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HYDROGEN LEAKAGE: A POTENTIAL RISK FOR THE HYDROGEN ECONOMY

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Hydrogen is expected to play a key role in the decarbonization of the energy system. As of June 2022, more than 30 hydrogen strategies and roadmaps have been published by governments around the world. Hydrogen has been identified as a potential safety issue based on the fact that it is the smallest molecule that exists and can easily pass through materials. To date, however, very little attention has been paid to the potential contribution of hydrogen leakage to climate change, driven by hydrogen's indirect global warming effect through mechanisms that extend the lifetime of methane and other greenhouse gases (GHG) in the atmosphere (Paulot et al. 2012; Derwent et al. 2020).

A literature analysis turns up very little data on hydrogen leakage along the existing value chain, and that which does exist comes from theoretical assessments, simulation, or extrapolation rather than measures from operations. As the production methods and uses of hydrogen evolve over time, there is even less data available on what could represent key parts of the hydrogen economy going forward. In the future, leaked hydrogen will likely be concentrated in a few key processes (e.g., green hydrogen production, delivery, road transport, and chemical production). There is a risk of increased leakage rates in the future mostly because the leaking processes that will be key by 2050 do not exist at scale today. A high-risk scenario based on hydrogen demand from the International Energy Agency (IEA) net-zero scenario (528 million tons [Mt] by 2050) (IEA 2021) could potentially lead to a 5.6 percent economy-wide leakage rate, compared with an estimated 2.7 percent in 2020.

Using a wide analytical lens encompassing hydrogen leakage detection, prevention, and regulation, this commentary identifies the following three main requirements for mitigating this risk:

This commentary represents the research and views of the authors. It does not necessarily represent the views of the Center on Global Energy Policy. The piece may be subject to further revision.

The Center on Global Energy Policy would like to thank the Environmental Defense Fund for their gift to CGEP in support of research related to hydrogen leakage. Contributions to SIPA for the benefit of CGEP are general use gifts, which gives the Center discretion in how it allocates these funds. More information is available at https://energypolicy.columbia.edu/about/partners.

- Gathering and analysis of data, especially cross-referenced data from actual measures, to better understand current and future hydrogen leakage rates.
- Research and development to improve hydrogen leakage detection, prevention, and mitigation. Hydrogen sensors must be able to detect leakage at much lower detection thresholds than those existing and among various types of applications. Such technologies are available but need to be transferred and developed at scale.
- Regulations that look beyond safety concerns related to hydrogen's flammability to include the use of hydrogen in different parts of the energy system and tackle leakage of substances more broadly, including hydrogen. It is important that the regulating entities involved coordinate at national and international levels to achieve coherent regulations.

Hydrogen Use and Related Climate Risk

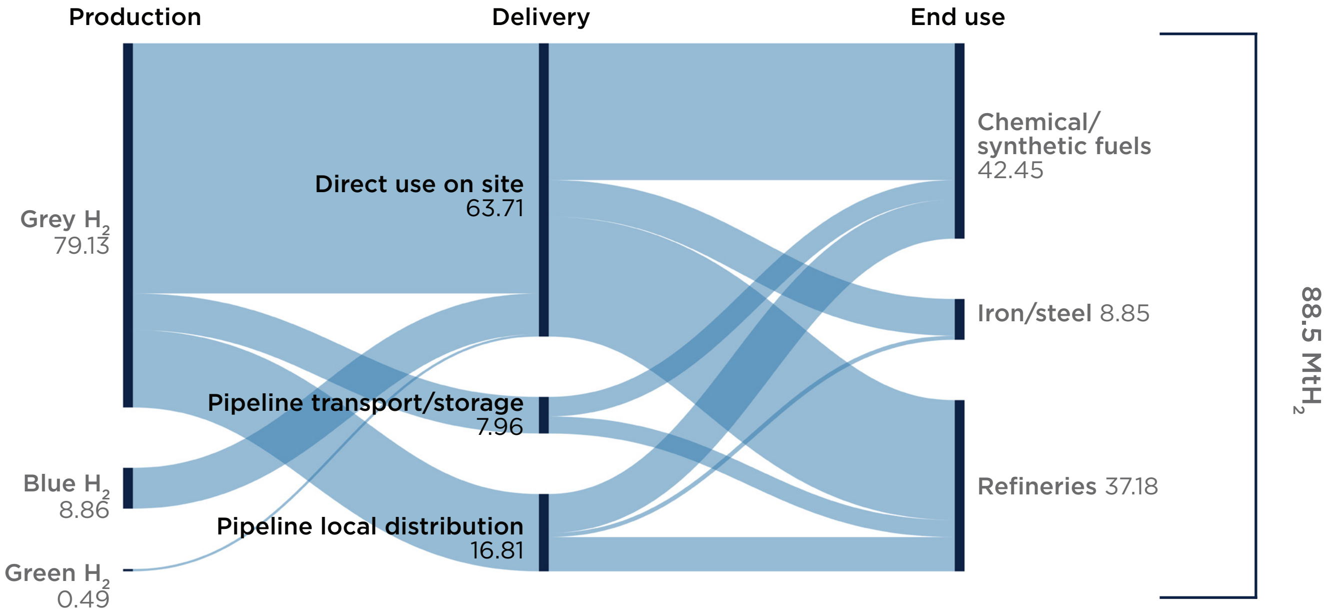
Hydrogen is emerging as a central pillar of the transition to a net-zero emissions energy system to address the climate crisis. Today, hydrogen is used at scale in several key industrial processes, namely, chemicals, refineries, and iron and steel, totaling around 90 Mt-H_2/yr globally (IEA, Net Zero by 2050, 2021). More than 90 percent of the hydrogen produced today is gray hydrogen, meaning it is produced through carbon-intensive methods using fossil fuels. Under the IEA's net-zero emissions scenario, hydrogen use would more than quintuple by 2050, increasing to 528 Mt-H_2/yr (IEA 2021), and come to span a much wider range of applications, including energy storage mediums and fuel for power generation, industrial heat, low-carbon fuel feedstock, natural gas blending, and transportation fuel. In the interim, low-carbon hydrogen production, both green (based on low-carbon electricity electrolysis) and blue (based on reforming fossil fuels with carbon capture and storage), will gradually make up more and more of the total share of hydrogen production. By 2050, it will comprise the overwhelming majority at 520 Mt-H_2/yr globally or 97 percent of total supply (see Figure 1).

