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Safety aspects of hydrogen and its main derivatives: A literature review for policy makers

The bottom line. This Live Wire focuses on safety concerns associated with hydrogen and its main derivatives: ammonia and methanol. After an exhaustive review of the literature and measures on hydrogen safety, the study summarized here found robust, well-established standards developed by reputable institutions. This brief emphasizes the critical importance of adhering to these standards and encourages their full implementation to ensure effective and consistent safety practices.

In a word...

Hydrogen is the simplest and most abundant element in the universe

Since its discovery almost 250 years ago by Henry Cavendish and Antoine Lavoisier, hydrogen has been seen as a tool of progress. Currently, hydrogen is used in many different applications, but not directly; instead, most applications use its two main derivatives, ammonia and methanol.

Hydrogen produced from renewable sources can provide environmentally clean, affordable, and secure fuel for electricity generation, transportation, and other sectors (Tchouvelev 2016). While it holds immense potential to revolutionize the energy sector, it also presents unique safety challenges that must be addressed to ensure it is produced, stored, and utilized safely (DOE 2016). Widespread adoption of hydrogen requires understanding its properties and the associated safety concerns.

Since hydrogen is not found in its free form in nature, it must be produced. Clean hydrogen—produced from renewable energy sources and fossil fuels with responsible carbon capture and storage—can play an important role in the global energy transition, accelerating progress toward global climate goals.

As an energy carrier, hydrogen can be used to store, move, and deliver energy. Derivative chemical products with high added value, such as ammonia or methanol, can also be obtained from hydrogen. These derivatives enable efficient storage and transport of hydrogen, making them crucial components in the shift toward sustainable energy systems. By leveraging these technologies, industries can reduce their carbon footprint and contribute to a more sustainable future.

The deployment of clean hydrogen is particularly important for decarbonizing hard-to-abate sectors, such as steel production and long-haul transportation. But as global efforts to develop clean hydrogen intensify, it is essential to guarantee that risks are managed effectively.

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This brief offers an overview of the main risks associated with hydrogen and its primary derivatives, ammonia and methanol. It aims to enhance policy makers' understanding of hydrogen safety and promote the development of safe and sustainable hydrogen policies. To this end, it synthesizes current research, identifies potential risks, and offers actionable recommendations to ensure the safe and efficient integration of hydrogen technologies. International best practices will not be addressed since there are no clear global leaders in hydrogen safety.

Let's start with hydrogen, before moving on to ammonia and methanol. What are its chief properties and safety concerns?

Safe utilization of hydrogen requires meticulous management of the safety challenges presented by its unique properties

Hydrogen is a colorless, odorless, and highly flammable gas under standard conditions. It is the lightest element, with a molecular weight of just 2.02 grams per mole. Hydrogen's wide flammability range in air (4–75 percent by volume), low ignition energy (0.02 millijoules [mJ]), and high diffusivity mean that it can easily spread in and mix with air. In addition, hydrogen burns with an almost invisible flame, posing challenges for detection and firefighting (DOE 2016).

Among the primary concerns is hydrogen's explosiveness. Even minor leaks can quickly result in the formation of explosive mixtures with air, highlighting the critical need for stringent leak detection and effective ventilation measures (DNV 2021).

> **"Clean hydrogen—produced from renewable energy sources and fossil fuels with responsible carbon capture and storage—can play an important role in the global energy transition, accelerating progress toward global climate goals."**

The storage and handling of hydrogen thus poses significant challenges. Hydrogen can be stored either as a compressed gas or in a cryogenic liquid state. Compressed hydrogen storage requires high-pressure systems that can withstand pressures up to 700 bars. Alternatively, storing hydrogen as a liquid necessitates extremely low temperatures, below −253°C, demanding advanced insulation and careful handling to prevent boil-off and leaks. Both storage methods require robust containment solutions to minimize the risk of leaks and ensure safety (Calabrese et al. 2024).

Another crucial issue is material compatibility. Hydrogen has the potential to cause embrittlement in certain metals, which can lead to the failure of pipelines and of tanks and other storage vessels. Special materials and protective coatings are required to maintain the integrity of hydrogen storage and transport systems (Calabrese et al. 2024).

Finally, the detection and monitoring of hydrogen leaks present their own set of challenges. Given that hydrogen is both odorless and colorless, detecting leaks without specialized sensors can be exceedingly difficult. Reliable hydrogen detection systems must therefore be implemented at the outset of any project to detect leaks early and prevent hazardous situations.

Fully realizing hydrogen's potential as a clean energy source, while ensuring the safety of people and infrastructure, requires addressing these safety concerns using rigorous controls, safety protocols, and continuous monitoring.

