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Review of Hydrogen Leakage along the Supply Chain:

Environmental Impact, Mitigation, and Recommendations for Sustainable Deployment

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Abstract

Hydrogen is recognized as a pivotal element in the shift toward a low-carbon economy, presenting a clean energy alternative for sectors that are particularly challenging to decarbonize. Nevertheless, hydrogen's efficacy as a sustainable solution faces constraints due to the potential environmental impacts linked to leakage across its supply chain—from production through to end-use. This paper offers a detailed review of hydrogen leakage rates, examines technological and regulatory measures aimed at minimizing leakage, and assesses the environmental implications of hydrogen release into the atmosphere.

This paper explains why even minimal hydrogen leakage can exacerbate climate change by prolonging the atmospheric presence of methane and modifying ozone levels, thus producing indirect global warming effects. Addressing these issues necessitates a comprehensive approach encompassing investment in advanced containment materials, improved leak detection systems, retrofitting of existing infrastructure, and stringent regulatory standards. Policy incentives that encourage low-leakage technologies, alongside industry training initiatives, are also essential.

Implementing these mitigation strategies will enable stakeholders to reduce the potential environmental risks of hydrogen leakage. Indeed, effective management of hydrogen leakage is critical to ensuring that this clean energy carrier realizes its potential in reducing greenhouse gas (GHG) emissions, contributing to overarching goals of sustainability and climate resilience.

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1. Introduction

The urgent imperative to address anthropogenic climate change has heightened global focus on low-carbon energy carriers, with hydrogen seen as central to decarbonization strategies. The International Energy Agency (IEA) projects that hydrogen could meet up to 10% of global energy demand by 2050, leveraging its carbon-free combustion, versatility, and integration with renewable energy systems[1]. Unlike traditional fossil fuels, hydrogen produces only water upon combustion, making it an optimal energy source for sectors such as steel, cement, and chemicals—industries that are both carbon-intensive and foundational to economic growth[2]. Together, these sectors account for nearly 30% of global CO_2 emissions, and their dependence on high-temperature processes and fossil fuels presents substantial decarbonization challenges[3].

However, hydrogen's role as an energy carrier introduces unique challenges throughout its supply chain. Its handling and storage are complicated by properties such as high diffusivity, low molecular weight, and a broad flammability range, all of which elevate the risks of leakage and introduce significant safety and environmental concerns[4,5]. Although considered as a clean energy carrier, due to hydrogen's smaller molecular size compared to methane, the environmental impact of hydrogen leakage in improperly retrofitted natural gas infrastructures could be comparable, raising concerns over unintended emissions during transport and storage[6,7]. Research by Cooper et al. (2022) indicates that hydrogen leakage can indirectly contribute to greenhouse effects by extending methane lifetimes and increasing tropospheric ozone, thereby amplifying global warming through enhanced radiative forcing[8]. The long-term impact of hydrogen on atmospheric chemistry highlights the critical need for robust leakage mitigation strategies across hydrogen supply chains[9].

Establishing effective hydrogen supply chains requires thorough assessment and mitigation of hydrogen leakage rates across diverse production, storage, and transportation configurations. Research by Swain and Swain (1992) revealed that hydrogen leaks approximately three times faster than methane under comparable conditions due to its higher diffusion coefficient, impacting leak dynamics in both residential and industrial environments[10]. While extensive research exists on hydrogen production technologies, studies that consolidate and compare leakage rates across different supply chain segments—such as liquid hydrogen (LH_2) storage, compressed gas, and underground storage—remain limited.

Along the supply chain, hydrogen leakage is a persistent item that deserves an overarching consideration. Downstream, controlling leakage is essential in hydrogen-fuelled applications such as mobility solutions utilizing hydrogen fuel cell technology. Computational fluid dynamics (CFD) simulations by Song et al. (2024) indicate that confined spaces with elevated hydrogen concentrations in fuel cell vehicles pose notable ignition and explosion risks[7]. Moving upstream, Ratnakar et al. (2021) identified challenges in storing liquid hydrogen, where the ultra-low temperatures required for liquefaction (-253°C) necessitate advanced insulation technologies to prevent boil-off and minimize leakage during transport and storage[6]. In effect, without effective containment, hydrogen leakage at any stage of the supply chain could negate the environmental benefits of hydrogen—a leak would indirectly contribute to enhancing the greenhouse gas (GHG) effect[2].