Most analyses of climate risks related to hydrogen are limited to GHG emissions from various hydrogen production processes—a point highlighted by the attempt to color-code these processes according to their footprint range. However, hydrogen molecules themselves pose a particular climate risk in the atmosphere. Though hydrogen molecules (H_2) does not directly trap heat, it has an indirect global warming effect by extending the lifetime of other GHGs. Certain GHGs such as methane, ozone, and water vapor are gradually neutralized by reacting with hydroxide radicals (OH) in the atmosphere. When H_2 reaches the atmosphere, however, the H_2 molecule reacts with OH instead, depleting atmospheric OH levels and delaying the neutralization of the GHGs, which effectively increases the lifetime of these GHGs (Derwent et al. 2020). Hydrogen molecules last only a few years in the atmosphere, so they exert a substantial near-term warming effect. A recent preprint study modeling continuous emissions of H_2 estimated that over a 10-year period hydrogen has an approximately 100 times stronger warming effect than carbon dioxide (CO_2) (Ocko and Hamburg 2022). The indirect global warming effect of hydrogen leakage into the atmosphere is rarely considered on a large scale.

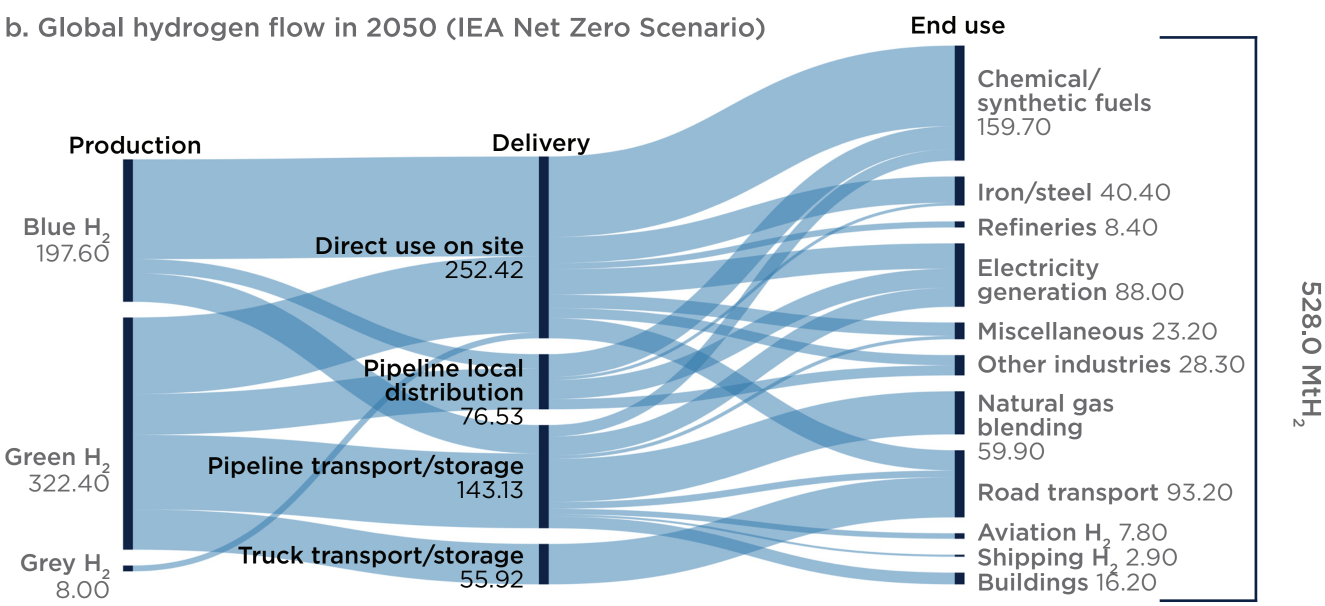
Given that the use of hydrogen is projected to expand significantly across various scenarios consistent with reaching net-zero targets, it is important to ensure that it does not contribute to rather than reduce GHG emissions. There is currently very little information on hydrogen leakage risks beyond safety concerns, and only a few independent studies have systematically studied the topic (Frazer-Nash Consultancy 2022).

Figure 1 : Sankey diagrams of global hydrogen flow (million metric tons of H_2 per year) by process

a. Global hydrogen flow in 2020



b. Global hydrogen flow in 2050 (IEA Net Zero Scenario)



Note: As defined here, blue hydrogen includes both carbon capture and storage (0.71 Mt) and carbon capture and utilization (8.15 Mt) facilities currently in operation. End-use volumes given for aviation and shipping include only molecular hydrogen demand. Hydrogen derivatives such as ammonia used in those sectors are included within the chemical/synthetic fuels end-use.

Source: IEA, Net Zero by 2050, May 2021, https://www.iea.org/reports/net-zero-by-2050.

Hydrogen Leakage: Knowns and Unknowns

Hydrogen leakage risks have been identified along the entire value chain of hydrogen. In assessing these risks, this commentary divides the hydrogen value chain into three categories: production, delivery, and end use (see Figure 1).

Production Leakage Risks

Gray and blue hydrogen production facilities are typically part of integrated industrial facilities where the hydrogen is directly consumed in the production of, for instance, ammonia, methanol, or direct reduced iron (IEA 2021). These industrial facilities have a well-established history of regulating hydrogen safety with a focus on limiting the concentration of flammable gases, including hydrogen, in the air (Rivkin, Burgess, and Buttner 2015). Measurements of leakage rates from industrial gray and blue hydrogen production are rarely implemented and reported. Most of the studies that address gray and blue hydrogen leakage are simulations based on or extrapolated from similar studies of other gases. Xia et al. (2019) found that gray hydrogen production based on steam methane reforming (SMR) could have a less than 1 percent total leakage rate from SMR facilities based on detected nitrogen leakage. Blue hydrogen production is believed to have a slightly higher risk of leakage due to the added complexities of its production system, including an additional separation process. Its leakage rate has been estimated to be approximately 1.5 percent based on a combination of natural gas leakage data and what is known about the correlation between hydrogen leakage properties and those of natural gas (Barrett and Cassarino 2011).

Green hydrogen production currently represents a small share of global hydrogen production, but that share is expected to play a significant role in the future. Assessing the risk of hydrogen leakage during green hydrogen production is difficult as the topic has rarely been studied. The literature on green hydrogen has instead examined hydrogen “losses,” or the difference between the theoretical, calculated quantity of hydrogen that is supposed to be produced and the amount that is actually measured. As part of the University of California–Irvine’s power-to-gas demonstration with a proton exchange membrane (PEM) electrolyzer, one study suggested that the difference between wet and dry hydrogen after the pressure swing adsorption dryer, which comprises two dryer beds that absorb water at elevated pressure, could be caused by the venting of a fixed amount of hydrogen gas (Stansberry 2018, 81). Similarly, a National Renewable Energy Laboratory (NREL) study of a prototype PEM electrolyzer found that most hydrogen losses (estimated at 3.4 percent) occur in the dryer, resulting in a total loss of about 4 percent (Harrison and Peters 2013). If these hydrogen losses are not properly treated, they will eventually leak into the atmosphere.

Delivery Leakage Risks

Compared with the production and end-use phases, the delivery phase of hydrogen (i.e., transport from production site to end user) is the most widely studied, including through both simulation-based and experimental-based research. There are also existing regulations around hydrogen delivery leakage (e.g., Department of Energy [DOE] targets 2022).