Hydrogen is no more or less dangerous than other flammable fuels, including gasoline and natural gas. The safety concerns surrounding hydrogen are not a cause for alarm, but are simply different from the customary concerns surrounding gasoline or natural gas. In fact, some of hydrogen's particularities actually provide safety benefits compared with gasoline or other fuels. Some of the most notable differences are listed below (NHA 2010).

Hydrogen is lighter than air and diffuses rapidly. Hydrogen has high diffusivity (3.8 times faster than that of natural gas); this means that, when released, it dilutes quickly into a nonflammable concentration. Hydrogen rises twice as fast as helium and six times faster than natural gas—at a speed of almost 45 miles per hour (20 m/s). Therefore, unless a roof, a poorly ventilated room, or some other structure contains the rising gas, the laws of physics prevent hydrogen from lingering near a leak (or near people using hydrogen-fueled equipment). Simply stated, to become a fire hazard, hydrogen must first be confined—but confining the lightest element in the universe is very difficult. Engineers consider these properties when designing structures where hydrogen will be used. Their designs help hydrogen escape up and away from users in case of an unexpected release.

Hydrogen is odorless, colorless, and tasteless, so most human senses will not help detect a leak. For that and other reasons, the industry often uses hydrogen sensors to help detect leaks and has maintained a high safety record using these for decades. By comparison, natural gas is also odorless, colorless, and tasteless, but the industry adds a sulfur-containing odorant, called mercaptan, to make it detectable by smell. However, all known odorants contaminate fuel cells (a popular application for hydrogen). Researchers are investigating other possible hydrogen detection methods: tracers, new odorant technologies, advanced sensors, and others.

Hydrogen flames have low radiant heat. Hydrogen combustion primarily produces heat and water. Since it produces not carbon but a heat-absorbing water vapor, a hydrogen fire has significantly less radiant heat than a hydrocarbon fire. The heat released near a hydrogen flame is low (though the flame itself is just as hot), meaning that the risk of secondary fires is also low. This fact has significant implications for the public and for rescue workers.

> **“To become a fire hazard, hydrogen must first be confined—but confining the lightest element in the universe is very difficult.”**

Combustion. Like any flammable fuel, hydrogen can combust. However, its buoyancy, diffusivity, and small molecular size make it difficult to contain, so a situation where it might combust is hard to create. An adequate concentration of hydrogen, an ignition source, and the right amount of oxidizer (like oxygen) must all be present at the same time for a hydrogen fire to occur. Hydrogen has a wide flammability range (4–75 percent in air) and might require quite a low amount of energy to ignite (0.02 mJ). However, the energy required to ignite it is high at low concentrations (below 10 percent)—similar to the energy required to ignite natural gas and gasoline in their respective flammability ranges—making hydrogen realistically more difficult to ignite near the lower flammability limit. On the other hand, if conditions allow an increase of hydrogen’s concentration toward the stoichiometric (most easily ignited) mixture of 29 percent (in air), then the ignition energy drops to about one-fifteenth of that required to ignite natural gas (or one-tenth for gasoline). Table 1 summarizes the main properties of widely used fuels.

Explosion. An explosion cannot occur in a tank or any containment that stores only hydrogen. An explosion requires an oxidizer in a specific concentration (e.g., pure oxygen in a concentration of at least 10 percent or air in a concentration of 41 percent). Hydrogen can be explosive at concentrations of 18.3–59 percent. While this range is wide, it is worth

Table 1. Comparison of the properties of widely used fuels

	Hydrogen	Ammonia	Gasoline vapor	Natural gas
Flammability limits (in air)	4–75%	15–28%	1.4–7.6%	5.3–15%
Explosion limits (in air)	18.3–59.0%	15–28%	1.1–3.3%	5.7–14%
Ignition energy (millijoules)	0.02	0.2	0.20	0.29
Flame temperature in air (ºC)	2,045	1,800	2,197	1,875
Stoichiometric mixture (most easily ignited in air)	29%	15%	2%	9%

Source: Original compilation based on NHA (2010), New Jersey Department of Health (2016), National Institute for Occupational Safety and Health (2024), and Kobayashi et al. (2018).

remembering that gasoline can be more hazardous, since it can explode at much lower concentrations (1.1–3.3 percent). Further, there is very little likelihood that hydrogen will explode in open air, because of its tendency to rise quickly. This is the opposite of heavier gases such as propane or gasoline fumes, which hover near the ground, creating a greater explosion risk.