This paper's objectives are to comprehensively review hydrogen leakage across different supply chain configurations, evaluating the current leakage mitigation solutions, and assessing the environmental impacts of hydrogen leaks along the supply chain. While analyses for hydrogen deployment in various

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[1] IPCC, "Climate Change 2022: Mitigation of Climate Change," IPCC, 2022.
[2] Ocko, I. B., & Hamburg, S. P., "Climate consequences of hydrogen emissions," *Atmospheric Chemistry and Physics*, 22(14), 2022.
[3] Azadnia, A. H., McDaid, C., Andwari, A. M., & Hosseini, S. E. (2023). *Renewable and Sustainable Energy Reviews*, 182, 113371.
[4] Swain, M. R., & Swain, M. N. (1992). International Journal of Hydrogen Energy, 17(10), 807-815.
[5] Mejia, A. H., Brouwer, J., & Mac Kinnon, M. (2020). *International Journal of Hydrogen Energy*, 45(15), 8810-8826.
[6] Ratnakar, R. R., et al. (2021). International Journal of Hydrogen Energy, 46(47), 24149-24168.
[7] Song, B., Wang, X., Kang, Y., & Li, H. (2024). *International Journal of Hydrogen Energy*, 83, 173-187.
[8] Cooper, J., Dubey, L., Bakkaloglu, S., & Hawkes, A. (2022). Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming. *Science of The Total Environment*, *830*, 154624.
[9] IEA (2024), Global Hydrogen Review 2024, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2024.
[10] Qin, C., Tian, Y., Yang, Z., Hao, D., & Feng, L. (2024). *International Journal of Hydrogen Energy*, 89, 1025-1039,

industrial sectors are available, focused studies on leakage mitigation remain sparse. By consolidating existing literature on hydrogen leakage, this paper aims to provide a robust foundation for stakeholders and policymakers to develop targeted strategies for safe hydrogen deployment, thereby maximizing hydrogen's potential as a sustainable energy carrier.

2. Environmental Analysis

Before examining hydrogen leakage across the various supply chain stages, it is imperative to understand the effects of unintended hydrogen release into the atmosphere.

Table 1 shows the equivalent Global Warming Potential (GWP) effect of hydrogen and other notable gases. Indeed, while hydrogen itself is not a greenhouse gas, its leakage has been shown to disrupt atmospheric chemistry, potentially offsetting some of its emissions benefits through interactions with pollutants like methane and ozone. The significance of fugitive hydrogen emissions and its environmental impact thus poses two primary concerns. On one hand, when hydrogen escapes containment, it can lead to localized site-specific hazards; while on the other, once it disperses into the atmosphere, it intensifies broader climate impacts. This paper will primarily focus on the broader atmospheric effects of hydrogen leakage. In what follows, the paper provides an account of the adverse environmental effects posed by hydrogen leakage: first, its impact on atmospheric composition; second, its role as an indirect GHG; and finally, contextualising what fugitive emissions could amount to in the future.

Table 1: GWP of selected gases over 20 and 100-year time horizons

Gas	*Chemical Formula*	*GHG Gas*	*GWP-20 (Kg Co₂-eq)*	*GWP-100 (Kg Co₂-eq)*	*Notes*
Carbon Dioxide[11]	CO_2	Yes	1	1	Baseline GWP reference gas for other greenhouse gases.
Methane[11]	CH_4	Yes	81.2	27.9	Potent greenhouse gas with a short atmospheric lifetime; primarily from fossil fuel extraction, agriculture, and biomass burning.
Nitrous Oxide[11]	N_2O	Yes	273	273	Long-lived greenhouse gas with high GWP; primarily from agricultural and industrial activities.
Hydrogen[12,13]	H_2	No	37.3± 15.1	11.6± 2.8	Impacts atmospheric chemistry, extending methane lifetime and affecting ozone formation.
Ammonia[14,15,16]	NH_3	No	~0 (producing ammonia through steam methane reforming, water-gas shift reaction, and Haber-Bosch lead to around 2.7 while renewable production is ~0)		Primarily contributes to indirect effects through particulate matter formation in the atmosphere.
Methanol[14,17]	CH_3OH	No	~0 (LCA approach shows 68.7 from coal to ~0 if made through renewable sources)		Indirect effects due to secondary organic aerosol formation and minor greenhouse gas properties.