Pipelines, including both dedicated hydrogen pipelines and natural gas blending systems, are the most important systems for hydrogen delivery. In and of themselves, these systems demonstrate a low risk of leakage. Weller, Hamburg, and von Fischer (2020) and Mejia and Brouwer (2019) found a roughly 0.4 percent leakage rate for hydrogen simply passing through a pipeline. In the future, however, full hydrogen delivery systems will include necessary storage facilities (e.g., pressurized tank storage, liquefaction tank storage, and salt caverns) that will incur mechanical loss (e.g., from pressurization, depressurization, permeation leakage, and accidents), and the life-cycle loss of hydrogen from integrated transportation/storage systems is estimated to be 2 percent (Panfilov 2015; US DOE 2022).

Another hydrogen delivery method is truck delivery to fueling stations, which are many in number but have a low capacity of only a few hundred to a few thousand tons (Park et al. 2014). Compared with pipeline systems, this method is both less important in terms of scale and leakier, mostly due to boil-off losses (US DOE 2017; Petitpas 2018). For particularly small facilities (<100 kg per day), the loss can contribute to a significant proportion of total accounted hydrogen, estimated to be above 20 percent. Even for average-sized fueling stations (several hundreds to several thousands of kilograms per day), the leakage rate can be 3–6 percent depending on pressure and charging times (US DOE 2017; Petitpas 2018). Given the average size of fueling stations, this study assumes an average leakage rate of 5 percent for truck transport and storage systems.

End-Use Leakage Risks

End-use leakage risks are the least understood of the three categories, especially in terms of future hydrogen end uses that do not exist today. The largest consumers of hydrogen by scale are and will remain within the industrial sector (see Figure 1). Among the current end users of hydrogen, the overwhelming majority are chemical plants, refineries, and iron and steel producers (IEA 2019). In the IEA's net-zero scenario, these end users are expected to consume around 200 Mt of hydrogen by 2050. Like the case of the chemical industry, current regulations around hydrogen leakage focus on safety measures: how refineries and chemical plants can minimize hydrogen leakage to prevent large-scale hazards (e.g., fires and explosions) as evidenced in quantitative risk analysis studies (Mohammadfam and Zarei 2015; Spouge 2005) and plant surveys (Pattabathula, Rani, and Timbres 2005). The task of quantifying and monitoring small, distributed leaks is not a priority and is therefore largely absent from the literature. To the knowledge of the authors, no explicit leakage rates have been published for industrial facilities, most of which use hydrogen produced on-site as an integrated system. Combining knowledge of integrated systems with that of gray hydrogen production leakage, this analysis assumes a leakage rate of around 0.5 percent for industrial facilities such as chemicals and synthetic fuel, iron and steel, and refineries (excluding the production process).

Other end-use cases include the following:

- Electricity generation: The IEA's net-zero scenario expects 88 Mt/yr of hydrogen to be used for power generation. Combining Alvarez et al. (2011), which analyzed methane leakage for turbines, with Mejia and Brouwer (2019), which analyzed the correlation between methane and hydrogen leakage, the authors estimate that the process of converting hydrogen to power based on gas-turbine technology has a *3 percent* hydrogen leakage rate.

- Transportation: Shen et al. (2021) conducted a simulation study to analyze the effect of the diameter of a storage tank leakage point. Hao et al. (2020) analyzed the leakage leading to hydrogen concentration in a confined space. This study assumes that road transport leakage is similar to hydrogen storage tank leakage during delivery, with the exception of potential boil-off loss during charging, leading to a leakage estimate of *2.3 percent* (Alvarez et al. 2011; Mejia and Brouwer 2019). The leakage rates for shipping and aviation have been extrapolated from, in the former case, road transport for similar fuel-cell based technologies (*2.3 percent*) and, in the latter case, power generation based on turbine-based technologies (*3 percent*).
- Buildings: Buildings using hydrogen represent a relatively small risk of leakage. Most fuel used by buildings (about 16.2 Mt/yr) is for heating via various kinds of appliances. Borrowing from a study of California's natural gas emissions from homes and again accounting for methane versus hydrogen leakage correction, this commentary assumes a leakage rate of about *0.8 percent* (Fischer et al. 2018; Mejia and Brouwer 2019).

Table 1: Hydrogen leakage summary

Leakage source process	Category	Scale (Mt)	2050 high-leakage center case	References	2050 low-leakage center case
Grey hydrogen	Production	8	1.0%	[Xia et al. 2019]	0.5%
Blue hydrogen	Production	197.6	1.5%	[Barrett & Cassarino, 2021	1.0%
Green hydrogen	Production	322.4	4.0%	[Harrison & Peters, 2013]	2.0%
Natural gas blending	Application	59.9	0.9%	[Alvarez et al. 2011] [Mejia & Brouwer, 2018]	0.5%
Chemical synthetic fuels	Application	159.7	0.5%		0.2%
Iron and steel	Application	40.4	0.5%		0.2%
Electricity generation	Application	88	3.0%	[Alvarez et al. 2011] [Mejia & Brouwer, 2018]	1.5%
Road transport	Application	93.2	2.3%	[Alvarez et al. 2011] [Mejia & Brouwer, 2018]	1.0%
Aviation	Application	7.8	3.0%		

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Leakage source process	Category	Scale (Mt)	2050 high-leakage center case	References	2050 low-leakage center case
Shipping	Application	2.9	2.3%		1.0%
Refineries	Application	8.4	0.5%		0.2%
Buildings	Application	16.2	0.8%	[Fischer et al. 2018]	0.5%
Other industries	Application	28.3	0.5%		0.2%
Miscellaneous	Application	23.2	0.5%		0.5%
Pipeline transport and storage	Delivery	143.1	2.0%	[Panfilov, 2015] [US DOE targets, 2022]	1.0%
Pipeline local distribution	Delivery	76.5	0.4%	[Weller et al. 2020] [Mejia & Brouwer, 2018]	0.2%
Truck transport and storage	Delivery	55.9	5.0%	[US DOE, 2017] [Petipas, 2018]	2.5%
Direct use on site	Delivery	252.4	0.2%	[Panifilov, 2015] [Mejia & Brouwer, 2018]	0.2%

Note: Based on 2020 reference.