> **“Occasional explosions at hydrogen refueling stations contribute to the public’s perception of hydrogen as unsafe, though the explosion risk is not greater than for other gases.”**

The need for an oxidizer for a hydrogen explosion means the explosion risk is lower than commonly perceived. It nevertheless remains a safety concern that needs to be addressed. Occasional explosions at hydrogen refueling stations, for example, in Germany in June 2024 or in Norway in January 2024 (Elective 2024), contribute to the public’s perception of hydrogen as unsafe, though the explosion risk is not greater than for other gases. But since hydrogen is a relatively new industry, these incidents create significant public aversion. Implementing more security measures and disseminating risk assessments—for example, the “Hydrogen Leakage Risk Assessment for Hydrogen Refueling Stations,” published in the *International Journal of Hydrogen Energy* in 2023—could help improve hydrogen’s image (Wang and Gao 2023).

Asphyxiation. All gases except oxygen can cause asphyxiation. However, hydrogen’s buoyancy and diffusivity mean that in most scenarios, it is unlikely to be confined sufficiently for asphyxiation.

Toxicity/poison. Hydrogen is nontoxic and nonpoisonous. It will not contaminate groundwater (it is a gas under normal atmospheric conditions), nor will its release pollute the environment. Hydrogen does not create “fumes.”

Cryogenic burns. Any cryogenic liquid (hydrogen becomes a liquid below -423°F) can cause severe freeze burns upon contact with skin. However, the current method to keep hydrogen ultra-cold uses double-walled, vacuum-jacketed, superinsulated liquid hydrogen storage containers that are designed to vent hydrogen safely in gaseous form if a breach of either the outer or the inner wall is detected. These robust construction and redundant safety features dramatically reduce the likelihood of human contact.

For more information on hydrogen’s properties and main safety concerns, the following sources may be consulted:

- ✓ “Properties and Effects of Hydrogen” (EIGA 2019, chapter 4)
- ✓ “Hydrogen Has Unique Physical Properties Making It Significantly More Reactive When Compared to Methane” (Accufacts Inc. 2022, chapter 4)
- ✓ *Hydrogen Technologies Safety Guide* (NREL 2015)
- ✓ “Safety Aspects of Green Hydrogen Production on Industrial Scale” (ISPT 2023)
- ✓ “Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment” (Calabrese et al. 2024)
- ✓ The Hydrogen Incident and Accidents Database- HIAD 2.1 (European Commission 2023c)
- ✓ “Hydrogen: How to Meet the Safety Challenges” (Dräger 2020)
- ✓ “Regulatory Framework, Safety Aspects, and Social Acceptance of Hydrogen Energy Technologies,” chapter 6 of Science and Engineering of Hydrogen-Based Energy Technologies (Tchouvelev, de Oliveira, and Neves 2018)
- ✓ The Center for Hydrogen Safety (CHS 2024), a global non-profit founded in 2019 to provide guidance, education, and collaborative forums on hydrogen safety and global best practices
- ✓ *Hydrogen Safety Review* (NETL 2023)
- ✓ *Fundamentals of Hydrogen Safety Engineering* II (Molkov 2012).

Apart from the above references, the European Commission Joint Research Centre, through the Major Accidents Hazards Bureau and in particular the Minerva Portal, organized a two-part webinar on hydrogen risks—the first part in September 2023 and the second in February 2024 (European Commission 2023a, 2024). It was a comprehensive webinar; many countries participated (e.g., Germany, the Netherlands, Japan, Finland, France, and the United Kingdom). Participants discussed the most relevant safety issues in the industry, revealing different concerns at the national and international levels. For the purpose of this Live Wire, a European Commission document outlining relevant reliable hydrogen safety resources is particularly noteworthy (European Commission 2023b).

Development institutions such as the Inter-American Development Bank (IDB) have conducted studies on green hydrogen's safety. "Environmental, Health, Safety, and Social Management of Green Hydrogen in Latin America and the Caribbean" was published in May 2023.

Moving on to ammonia, what are its chief safety challenges?

Although no more or less dangerous than other fuels, ammonia's safety profile is distinct

Ammonia (NH_3) is a clear, colorless gas with a pungent odor at room temperature and under atmospheric pressure. Under normal conditions, it is highly soluble in water and forms a solution known as ammonium hydroxide (NH_4OH), which is a weak base. For industrial purposes, ammonia is typically pressurized and cooled to be stored and transported as a liquid to increase efficiency and safety.

Ammonia is typically produced via the Haber-Bosch process, a high-temperature and high-pressure catalytic reaction between nitrogen (N_2) and hydrogen (H_2):

$$N_2(g)+3H_2(g) \rightleftharpoons 2NH_3(g)$$

This process is one of the largest industrial uses of fossil fuels and contributes approximately 1 percent of global carbon emissions. However, ammonia has an indispensable role in agriculture, where it is used to produce fertilizers such as urea, ammonium nitrate, and ammonium sulfate. The vast majority of ammonia produced (about 80 percent) is directed toward fertilizers, while 18 percent is used in industrial processes, and a small percentage is used in refrigeration and air-conditioning systems.