Source: Adapted from [11,12,13,14,15,16,17]

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[11] IPCC. (2021). *Sixth Assessment Report (AR6), Working Group I, Chapter 7: Supplementary Material*.
[12] Derwent, R., Collins, W., Johnson, C., Stevenson, D., & Sanderson, M. (2023). Hydrogen's impact on climate via tropospheric chemistry: A Global Warming Potential analysis. *Communications Earth & Environment, 4*, Article 857.
[13] Derwent, R., Collins, W., Johnson, C., Stevenson, D., & Sanderson, M. (2023). *Supplementary Materials for Hydrogen's impact on climate via tropospheric chemistry*.
[14] Greenhouse Gas Protocol. (2024). *Global Warming Potential Values (August 2024)*.
[15] Tuller, M. (2022). *Life Cycle Analysis of Green Ammonia and Its Application as Fertilizer Building Block*. Ammonia Energy Association.
[16] AREA. (2011). *Low GWP Refrigerants Position Paper*. AREA European Association of Refrigeration, Air Conditioning and Heat Pump Contractors.
[17] Methanol Institute. (2022). *Carbon Footprint of Methanol: A Comparative Study*.

2.1 Hydrogen's Impact on Earth's Atmospheric Composition

Two primary pathways are observed, summarized visually in Figure 1, in which hydrogen leakage impacts atmospheric composition:

- First, by affecting atmospheric methane levels and hydroxyl radical concentrations;
- Second, by contributing to alterations in both tropospheric and stratospheric ozone.

2.1.1 Impact of Hydrogen Leakage on Atmospheric Methane and Hydroxyl Radicals

By a good margin, the primary atmospheric chemistry concern with leaked hydrogen is its effect in prolonging the life of methane in the atmosphere. Methane (CH_4)—a potent greenhouse gas with a global warming potential approximately 30 times that of carbon dioxide CO_2 over a 100-year period—is partially regulated by hydroxyl radicals (•OH), which act as an oxidative 'sink' by breaking down methane into less impactful compounds through the reaction:

$$CH_4 + OH \rightarrow CH_3 + H_2O \qquad (1)$$

Methane's reaction with OH radicals is typically favored due to a higher reaction rate constant, meaning that in most scenarios, methane will react with OH faster than hydrogen. However, when hydrogen is present in excess, as can occur in cases of growing hydrogen leakages, it begins to compete with methane for OH radicals through the following reaction:

$$H_2 + OH \rightarrow H^* + H_2O \qquad (2)$$

This competition reduces the availability of OH radicals for methane degradation, thereby prolonging methane's atmospheric lifetime. Consequently, hydrogen leakage indirectly contributes to global warming by allowing methane to persist longer in the atmosphere. As a function of scale, this hydrogen interaction with OH radicals could increase global atmospheric methane levels by 5–10% if hydrogen leakage rates reach approximately 1–2% of production volume[18].

This interaction is a major factor contributing to the indirect GWP of hydrogen. Studies have modelled scenarios under various leakage rates to estimate hydrogen's indirect warming potential due to its impact on methane. According to Goita et al. (2024), if hydrogen deployment were to reach global scales without adequate leakage controls, the methane amplification effect alone could lead to an equivalent increase in global temperature by 0.1-0.2°C over the next century[19]. In the context of international climate goals, this temperature increase poses challenges to achieving the Paris Agreement targets.

2.1.2 Hydrogen's Contribution to Tropospheric and Stratospheric Ozone Alterations

Beyond prolonging methane in the atmosphere, hydrogen leakage has additional adverse effects, particularly in the two atmospheric layers closest to us—the troposphere and the stratosphere. In the troposphere, hydrogen acts as a precursor to ozone by reacting with nitrogen oxides (NO_x), a process that can elevate ground-level ozone concentrations, especially in urban areas with high NO_x emissions. Elevated tropospheric ozone is associated with significant health risks; numerous studies link increased ozone exposure to respiratory issues, including asthma, reduced lung function, and other illnesses[20]. In agricultural regions, high ozone levels can also negatively impact crop yields and food security by reducing plants' photosynthetic efficiency[8].