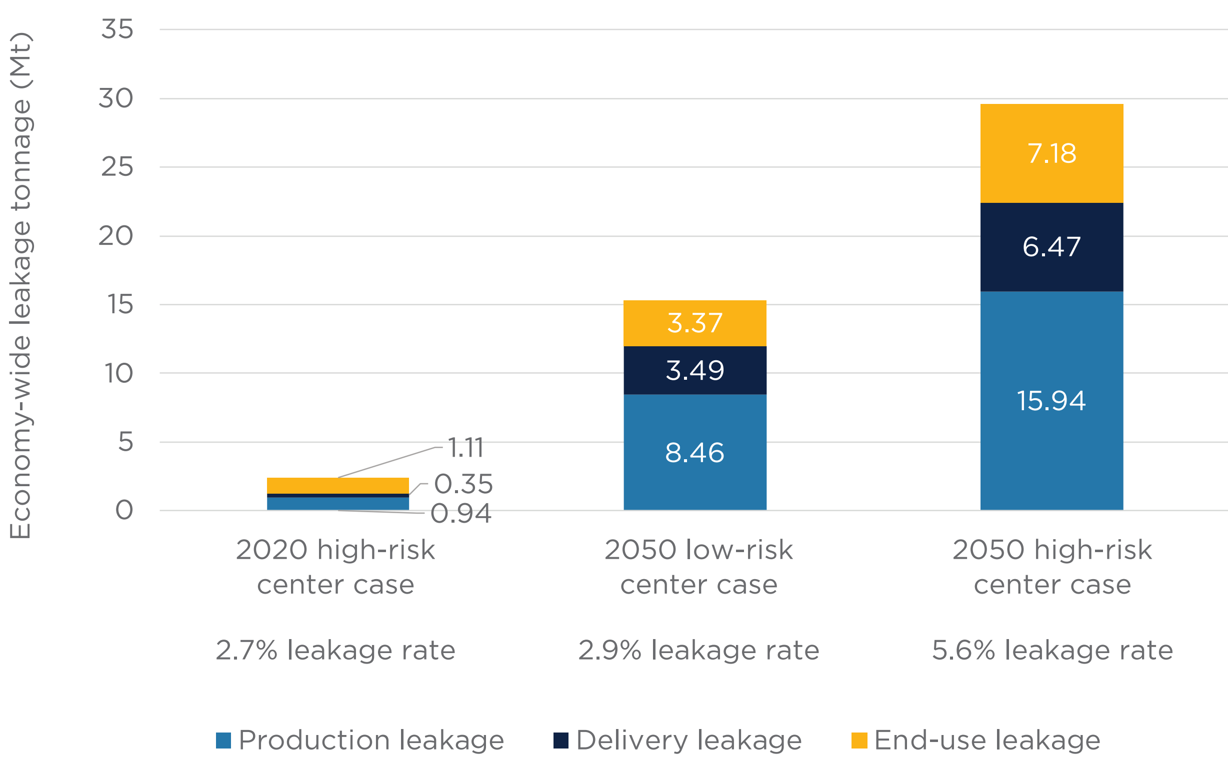
Table 1 summarizes the hydrogen leakage rates reported in the existing literature. Most of this literature cannot be cross-referenced, so some results were extrapolated from comparisons with similar technologies. Given that data on industrial facilities is missing, the leakage rate is assumed to be 0.5 percent. Production and delivery leakage are better understood than end-use leakage, data on which is largely absent. Table 1 enables a coarse estimate of the economy-wide hydrogen leakage rate by multiplying the hydrogen scale (tonnage) and the associated leakage rate (percentage). The summarized leakage rates are for the current situation (2020) and are used as a basis for estimates concerning the high-risk case by 2050, which assumes that the hydrogen leakage rates will not drop over the next three decades (i.e., the leakage rate will remain the same). Another set of leakage rates for the 2050 low-risk case is assumed to represent the technical/regulatory improvement (generally divided by two), leading to a lower risk compared with 2020.

Economy-Wide Leakage Risk Summary

Figure 2 shows the results for economy-wide hydrogen leakage in terms of both tonnage (Mt) and percentage (of total hydrogen produced). The total economy-wide leakage for 2020 is estimated to be 2.4 Mt or 2.7 percent. This relatively low result is driven by both the scale of hydrogen demand (approximately 90 Mt/yr) and a generally small leakage rate assumption for industrial end uses.

The 2050 economy-wide leakage rate and total tonnage amount are higher than those for 2020 because the scale of the hydrogen economy will be much broader (528 Mt/yr), and certain leaky processes will be more widely used (if they were used at all) than they were in 2020 (see Figure 1). The leakage rate stands between 2.9 percent (low-risk case) and 5.6 percent (high-risk case), and the total leakage volume stands between 15.3 Mt and 29.6 Mt. This can represent a non-negligible contribution to global warming and up to a $59 billion/yr value loss of hydrogen (assuming $2/kg-$H_2$).

Figure 2 : Economy-wide hydrogen leakage by process, 2020 and 2050



Source: Authors' models.

Detection, Monitoring, and Prevention Technologies

Hydrogen sensors, leak detection, and other safety infrastructure and techniques are still not at the scale of commercial production required to cover desired application scenarios. As the market has begun to adapt to meet new demands for hydrogen use, however, several technologies have been developed or are being refined to meet the challenge of fast, reliable hydrogen leakage detection across a range of production and fueling environments.

Table 2: Performance targets for hydrogen sensor development

Target	Dynamic range	Detection limit	Response /recovery time	Accuracy	Power consumption	Lifetime	Ambient temperature	Ambient pressure	Ambient humidity
Unit	*Volume %*	*Volume %*	*Seconds*	*%*	*Watts*		*°C*	*Kilopascals*	*%*
Stationary	≤ 4	≤ 4	< 30 / < 30	± 10	n/a	3 to 5 years	-50 to +50	80 to 110	20 to 80
Automotive	≤ 4	0.1	< 1 / < 1	± 5	< 1	6,000 hours	-40 to +85	62 to 107	0 to 95

Source: US Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office, "Multi-Year Research, Development, and Demonstration Plan," section 3.7: Hydrogen Safety, Codes and Standards, 2015, https://www.energy.gov/sites/default/files/2015/06/f23/fcto_myrdd_safety_codes.pdf, cited in Iwan Darmadi, Ferry Anggoro Ardy Nugroho, and Christoph Langhammer, "High-Performance Nanostructured Palladium-Based Hydrogen Sensors—Current Limitations and Strategies for Their Mitigation," American Chemical Society Sensors 5 (November 2020): 3306–3327, https://pubs.acs.org/doi/10.1021/acssensors.0c02019.

Some of the simplest and most effective methods of hydrogen detection (detection tape and smart coatings) have been developed over the past few decades with input from several research and engineering institutions. The National Aeronautics and Space Administration (NASA), one of the largest consumers of liquid hydrogen in the US, uses hydrogen extensively in its space shuttle program as a rocket propellant and to operate electricity-generating fuel cells. A leak in the space shuttle *Endeavor* in 2007 led to research and development on chemochromic tape. Patented in 2014, this new technology changes colors in less than three minutes and at concentrations as low as 0.1 percent hydrogen in the air (Granath 2015), well below the combustion threshold of 4 percent (Darmadi, Nugroho, and Langhammer 2020).