> **"Ammonia toxicity poses a particular threat to aquatic habitats in coral reefs, polar regions, and mangroves, with potential implications for food chain dynamics. Effective spill management is crucial to prevent contamination and protect aquatic environments."**

The Haber-Bosch process is often considered to have high energy and cost requirements, but the vast majority of the energy inputs, carbon dioxide emissions, capital, and operational costs are actually related to hydrogen production; the synthesis of ammonia from hydrogen requires relatively small additional effort and investment.

Many low-emission ammonia plants are now under development or have recently become operational, demonstrating the technical feasibility of decarbonizing ammonia production. Low-emission ammonia plants constituting over 22.5 million tons of capacity are likely to become operational in 2030; more than 293.3 million tons are under development (Ammonia Energy Association 2024b).

Ammonia is no more or less dangerous than other fuels, including hydrogen, gasoline, and natural gas. Its safety profile is quite different, however, with toxicity and causticity replacing flammability. As with hydrogen, the safety concerns surrounding ammonia are not a cause for alarm as they are already well known and well managed in existing sectors (refrigeration, chemicals, agriculture), but knowledge transfer is critical to ensure that other sectors adopt ammonia safely. A very important future use of green ammonia will be as a shipping fuel.

Some of the most notable risks related to ammonia are as follows.

Exposure risk. Exposure to ammonia can be hazardous due to its corrosive properties and causticity. Ammonia can corrode metals such as copper, brass, zinc, and some alloys, causing structural failures in equipment and containment systems. This poses risks to industrial infrastructure and can lead to leaks or spills, which may cause further hazards.

Causticity specifically relates to ammonia's immediate harmful impact on living organisms through direct contact—unlike toxicity, which involves longer-term systemic effects. Ammonia is highly alkaline and can cause severe damage to skin, eyes, and mucous membranes upon direct contact. Inhalation of ammonia vapors can lead to respiratory tract irritation, swelling, or even permanent damage, depending on concentration levels. To mitigate this risk, the US Occupational Safety and Health Administration has set the permissible exposure limit for ammonia at 50 parts per million (ppm) over an eight-hour workday, and the short-term exposure limit is 35 ppm for 15 minutes.

Toxicity. Toxicity refers to the potential harmful effects of substances on aquatic life. When a spill occurs, toxic materials can infiltrate water bodies, causing severe ecological damage. Prolonged exposure can disrupt marine ecosystems, poisoning fish, plants, and microorganisms. According to the Environmental Defense Fund's 2022 report" Ammonia at Sea: Studying the Potential Impact of Ammonia as a Shipping Fuel on Marine Ecosystems," toxicity poses a particular threat to aquatic habitats in coral reefs, polar regions, and mangroves, with potential implications for food chain dynamics. Effective spill management is crucial to prevent contamination and protect aquatic environments. This includes stringent protocols for handling and containment, and emergency response measures to minimize toxic exposure and mitigate long-term environmental impacts.

Flammability and explosive potential. Ammonia is classified as a flammable gas, despite its narrow flammability limits: from 15 percent to 28 percent by volume in air. When mixed with air, especially at high concentrations, ammonia can form explosive mixtures, posing significant risks in industrial settings. However, ammonia's relatively high auto-ignition temperature (651°C) makes accidental ignition less likely compared with more volatile fuels like methane or hydrogen.

Storage and handling. Given its hazards, ammonia must be stored and handled following stringent safety protocols. Storage tanks must be made of materials that can resist ammonia's corrosive effects. These tanks are often equipped with safety features such as pressure release valves, and they must be inspected regularly for leaks or structural weaknesses.

If a leak occurs, ammonia can spread rapidly and must be contained and evacuated immediately. Facilities handling ammonia in large quantities are often required to have emergency response plans, including ammonia detection systems, personal protective equipment for workers, and access to medical facilities.

The following are some useful resources on the safety of ammonia:

- ✓ "Safety Assessment of Ammonia as a Transport Fuel" (Risø National Laboratory 2005)
- ✓ "Hydrogen and Ammonia Infrastructure: Safety and Risk Information and Guidance" (Lloyd's Register 2020)
- ✓ "Review of Global Regulations for Anhydrous Ammonia Production, Use, and Storage" (Institution of Chemical Engineers 2016)
- ✓ "Ammonia Safety Study" (Zero Carbon Shipping 2022)
- ✓ Ammonia Safety in Ammonia Plants and Related Facilities Symposium, an annual event, organized by the American Institute of Chemical Engineers since 1955.