Hydrogen's impact on the stratosphere, however, involves distinct mechanisms. Hydrogen that reaches the stratosphere can react to produce water vapour, which acts as a greenhouse gas at these altitudes. Increased stratospheric water vapour contributes to ozone depletion by interacting with halogen

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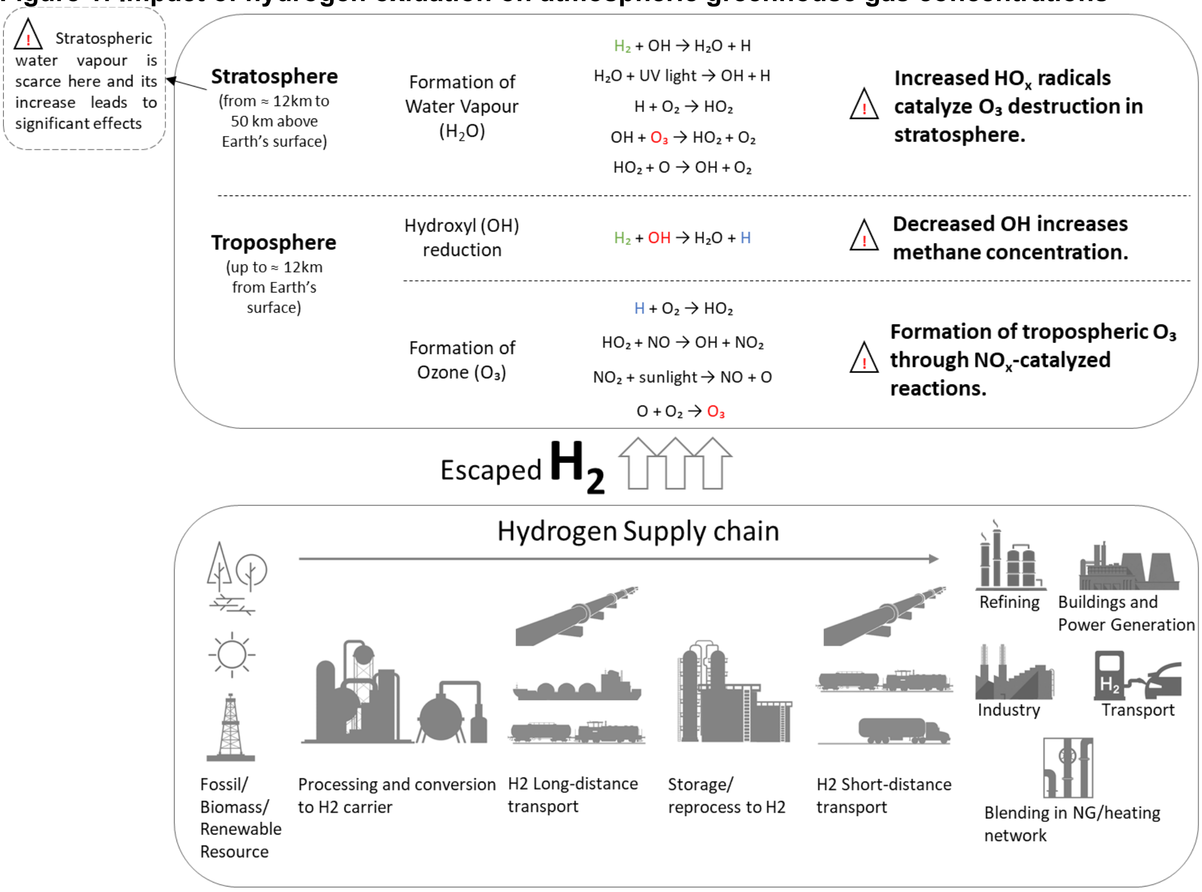
[18] Arrigoni, A., & Diaz, L. B. (2022). Hydrogen emissions from a hydrogen economy and their potential global warming impact.

[19] Goita, E., Beagle, E. A., Nasta, A. N., Wissmiller, D. L., Ravikumar, A., & Webber, M. E. (2024). Effect of Hydrogen Leakage on the Life Cycle Climate Impacts of Hydrogen Supply Chains.

[20] Donzelli, G., & Suarez-Varela, M. M. (2024). Tropospheric Ozone: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. *Atmosphere*, *15*(7), 779.

compounds. According to Arrigoni and Diaz (2022), even small rises in stratospheric water vapour can enhance the catalytic destruction of ozone molecules, weakening the stratospheric ozone layer that protects Earth from harmful UV radiation. This depletion poses additional health risks, as increased UV-B exposure at Earth's surface is linked to higher rates of skin cancer, cataracts, and other UV-induced conditions [18].