Further research into detection tape and smart coatings has ensued through public-private research partnerships with the support of the US DOE Hydrogen and Fuel Cell Technologies Office and NREL. Made of a silicone base, the chemochromic detection tape relies on partial oxidation of a transition metal oxide, resulting in a change in color in the presence of hydrogen. The tape can be readily used on flanges, welded seams and joints, rigid pipelines, and flexible tubing, as well as in indoor and outdoor hydrogen fueling stations and production facilities. Though lab testing is ongoing, the tape has been shown to respond under conditions of continually changing temperatures and humidity and to be UV resistant (US DOE 2016).

A similar technology is a thin film, vacuum-deposited pigment that changes color and resistance in the presence of hydrogen and can be used with wireless radio-frequency identification sensors for remote detection. Testing of this technology is likewise ongoing, but preliminary results indicate that it has a slightly faster response time and a slightly less durable pigment coating (Lee et al. 2015).

The preceding discussion alludes to several key considerations in developing hydrogen-sensing technologies: What is the precise concentration of hydrogen required for detection to occur? What ambient conditions are necessary in terms of temperature, humidity, and background gas composition? What is the working lifetime of the sensor technology?

Other methods and devices are also in use, including thermal conductivity, semiconducting oxides, ultrasonic physical principles, and drive hydrogen detection. These technologies may have potentially longer working lifetimes but require skilled operators or continual maintenance and upkeep to function properly.

A solid-state sensor has been developed that is capable of continuous monitoring and assessment of a cumulative, yearly leakage rate. Consisting of a metal hydride thin film and a microelectromechanical system (MEMS) structure with a palladium-nickel capping layer, this technology has demonstrated subsecond response times to 0.25 percent hydrogen in air and sensitivity to hydrogen concentrations below 200 parts per million (ppm) (DiMeo et al. 2006). Over the past decade, optical gas imaging cameras have come into use for leak detection, and hydrogen applications are being tested. Generally, CO_2 is added to the hydrogen as a tracer gas in concentrations of less than 5 percent, after which the camera visualizes the leaking tracer gas at its source as the leak occurs (Beynon 2015). This technology is useful in outdoor applications, but factors such as dispersion conditions, wind direction/speed, plume polarity, ambient temperature, and background complexity can affect the accuracy of the camera detection and must be considered (Zeng and Morris 2020).

MEMS are currently used to detect hydrogen leaks from electronic products such as mobile phones with a detection limit of 10–500 ppm (Darmadi, Nugroho, and Langhammer 2020). This low detection limit could have implications for the immediate detection of leaks in production facilities if the technology could be transferred to and applied in industrial facilities on a large scale. Nanostructured palladium transducer materials are capable of very high sensitivity and fast detection for hydrogen-air mixtures, but more research is needed to bring them into the consumer realm.

Pellistor sensors, which come in two subtypes (catalytic and thermal conductivity), use the differential resistance of ceramic pellets to determine changes in gas concentrations. Coated with supported palladium, these sensors have been used to detect hydrogen at levels of 0.1–2.0 percent in the air at atmospheric pressure, though the accuracy of their response is reduced when the pellistor overheats (Jones and Nevell 1989). Like other more complex hydrogen leakage technologies, pellistor sensors represent a promising area but will need more testing under controlled conditions before they can be applied widely in commercial settings.

Other notable technologies include electrochemical sensors that use a liquid electrolyte, mass spectrometers, and gas chromatographs. These tend to be affected by varying temperatures or have long response times that may make them challenging to use in commercial settings, but research is ongoing. For indoor applications in places such as storage areas, portable, handheld hydrogen gas sensors offer ease of use and have been demonstrated to detect hydrogen at a minimum of 550 ppm (Mandelis 2013).

Review of Current Regulations

Production, Transportation, Delivery, and Storage of Hydrogen

In 2020, several countries with ambitious decarbonization goals and a desire to be part of the global hydrogen market announced new national hydrogen strategies. These strategies are currently outpacing the development and enforcement of hydrogen-specific regulatory frameworks and policies (e.g., safety codes and protocols, infrastructure standards, best practices, and certifications) for the production, transportation, storage, and use of hydrogen.

Although international standards for hydrogen use have been developed by the International Organization for Standardization, the International Electrotechnical Commission, and the European Industrial Gases Association, most of the countries that have announced national hydrogen strategies and roadmaps lack comprehensive and robust regulatory frameworks and oversight bodies to support their transition to hydrogen economies. A summary of the existing landscape of hydrogen regulations in major hydrogen markets can be found in the appendix (see Table A1).

Notably, South Korea and Japan were first movers in the nascent global hydrogen market back in 2017. South Korea holds the additional distinction of introducing the world's first "hydrogen law" (Economic Promotion and Safety Control of Hydrogen Act 2021) to support its domestic and international hydrogen ambitions. In the United States, both public and private sector stakeholders are looking to the Federal Energy Regulatory Commission (FERC), Pipeline and Hazardous Materials Safety Administration (PHMSA), Department of Energy (DOE), and state and local regulators to lay the regulatory groundwork for a well-functioning national hydrogen ecosystem.

Countries seeking to develop well-rounded hydrogen economies—such as Finland, Norway, and Spain—will need to expand their existing (gas) regulatory frameworks to include hydrogen, while others such as Belgium, Chile, France, Germany, Morocco, and the United Kingdom will need to propose new laws and policies to accommodate their hydrogen goals. Despite several encouraging developments in some European Union (EU) countries and sectors, the EU as a whole lacks a comprehensive regulatory system to attract the requisite financing for establishing an EU-wide hydrogen economy as part of meeting the EU's ambitious 2050 decarbonization goals. Developing this system will require a massive, well-coordinated effort. Other countries aspiring for regional or global hydrogen dominance—such as Australia, China, Denmark, India, Mexico, Russia, Saudi Arabia, and the United Arab Emirates (UAE)—will need to develop dedicated hydrogen laws, bodies, and policies to provide the necessary oversight for pilots, demonstrations, hydrogen hubs, and the full-scale production, transportation, storage, and application of hydrogen, in addition to careful monitoring of hydrogen leakage.

Presently, with very few exceptions, most aspiring leaders of the emerging global hydrogen market lack the dedicated legislation, regulatory frameworks, and internationally recognized standards to be considered best in class in the global hydrogen economy.

Findings and Recommendations

Finding 1: There is almost no data on and regulation of present hydrogen leakage rates and risks beyond required safety management. Hydrogen leakage data is not available for many industrial production and application processes. Most sources are not cross-referenced for those processes where leakage data is available but are rather simulation based and sometimes extrapolated from similar studies. Moreover, the data does not include device-level analysis and therefore cannot support bottom-up analysis, which is the typical way of assessing economy-wide, aggregated leakage rates. The current literature does not provide a clear understanding of the actual status of hydrogen leakage today.

Finding 2: Few technologies are available for hydrogen leakage detection and monitoring. Few commercial products have been identified to support hydrogen leakage detection, a step that is essential to fully understanding the current and future situation. This market shortage is partially due to lack of regulation: many countries have not developed dedicated legislation and regulatory frameworks for hydrogen production, transportation, storage, and end use, including in regard to hydrogen leakage monitoring. The need for more commercial products may be exacerbated by the expansion of the hydrogen economy, especially distributed sources such as fueling stations, fuel-cell vehicles, and end-use appliances.