Further, numerous organizations maintain ammonia safety standards; examples include the International Institute of All-Natural Refrigeration, a global organization dedicated to promoting the use of natural refrigerants in cooling and refrigeration systems. The institute provides resources, standards, and technical guidance to ensure the safe, efficient, and environmentally friendly use of natural refrigerants such as ammonia and carbon dioxide in various applications. The following standards cover the ammonia detection and alarm requirements in the IIAR Standards:

- ✓ ANSI/IIAR 2-2021 Standard for Design of Safety Closed-Circuit Ammonia Refrigeration Systems (IIAR 2019).
- ✓ ANSI/IIAR 6-2019 Standard for Inspection, Testing, and Maintenance of Closed-Circuit Ammonia Refrigeration System (IIAR 2021).

The Compressed Gas Association develops and maintains standards related to the safe storage, handling, and transportation of ammonia, particularly anhydrous ammonia used in industrial applications. These standards cover various aspects related to the use of ammonia (for example, equipment design, safety practices, and regulatory compliance); help ensure ammonia is used safely in industrial applications; and minimize the risks associated with its toxicity and flammability.

Ammonia is gaining attention as a potential alternative marine fuel owing to its carbon-free combustion and relatively high energy density compared with other hydrogen carriers. Several reports, including the Global Centre for Maritime Decarbonisation's "Safety and Operational Guidelines for Piloting Ammonia Bunkering in Singapore" (GCMD 2023) and the European Maritime Safety Agency's report "Potential of Ammonia as Fuel in Shipping" (EMSA 2022), highlight ammonia's potential as a shipping fuel, its benefits, and the regulatory framework supporting its adoption. They highlight the safety challenges and the need for further technological and regulatory advancements to support its widespread use.

Several other organizations are also working on reports or tools regarding the use of ammonia as a fuel. For instance, the Clean Marine Fuels Working Group within the World Ports Sustainability Program has signed a memorandum of understanding with the Society of Gas as a Marine Fuel to develop safety tools for ammonia as a fuel (WPSP 2024).

The Netherlands updated its PGS-12 guidelines for ammonia storage and handling, preparing for increased ammonia imports to the country (Ammonia Energy Association 2024d). (The DCMR (the Dutch environmental protection agency) has permitted OCI Global to build a 60,000-ton ammonia storage tank in Rotterdam.) Some key changes for the PGS-12 code in the Netherlands include (1) submerged pumps for ammonia loading and unloading over the top of the tank (instead of on the side of the tank), and (2) a tertiary concrete outer wall to minimize the effect of any external impact (Yara 2023).

> **"The transition to ammonia as a marine fuel will require significant investment in infrastructure, including specialized bunkering facilities and retrofitting ships with ammonia-compatible engines."**

A main safety concern with using ammonia as a marine fuel revolves around its toxicity and the potential for leaks during bunkering, storage, and on-board handling. A GCMD (2023) report on ammonia bunkering in Singapore emphasizes the need for robust safety guidelines, including the development of double-walled bunkering lines and tanks to minimize the risk of leaks, the implementation of advanced ventilation and neutralization systems to prevent ammonia build-up, and efforts ensuring that all personnel involved in ammonia handling are properly trained and equipped with suitable personal protective equipment.

The transition to ammonia as a marine fuel will require significant investment in infrastructure, including specialized bunkering facilities and retrofitting ships with ammonia-compatible engines. It will also require establishing a comprehensive regulatory framework that addresses safety, environmental impact, and operational protocols. The industry has progressed beyond research and pilot projects, and some ammonia vessels are under construction (e.g., a vessel being constructed by NYK, IHI, Japan Engine Corporation and Nihon Shipyard, due for delivery in November 2026). Established ammonia safety measures are thus of the utmost importance (Ammonia Energy Association 2024a).

Ammonia is a critical industrial chemical that offers significant benefits but also presents inherent risks. Its expanding role as a marine fuel brings new safety challenges that must be addressed through rigorous safety standards, technological innovation, and international collaboration. With the global shift toward decarbonization, ammonia's role both as a key agricultural input and a potential clean fuel highlights the importance of managing these risks effectively.

Some useful resources on the safe use of ammonia as a bunkering fuel are listed below.

- ✓ "Commercialising Early Ammonia-Powered Vessels" (Global Maritime Forum 2023)
- ✓ "Ammonia at Sea: Studying the Potential Impact of Ammonia as a Shipping Fuel on Marine Ecosystems" (Environmental Defense Fund 2022)
- ✓ "Ammonia Powered Bulk Carrier" (Green Shipping Program 2023)
- ✓ "External Safety Study—Bunkering of Alternative Marine Fuels for Seagoing Vessels" (DNV 2021)
- ✓ "Final publication of International Maritime Organization (IMO) Guidelines for Ammonia as a Fuel in Q4 2024." These guidelines are expected to be adopted at the December 2024 Maritime Safety Committee meeting (Ammonia Energy Association 2024c)
- ✓ "Fuel for Thought: Ammonia Report" (Lloyd's Register 2024).

