together experts, researchers, and industry leaders to drive horizontal and vertical innovation in hydrogen technologies.
2. Advanced Hydrogen Production Methods (Idrissov, 2024):
    - Research into novel reforming technologies such as methane pyrolysis and electrified Steam Methane Reforming (SMR).
    - Autothermal Reforming (ATR) is gaining prominence for blue hydrogen production due to its energy efficiency and compatibility with carbon capture technologies.
3. Cost Reduction Initiatives (Birol, 2019):
    - The cost of producing hydrogen from renewable electricity could fall 30% by 2030 due to declining costs of renewables and scaling up of hydrogen production.
    - Governments are supporting R&D to reduce costs and improve the performance of fuel cells, hydrogen-based fuels, and electrolyzers.
4. Regulatory Improvements:
    - Efforts to eliminate unnecessary regulatory barriers and harmonize standards to facilitate hydrogen adoption (Birol, 2019).
    - Development of risk-based regulations to ensure the safe use of hydrogen across various applications (OECD, 2023).
5. Market Expansion:
    - The global green hydrogen market is projected to reach 150 GW of production capacity by 2030 (Saathoff, 2024).
    - After 2025, nearly all new hydrogen production is expected to be clean (Gulli, Heid, Noffsinger, Waardenburg, & Wilthaner, 2024).
6. Industry Applications (Gulli, Heid, Noffsinger, Waardenburg, & Wilthaner, 2024):
    - Industry is projected to drive most clean hydrogen uptake until 2030, followed by wider adoption in new applications by 2050.
    - By 2050, clean hydrogen demand could account for up to 73 to 100 percent of total hydrogen demand.

The future of hydrogen energy looks promising, with a strong focus on safety, efficiency, and integration with renewable energy sources. As research progresses and technologies improve, hydrogen is poised to play a crucial role in the global transition to sustainable energy systems.

6 CONCLUSIONS

The rapid growth of the hydrogen industry necessitates a robust approach to safety, risk management, and protection. Recent incidents emphasize the importance of comprehensive safety measures to maintain public trust and ensure the sustainable development of hydrogen as a key energy source.

Key hazards and risks include:

- *Flammability and Explosivity*. Hydrogen's high flammability and wide explosive range pose significant risks.
- *Leakage*. Hydrogen can easily escape through tiny openings due to its small molecule size, increasing the risk of undetected leaks.
- *Embrittlement*. Hydrogen can cause certain metals to become brittle, potentially leading to structural failures.
- *Asphyxiation*. In confined spaces, hydrogen can displace oxygen, creating an asphyxiation hazard.

Risk management and protection strategies must include:

- *Rigorous safety standards*. Continuously updating stringent safety regulations and standards specific to hydrogen technologies.
- *Advanced detection systems*. Using state-of-the-art leak detection and monitoring systems to identify potential hazards quickly.
- *Proper training*. Ensuring all personnel working with hydrogen receive comprehensive safety training and regular updates.
- Engineered safety features. Incorporating fail-safe mechanisms, proper ventilation, and explosion-proof equipment.
- *Risk assessment*. Conducting thorough and regular risk assessments to identify and mitigate potential hazards.
- *Emergency response planning*. Developing and regularly practicing emergency response procedures specific to hydrogen-related incidents.

Recent developments show significant improvements in hydrogen safety, with many countries establishing specific policies and regulations. Incidents like the explosions at Gangwon Technopark and Sinopec in China highlight the ongoing need for vigilance and continuous improvement in safety measures. The industry must learn from past incidents and invest in new safety technologies and methodologies.

Global standards for hydrogen safety are becoming increasingly stringent, reflecting the growing demand and use of hydrogen as a renewable energy source. The industry must maintain a proactive stance on safety, continuously evaluating and upgrading protocols as technology evolves. By prioritizing safety through comprehensive hazard analysis, regulatory compliance, advanced prevention technologies, and ongoing training, the hydrogen industry can ensure its role as a key component of our energy future without compromising safety. This balanced approach is crucial for building public trust, securing investments, and realizing the full potential of hydrogen as a clean energy source.

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