Finding 3: Hydrogen leakage seems to be concentrated in a few key processes. By 2050, green hydrogen production, transportation, and storage (both pipeline and trucks); road transport vehicles; electricity generation; and chemical synthetic fuel production are expected to become the major sources of leakage. Together, they would contribute 77 percent of economy-wide hydrogen leakage. The main reasons for this large contribution are their broad scale (chemical and synthetic fuels production), high leakage risks (road transport vehicles, truck transportation, and storage), or both (green hydrogen production and pipeline transportation and storage).

Finding 4: Initial analysis suggests an increased risk of higher economy-wide hydrogen leakage rates in the future chiefly from new production and delivery expansion. Many key leakage processes for 2050 scenarios do not exist in the current hydrogen system. With the expansion of the hydrogen economy, the scaling up of production/use and deployment of new processes will increase the chance of leakage and therefore risk levels. The 2050 high-risk scenario will lead to a 5.6 percent economy-wide leakage rate. In short, hydrogen leakage is expected to be a challenge for the hydrogen economy.

Recommendation 1: Develop research and data-gathering programs to better understand the existing hydrogen systems. A lack of understanding of the current hydrogen system and the significance of leakage prevents the development of realistic solutions and appropriate regulations. The current hydrogen system is mostly based on industrial production and applications, and the research and data gathering on leakage that is required will likely be impossible without support from industrial partners. In order to understand and rigorously estimate the scale of hydrogen leakage, new regulations and policies should emphasize hydrogen leakage detection.

Recommendation 2: Require monitoring programs for new hydrogen pilots and scale up programs to assess the leakage risk of new processes. In the future, the real leakage risk will likely be new processes such as green hydrogen production, fuel-cell vehicles, and dedicated hydrogen deliveries. If the goal is to address this potential leakage, monitoring programs will need to be implemented for all new processes at the production, delivery, and end-use stages. Active control of these processes through regulations and policies before they scale up can help reduce risks and potential economic losses associated with the future hydrogen economy.

Recommendation 3: Devote special attention to certain key processes that demonstrate potential to be scaled up or to address high leakage risks. Based on the available data at this stage, it is estimated that a handful of processes identified in Finding 3 would contribute to an estimated 77 percent of total hydrogen leakage in the 2050 scenarios. Significant resources have been dedicated to scaling up the production and use of hydrogen but not to controlling leakages in the process. To the extent that leakage estimates are confirmed and leakage is concentrated around key processes, research on leakage prevention and regulations for a few key processes will have greater impact than that for others if the goal is to effectively reduce overall hydrogen leakage.

Recommendation 4: Expand support for research and development programs on hydrogen leakage detection, prevention, and mitigation. There is insufficient research on how to prevent and mitigate hydrogen leakage. Moreover, the commercial products that currently exist for this purpose do not meet the requirements of device level, high sensitivity, and distributed small hydrogen leakage source detections. If the goal is to develop a thriving hydrogen economy without hydrogen leakage, research and development funding should be prioritized for hydrogen leakage detection, prevention, and mitigation, with special attention dedicated to bringing technologies currently at the research level to the commercial level.

Appendix

Table A1: Current regulations for the production, transportation, delivery, and storage of hydrogen

Country	Regulation(s) (Y/N)	State of regulation(s)
Australia	N	To support an emerging hydrogen market, Australia will need to expand its current gas definitions regarding quality and value within both the Australian Gas Supply Act and the National Gas Law, neither of which explicitly references hydrogen. The Australian government and ministries will also need to collaborate with international regulation, codes, and safety standards organizations (such as the International Association for Hydrogen Safety and the Center for Hydrogen Safety) to develop responsive regulations (guidelines, procedures, and training materials for the production, handling, transportation, and use of hydrogen). In 2020, the Australian government was planning to apply the National Gas Law and relevant jurisdictional laws and regulations to determine the safe upper limits on the volume of hydrogen allowed to be blended in gas networks and to support hydrogen safety (e.g., Safe Work Australia) and state-based safety agencies for oversight (Bruce 2018, 74; COAG 2019, 32, 43, 50).
Austria	N	Austrian law does not include any specific regulations regarding the construction and operation of hydrogen production plants. If the country seeks to support a hydrogen economy, it will need to expand its existing laws and licenses on a case-by-case basis. To ensure legal certainty for investors, the Austrian government should assign hydrogen to the Natural Gas Tax Act (*Erdgasabgabegesetz*, Federal Law Gazette I 1996/201, as amended) and create tax concessions to promote non–fossil fuel sources (Selenic 2021; Rajal and Schneider 2020, 14).
Belgium	Y (limited)	Hydrogen presents a promising opportunity for Belgium to decarbonize its energy mix by integrating it into its hard-to-abate sectors (ammonia, steel production, refineries, and industrial heat) and developing it as a low-carbon energy carrier through the country's maritime ports and methane infrastructure. To take advantage of this opportunity, Belgium will need to adapt and define its legislative framework for hydrogen transport and distribution projects (Trinomics and LBST 2020, 10–12).
Canada	N	Canada lacks a comprehensive national policy and regulatory framework (including codes and standards) for hydrogen that can encourage investment in the production, transportation, storage, and use of hydrogen and low-carbon hydrogen technologies for pilots, commercial end use, etc. and allow for decarbonization by 2050 (Ministry of Natural Resources Canada 2020, xvii, 97–98).
Chile	Y (limited)	Chile's current regulatory framework and standards are not adequate for safe applications of hydrogen across the value chain per its national hydrogen strategy. As a "flammable gas," hydrogen is presently classified by Chile as a "dangerous substance" (Supreme Decree No. 43), and Decree-Law 2,224 12 grants the Chilean Ministry of Energy regulatory powers for the hydrogen industry. Chile's 2020 National Green Hydrogen Strategy only lays out the proposed next steps for standards, piloting, and safety, but much remains to be done to develop a cohesive and