Where does methanol fit in?

Methanol is a versatile chemical with numerous applications. Its principal safety concern is its toxicity

Methanol, also known as methyl alcohol, wood spirit, or wood alcohol, is a light, volatile, colorless liquid alcohol at room temperature and under atmospheric pressure. With a distinctive odor, it is the simplest alcohol and can be transported readily. It is widely used in industrial processes, including fuel production and chemical manufacturing.

Methanol can be produced by several methods. The most common industrial method is natural gas reforming, which involves the steam reforming of natural gas to produce synthesis gas (a mixture of hydrogen, carbon monoxide, and carbon dioxide), which is then converted to methanol. Another method is biomass gasification, where biomass is used as a feedstock and gasification produces synthesis gas, which is subsequently processed to methanol. An emerging method is direct synthesis from carbon dioxide and hydrogen, which involves the catalytic hydrogenation of carbon dioxide.

> **"Methanol's ability to dissolve in water means that contamination of groundwater and soil is a real risk, especially if containment measures are inadequate. These risks demand careful monitoring, as even short-term exposure to high concentrations can have harmful effects on biodiversity."**

Among methanol's various applications is its use as a chemical feedstock in the production of formaldehyde, acetic acid, and a variety of other chemicals. It also serves as a fuel for internal combustion engines, used either directly or as a component of blended fuels, for example, M85, which is 85 percent methanol. Methanol is also used as a solvent in laboratories and industrial processes. It is also used in windshield washer fluid and other antifreeze applications. Methanol can also be used as an energy carrier in fuel cells for the production of electricity. Its use in maritime transportation is becoming more common.

The DNV (2021) report "External Safety Study—Bunkering of Alternative Marine Fuel for Seagoing Vessels," mentioned above, also considers methanol's safety concerns as a bunkering fuel. Methanol is becoming an increasingly attractive option for reaching global climate goals, as discussed in The Maritime Executive article "Putting Methanol through Its 'Paces,' with a Focus on Safety" (2024). However, safety concerns regarding the adoption of methanol as a new fuel also need to be addressed. The Maritime Energy and Sustainable Development Centre of Excellence, in collaboration with the Methanol Institute, has carried out a more in-depth analysis in the report "Methanol as a Marine Fuel"(MESD Centre of Excellence and Methanol Institute 2021).

The main safety concern regarding methanol is its toxicity, for which its degradation products, formaldehyde and formate, are responsible. Methanol is highly toxic if ingested, inhaled, or absorbed through the skin. Ingestion of more than 20 milliliters can be lethal, while lesser quantities are known to cause irreversible blindness. Methanol's metabolism and toxicity are similar to those of ethylene glycol. Methanol must be handled and dispensed taking adequate precautions (IRENA and Methanol Institute 2021).

Exposure to even small quantities of methanol must be followed by immediate medical intervention, making it vital for industries handling methanol to have appropriate emergency response procedures in place. It is also important to consider chronic, low-level exposure, which poses a significant concern for workers handling methanol over extended periods. Even small but prolonged exposure to methanol can lead to cumulative health impacts, such as headaches, vision impairment, and neurological symptoms (Methanol Institute 2020; US Environmental Protection Agency 2016).

Fire and explosion risks are also prominent in methanol's risk profile. Because methanol has a low flash point and burns with a nearly invisible flame, it poses serious hazards in industrial environments. Methanol vapors are particularly dangerous as they can form explosive mixtures with air, compounding the risk of fires and explosions in confined or poorly ventilated areas. Facilities storing or transporting methanol must implement stringent fire prevention measures, including adequate ventilation and the use of fire-resistant materials. Emergency fire response systems should also consider the challenge of detecting methanol fires due to its flame characteristics. The nearly invisible nature of methanol flames also makes fire detection and firefighting particularly challenging; specialized sensors and fire suppression systems are required (IRENA and Methanol Institute 2021).

Environmental risks arise when spills or leaks occur during transport or storage. Methanol is biodegradable, and while its environmental persistence is lower than that of many other chemicals, large spills into water bodies can disrupt aquatic ecosystems by lowering oxygen levels and impairing aquatic life. Additionally, methanol's ability to dissolve in water means that contamination of groundwater and soil is a real risk, especially if containment measures are inadequate. These risks demand careful monitoring, as even short-term exposure to high concentrations can have harmful effects on biodiversity. Minimizing methanol's long-term ecological impacts requires regulatory compliance in its transportation and storage, coupled with stringent environmental protection protocols. Ensuring quick response measures and remediation plans in case of spills is also critical to protecting nearby ecosystems (Methanol Institute 2020).

Methanol also poses corrosion risks as it can degrade metals, rubber, and certain plastics over time, and can compromise the integrity of storage tanks, pipelines, and transport containers. Methanol can corrode stainless steel, for instance, particularly under conditions of water contamination, which accelerates the process. This degradation not only increases the likelihood of leaks and accidental releases but also raises maintenance costs for industries handling methanol. Industries must use containers made from resistant materials, such as specific alloys or treated plastics, and regularly inspect and maintain infrastructure to prevent failure. Risks can be reduced further by adding corrosion inhibitors to methanol storage systems and fully removing moisture (Methanol Institute 2020).

In the maritime sector, additional safety protocols are required. The 2021 DNV external safety study highlights the need for specific guidelines on methanol bunkering; it emphasizes the need for port facilities and ship operators to ensure they are adequately equipped to handle the fuel safely. Appropriate training and safety measures will be essential as methanol use becomes increasingly common in this sector (DNV 2021). Spills and transportation risks must also be considered, as methanol's toxicity and flammability can lead to large-scale hazards in the event of accidents during transit.

In conclusion, while methanol offers significant advantages as an industrial feedstock and alternative fuel, its risks, especially related to toxicity, fire, explosion, environmental contamination, and material degradation, require robust safety measures across its life cycle. From handling and storage to transportation and use, mitigating methanol's risks demands strict regulatory compliance, regular safety audits, and investment in corrosion-resistant infrastructure. Moreover, the development of industry-specific guidelines, particularly in emerging sectors such as maritime fuel applications, will be critical to ensuring that methanol's hazards do not overshadow its benefits. For safe and effective use of methanol in both industrial and fuel-related contexts, the priorities should be emergency preparedness, continuous worker training, and the adoption of cutting-edge safety technologies.

The Methanol Institute provides extensive resources on the safe handling of methanol. The resources include guidelines, manuals, and technical reports that cover various safety aspects, including detecting and extinguishing a methanol fire, health and safety modules, and guidelines for communication during crises. These resources are crucial for parties handling methanol to ensure they are prepared for unforeseen incidents (Methanol Institute n.d.).

Where can policy makers find up-to-date information on hydrogen safety?

Hydrogen components must follow strict guidelines and undergo third-party testing for safety and structural integrity

One of the most comprehensive resources regarding hydrogen safety is H_2 Tools, a portal of the US Department of Energy (DOE). The Pacific Northwest National Laboratory developed the H_2 Tools Portal with support from the DOE's Office of Energy Efficiency and Renewable Energy.

The goal of the portal is to support the implementation of practices and procedures that will ensure the safe handling and use of hydrogen in a variety of fuel cell applications.

The portal brings together and enhances the utility of a variety of tools and web-based content on the safety aspects of hydrogen and fuel cell technologies to help inform those tasked with designing, approving, or using systems and facilities, as well as those responding to incidents.

Based on more than 20 years of experience, the portal has a section dedicated to fuel cell codes and standards, and another section dedicated to best practices (H_2 Tools 2024a).

Among the resources collected in H_2 Tools, two are of particular importance:

- ✓ The Center for Hydrogen Safety. A global nonprofit founded in 2019 to provide guidance, education, and collaborative forums on hydrogen safety and global best practices.
- ✓ Hydrogen Safety Panel. With more than 20 years of experience, the panel is led by the Pacific Northwest National Laboratory and includes more than 20 experts, including, among others, engineers, scientists, code officials, safety professionals, and equipment providers. Their goal is to apply the best safety practices in a nonregulatory manner.

US DOE—Hydrogen and Fuel Cell Technologies Office. The HFTO within the DOE also has a website offering a compilation of many reliable resources on safety, codes and standards (HFTO 2024).

Fuel Cell and Hydrogen Energy Association. The FCHEA is the United States' leading industry association representing leading and innovative organizations that are advancing the production, distribution, and use of clean, safe, and reliable hydrogen energy. It publishes the "Hydrogen and Fuel Cell Safety Report," a bimonthly electronic publication providing information on the development of hydrogen and fuel cell codes and standards, and the related safety information (FCHEA 2024). The FCHEA also manages the H_2 Tools Codes and Standards Database, focused on the worldwide development of over 400 hydrogen and fuel cell standards (H_2 Tools 2024b).

Other relevant publications on regulations for the hydrogen industry are listed below.