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Country	Regulation(s) (Y/N)	State of regulation(s)
Chile (cont'd)	Y (limited)	coordinated regulatory development plan (Correa et al. 2020, p. 26). In February 2022, the Chilean government published its Safety Regulation for Hydrogen Facilities, (per Supreme Decree No. 13) establishing the minimum safety requirements for hydrogen facilities for energy purposes (Government of Chile 2022). This is the first regulation to emerge from Chile's detailed regulatory strategy for hydrogen, including rules for transportation, industrial vehicles, combustion appliances, dual electric generators, and dispensing stations (German Agency for International Cooperation 2020). Additionally, Chile's National Congress is currently discussing a bill that would establish a hydrogen blending mandate in the country's gas network by 2030 (Cámara de Diputados de Chile 2021). If Chile wants to meet large-scale demand for the domestic production of hydrogen as part of the country's clean energy transition, it will need to adapt existing national gas regulations and infrastructure (in conjunction with the Ministries of Mining and Environment as well as the Office of the Superintendent of Electricity and Fuels).
China	N	In March 2022, China, the world's largest hydrogen producer, released its first long-term hydrogen plan via its National Development and Reform Commission. The 14th Five-Year Plan (2021–2025) also featured a phased approach to developing the country's domestic hydrogen industry. In an effort to scale up production of low-carbon hydrogen, China is seeking to address existing gaps in technical expertise and infrastructure. The national plan contains provisions for developing rules for governance, infrastructure plans, innovations (pilots), and codes and standards (Nakano 2022; Yin 2022).
Denmark	N	In 2021, the Danish Energy Agency waived energy regulatory compliance requirements for two Power-to-X specialists developing hydrogen projects (Bellini 2021). If Denmark aspires to foster a well-rounded hydrogen economy, the Danish Ministry of Climate, Energy, and Utilities as well as the Danish Energy Agency need to make significant revisions to existing regulations pertaining to energy, electricity, infrastructure, and transportation (Trinomics and LBST 2020, 26).
European Union	Y (Intermediate)	The European Union has set ambitious targets for fully decarbonizing its energy system by 2050 via the Green Deal, the European Climate Law, the EU sector integration strategy, and the Fit for 55 plan (cutting emissions by at least 55 percent by 2030). In 2020, it launched its Hydrogen Strategy for a Climate-Neutral Europe to accelerate the rollout of Europe's hydrogen economy. It also announced the European Clean Hydrogen Alliance addressing the production, transmission and distribution, and industrial, mobility, energy, and residential applications of hydrogen. In December 2021, the European Commission announced a tripart "hydrogen and decarbonized gas package" with three key proposals to boost the production, storage, and transportation of hydrogen and renewable gases in new or existing gas networks: (1) a recast regulation for EU gas and hydrogen markets, (2) a recast directive on EU gas and hydrogen markets, and (3) a wholly new regulation to reduce methane emissions in the EU energy sector. Currently, there are approximately 20 Mission Innovation Hydrogen Valley projects in the EU and the United Kingdom), in addition

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Country	Regulation(s) (Y/N)	State of regulation(s)
European Union (cont'd)	Y (Intermediate)	to plans for small, local hydrogen hubs to kick-start an EU-wide hydrogen economy and decarbonize hard-to-abate sectors. However, the EU still needs to design and impose a legal framework for cross-border hydrogen networks and introduce new definitions for renewable gases and hydrogen in its recast EU Gas Directive (Wilson 2022, 5). As part of the March 2022 REPowerEU strategy, the EU announced its Hydrogen Accelerator, which foresees around 20 Mt of renewable hydrogen consumed by 2030, including 10 Mt of imported hydrogen and 10 Mt of European-produced hydrogen.
Finland	Y (beginning stages)	In 2020, Finland announced its National Hydrogen Roadmap as part of achieving its national goal of carbon neutrality by 2035. Although Finland has a "stable, predictable regulation framework," it has yet to develop regulations to repurpose its existing natural gas pipeline infrastructure, develop and communicate safety and security regulations, and investigate storage solutions. (Finland lacks natural storage formations such as salt caverns.) To date, Finland has only approved short-term regulations to accommodate the use of hydrogen in Power-to-X applications; it has not yet developed comprehensive regulations for economy-wide hydrogen production, storage, transport, and end use (Laurikko et al. 2020, 4).
France	Y (limited)	France recently issued an ordinance that establishes a legal framework for the use of hydrogen as a fuel. Law-Decree No. 2021-167 details the definitions of hydrogen for the French Energy Code, establishes the regulatory framework for the traceability of renewable and low-carbon hydrogen, and highlights policies and mechanisms to encourage investment and production that support France's 2030 clean energy transition goals. The ordinance also expands the oversight and monitoring authority of the French government in the electricity and gas sectors to cover hydrogen and extends the legal framework in the French Mining Code for underground hydrogen storage. France still lacks precise regulations for the transportation and distribution of hydrogen for various end uses (Bontemps et al. 2021; Lazerges and Sauzay 2020).
Germany	Y (Intermediate)	Germany was the first EU country to announce dedicated regulations for midstream hydrogen. In 2021, the German parliament introduced transitional regulations for hydrogen transportation networks. Per section 113(b) of Germany's Energy Act (2021), transmission system operators may identify gas pipelines that could be converted to hydrogen pipelines in the framework of Germany's Gas Network Development Plan. An independent network development plan for hydrogen networks is supposed to be drawn up by 2035. While Germany has rules for blending hydrogen in natural gas pipelines, it has yet to announce regulations (and thus provide legal certainty to investors and operators) for a pure hydrogen grid infrastructure (Tholen et al. 2021).
India	N	India launched a new green hydrogen policy following the announcement of its 2021 National Hydrogen Energy Mission (5 Mt of green hydrogen by 2030). However, it has yet to develop comprehensive national regulations, codes, and infrastructure and workplace safety standards governing hydrogen production, transportation, storage, and use, all of which are critical to its effort to fulfill its energy demands and meet its energy security goals (WRI India 2021; Chenoy 2009).

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Country	Regulation(s) (Y/N)	State of regulation(s)
Italy	Y (limited)	Italy's 2020 hydrogen strategy (Preliminary Guidelines on the National Hydrogen Strategy) outlines the country's goal to establish a national hydrogen ecosystem that can meet 2 percent of demand by 2030 and 20 percent by 2050. However, Italy's lack of a robust, comprehensive regulatory framework and national codes and standards for industry may impede it from fully developing a green hydrogen ecosystem (Government of Italy 2020; IPHE 2022).
Japan	Y	Japan was one of the first countries to announce a national hydrogen framework to decarbonize its economy back in 2017. The country currently regulates hydrogen through its High Pressure Gas Safety Act (No. 204 of June 7, 1951) but has yet to announce a regulatory framework and safety codes for a pure hydrogen economy. Japan also recognizes the need for greater public acceptance of hydrogen use and safety in the country (METI 1951; METI 2017).
Mexico	N	Mexico does not have a comprehensive and consistent regulatory framework for the hydrogen value chain as well as safety standards, codes, and permits. Although the Mexican Constitution makes no explicit mention of hydrogen regulation, the country has issued the "Mexican Standards" (Norma Oficial Mexicana [NOM]), specifically NOM-018-STPS-2015, which regulates hydrogen as a "hazardous substance" in the workplace, and NOM-017-CRE-2019, which sets minimum measurement requirements and methodologies to ensure compliance with "clean energy" thresholds for power plants using hydrogen. To help realize its goal of forging a well-governed hydrogen economy, Mexico will need to introduce dedicated hydrogen-centric regulations pertaining to hydrogen transportation as well as a hydrogen regulatory body (Woodhouse and Tellez 2021).
Morocco	Y (limited)	Morocco has announced both a national green hydrogen roadmap and a hydrogen strategy and has partnered with the International Renewable Energy Agency to facilitate the country's renewable hydrogen economy as part of its quest to become a major green hydrogen producer and exporter. However, the country lacks specific regulations around the production, transportation, storage, and use of hydrogen (Burgess, Elliott, and Edwardes-Evans 2021; Torres and Perner 2021; Bentaibi and Benoit 2021).
Norway	Y (beginning stages)	Norway's existing legal and regulatory framework covers aspects of hydrogen production, transportation, storage, and use, but if the country wants to support the development of the kind of hydrogen economy envisioned in its hydrogen strategy, it will need to expand its current laws and policies (pp. 20–24). Presently, hydrogen safety concerns are covered under various provisions of the Regulation on Carriage of Dangerous Goods by Road, the Regulation on the Handling of Dangerous Substances, the Regulation on the Pressure Equipment, the Regulation on Major Accidents, and the Regulation on Health and Safety in Explosive Atmosphere, but they may need to be codified within hydrogen-specific ordinances.