- ✓ "Risk-Based Regulatory Design for the Safe Use of Hydrogen"(OECD 2023).
- ✓ "Regulatory Framework, Safety Aspects, and Social Acceptance of Hydrogen Energy Technologies" (chapter 6 in Tchouvelev, de Oliveira, and Neves 2018).

> **"For safe and effective use of methanol in both industrial and fuel-related contexts, the priorities should be emergency preparedness, continuous worker training, and the adoption of cutting-edge safety technologies."**

Where do we go from here?

Several practical policy recommendations are proposed to enhance the safety of hydrogen and its derivatives

The issue of hydrogen safety has been rigorously addressed by well-established standards and highly reputable institutions. The implementation of these standards and measures is crucial for the safe handling of hydrogen. These recommendations are directed at policy makers, authorities, inspectors, and other interested stakeholders to promote widespread adherence to safety protocols and foster global cooperation in hydrogen safety.

Establish clear guidelines or recommendations—for example, the Anhydrous Ammonia Tank Car Checklist developed by the Fertilizer Institute for the safety of ammonia tank trains. Following these procedures is especially relevant when handling these substances, given their safety requirements. Also, other basic procedures, such as emergency response plans or drill emergencies, are recommended to promote workers' safety and damage control in the case of an accident.

Educate the public—and authorities—on the risk that hydrogen, ammonia, and methanol production entail. The main hazardous properties of hydrogen and its derivatives should be extensively communicated from a young age, and safe handling procedures should be emphasized. Personnel involved in handling, storing, and transporting hydrogen should receive comprehensive training. Risks must be communicated in an easy-to-understand manner—not only to the public but also to government authorities—so that decisions are made based on a thorough understanding of the risks.

Ensure that hydrogen storage facilities comply with relevant safety standards and implement stringent filling and emptying protocols for storage tanks so as to prevent pressure from exceeding a safe threshold. Personnel must be trained on safe handling practices, including the use of personal protective equipment, and must learn to implement procedures to minimize exposure during loading, unloading, and transfer operations. Hydrogen storage and distribution equipment must be regularly maintained and inspected.

Ensure all operations comply with applicable codes and standards and adhere to relevant international safety standards and regulations, such as those recommended by the International Organization for Standardization, the American Society of Mechanical Engineers, and the National Fire Protection Association. Label hydrogen storage areas and equipment with warning signs, and establish clear communication protocols for informing personnel, contractors, and emergency responders on hydrogen-related activities.

Conduct risk assessments regularly to identify potential hazards associated with hydrogen. Mitigation strategies—such as adequate ventilation, leak detection systems, and emergency shutdown procedures—must be implemented to ensure safety.

> **"Avoid regulations or policies that are overly restrictive. This is especially relevant in the case of greener fuels, which hold significant potential for the energy transition."**

Avoid regulations or policies that are overly restrictive—for example, those where innovation is burdened due to risk reduction beyond the desired levels. This is especially relevant for certain applications of hydrogen and its derivatives, for example, greener fuels, which hold significant potential for the energy transition.

Follow safety-by-design principles, especially for complex technologies with significant in-use phases. This approach focuses on addressing safety concerns early in the design process, and balances innovation and precaution by front-loading safety considerations. By minimizing risks from the outset, innovators can reduce the need for extensive mitigation later in the product life cycle. Effective safety-by-design practices require proactive collaboration among regulators, innovators, and stakeholders, ensuring regulatory preparedness and the development of appropriate safety frameworks and tools. Collaborative effort will increase innovation while maintaining high safety standards.

Take critical mitigation actions throughout the life cycle of electrolyzers and plants. The following is a list of some essential mitigation actions to take during operation (Zygier 2024):

- ✓ *Degradation management.* Mitigating the risk of membrane degradation is paramount to prevent failures. Operators must diligently adhere to prescribed maintenance schedules and procedures to sustain equipment's integrity.

- ✓ *Optimal operating conditions.* Adhering to manufacturers' specifications and consideration for local operational conditions are essential.

- ✓ *Early detection and monitoring.* Continuous monitoring of membrane and diaphragm conditions helps detect degradation early, thus reducing the likelihood of unexpected failures within the equipment's projected lifespan.

- ✓ *Monitoring key parameters.* Regular monitoring of critical parameters such as gas purity, voltage, and current ensures optimal performance and early detection of potential issues.

- ✓ *Proactive operational practices.* Proactive measures such as pausing production when equipment operates outside optimal parameters and developing effective purging and inerting procedures are essential safety practices.

- ✓ *Measures for gas handling and safety.* Effectively removing flammable and oxidizing gases from processing equipment minimizes losses and increases safety. Strict adherence to hydrogen hazard management—including good housekeeping, detectors, operational protocols, and preventive measures against fuel-air mixtures and ignition sources—ensures safe operations.

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