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Country	Regulation(s) (Y/N)	State of regulation(s)
Portugal	Y	In August 2020, Portugal's national energy sector regulator Entidade Reguladora dos Serviços Energéticos amended its Natural Gas Act legislation (via Decree-Law No. 62/2020) to include hydrogen production and the injection of hydrogen into the country's natural gas distribution grid. For Portugal to fully achieve a carbon-neutral economy by 2050, it will need to adapt its regulatory frameworks significantly, per Stage II (adopting the regulatory framework) and Stage III (strengthening the regulatory framework) of its national hydrogen strategy EN-H_2 (Cabrita 2021; CSIRO 2020; Republic of Portugal 2020).
Russia	N	Russia's hydrogen roadmap (2020–2024) outlines steps and timelines for eight areas, including regulatory development, and lists tasks to be carried out between 2021 and 2023. The roadmap lists specific agenda items such as identifying laws and regulations for the production, storage, transportation, and use of hydrogen, safety codes, and GHG emission tracking (Barlow and Tsafos 2021; Josefson and Rotar 2020). It does not, however, clearly identify or designate responsibility to specific entities (e.g., the Ministry of Energy) for developing Russia's hydrogen economy or delineate a hierarchy for execution. Thus, Russia has a long way to go before it can realize its plan of becoming a world-leading producer and exporter of hydrogen.
Saudi Arabia	N	Although Saudi Arabia announced a national hydrogen strategy to be launched in 2022, it currently has no official institutional framework, regulations (safety standards, technical codes, etc.), or formal governance for hydrogen projects (Hamra-Krouha et al. 2021, 2; Anouti et al. 2020, 11).
South Korea	Y	South Korea was an early mover in the hydrogen space, passing the world's first hydrogen economy law in 2021 (Economic Promotion and Safety Control of Hydrogen Act) for the "development of an ecosystem for a hydrogen economy and expanded public access to the alternative fuel" (Byung-wook 2021). This act is the central piece of legislation regulating the country's hydrogen industry (production, pricing, transportation, and safety) and covers hydrogen vehicles, charging stations, and fuel cells. In regard to safety, it establishes checks and balances for hydrogen equipment, including but not limited to technological safety at the design stage, on-site examination of facilities, and annual safety checks.
Spain	Y (beginning stages)	In 2020, Spain launched its hydrogen roadmap identifying "challenges and opportunities for robust development of renewable hydrogen in Spain." This roadmap is a complement to the goals and activities outlined in the key documents defining Spain's national climate strategy—the National Integrated Energy and Climate Plan (PNIEC) 2021–2030, the Draft Law on Climate Change and Energy Transition (PLCCTE), the Long-Term Decarbonization Strategy 2050, the Fair Transition Strategy, and the Energy Storage Strategy. However, Spain has a long way to go to develop hydrogen-specific regulatory bodies, laws, codes, and certifications (well beyond the EU's International Carriage of Dangerous Goods by Road regulations).

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Country	Regulation(s) (Y/N)	State of regulation(s)
The Netherlands	Y (limited)	The Dutch Ministry of Economic Affairs and Climate Policy currently lacks a comprehensive legal framework for regulating a hydrogen economy (production, transportation, storage, and use) per the goals of its 2020 National Hydrogen Strategy (van der Meer 2019). In 2020, however, it did launch its four-year Hydrogen Safety Innovation Programme that fosters public-private partnerships involving the national government, network operators, emergency services, knowledge institutes, and companies (Ministerie van Economische Zaken en Klimaat 2020).
Turkey	N	Currently, Turkey's Ministry of Energy and Natural Resources lacks both specific regulations for the production, transportation, and storage of hydrogen and regulatory bodies overseeing the construction, development, and management of hydrogen projects (Saygin and Sanli 2021).
UAE	N	The UAE unveiled its Hydrogen Leadership Roadmap in 2021 with the goal of capturing 25 percent of the global low-carbon hydrogen market by 2030. Although the UAE does have draft technical regulations for hydrogen-powered vehicles, it does not have stand-alone, comprehensive regulations or safety standards for a hydrogen economy. However, the UAE has pledged to develop regulations and forge government-to-government partnerships to develop its hydrogen industry (Lin 2022).
United Kingdom	Y (limited)	To cultivate a hydrogen economy as part of its decarbonization goals, the UK needs to conduct major reviews to determine specific regulations for dedicated hydrogen infrastructure and continue to assess the (highest) percentage of hydrogen that can safely be blended in existing gas pipelines (presently at 0.1 percent) in accordance with its established Gas Safety (Management) Regulations (DBEIS 2021, 79–80; Gas Safety (Management) Regulations 1996, No. 551).
United States	Y (limited)	In the United States, the Pipeline and Hazardous Materials Safety Administration is charged with protecting people and the environment by advancing the safe transportation of energy and other hazardous materials essential to daily life. Since 1970, PHMSA has regulated nearly 700 miles of hydrogen pipelines in accordance with 49 CFR Part 192.31, which includes "flammable gas" such as hydrogen in its definition of "natural gas" (PHMSA 2022). PHMSA is working in partnership with the US Department of Energy, the US Department of Commerce, and the National Institute of Standards and Technology to develop a national hydrogen roadmap, including safety-related regulations for the production, transportation, storage, and use of hydrogen.
Ukraine	N	Ukraine's regulatory framework for hydrogen is fragmented due to the limited application of hydrogen in industry. The country's "outdated and non-harmonized regulatory and technical safety regulations" are also significant barriers to the development of a national hydrogen economy. Current regulations include TC 197 (Order of the State Enterprise "UkrNDNC" No. 130 of June 22, 2020), which covers "activities related to the design, construction, manufacture, operation of technological objects, systems and equipment, the production and use of hydrogen" (Dubko 2021, 6, 89, 100–101).

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