Figure 1: Impact of hydrogen oxidation on atmospheric greenhouse gas concentrations



Source: Adapted from [2,21,22]

2.2 Hydrogen as an Indirect GHG

GWP is a metric that helps us understand and compare how much different greenhouse gases contribute to global warming over specific timeframes, typically 20 or 100 years. GWP measures the amount of energy each gas can absorb and later re-emit as infrared radiation, or 'heat energy,' in the atmosphere relative to CO_2. When gases like CO_2, CH_4, or nitrous oxide (N_2O) absorb infrared radiation, they trap this 'heat energy' and release it back into the atmosphere, creating a 'direct' warming effect, or direct GWP, which contributes to the phenomenon referred to as the greenhouse effect. Certain gases, however, like hydrogen, contribute to warming in a more indirect way. While hydrogen does not absorb much infrared radiation itself, it interacts with other chemicals in the atmosphere that influence warming. For example, as mentioned earlier, as more hydrogen is introduced into the atmosphere, the less hydroxyl radicals remain to react with atmospheric methane, allowing methane to remain in the

[21] Dutta, I., Parsapur, R. K., Chatterjee, S., Hengne, A. M., Tan, D., Peramaiah, K., ... & Huang, K. W. (2023). The role of fugitive hydrogen emissions in selecting hydrogen carriers. *ACS Energy Letters*, *8*(7), 3251-3257.
[22] NASA Science Editorial Team. (2019). *Earth's atmosphere: A multi-layered cake*. NASA Science.

atmosphere for longer. This means that hydrogen, by reducing OH availability, indirectly boosts the warming impact of methane, indirectly contributing to the greenhouse effect[23].

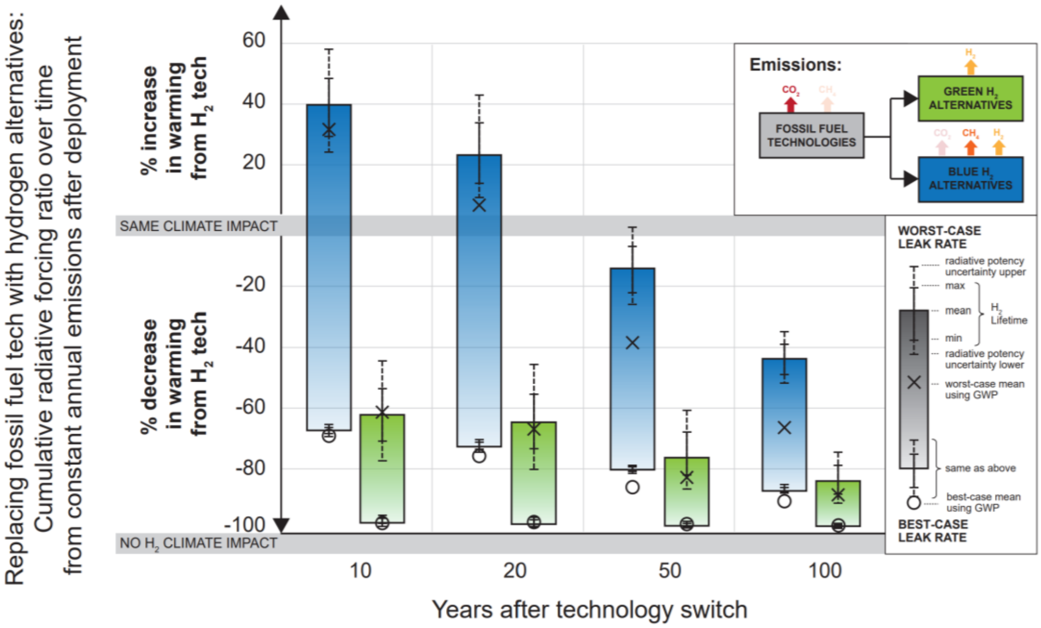
Currently, hydrogen levels in the atmosphere are about 530 parts per billion (ppb), making it the second most common reactive trace gas after methane[24]. Its sources include biomass burning and fossil fuel combustion, with around half of atmospheric hydrogen coming from the breakdown of methane and volatile organic compounds[25]. The indirect warming effect of hydrogen is significant as methane itself has a much stronger warming effect than CO_2, with 84–87 times the warming potential of CO_2 over 20 years (GWP-20) and 28–36 times over 100 years (GWP-100)[26].

The residence time of atmospheric hydrogen is relatively short-lived, typically remaining in the atmosphere for 2 to 7 years[8], and is removed primarily through two pathways: approximately 70–80% is absorbed by soil and microorganisms[23]. However, accurately estimating this soil sink remains challenging due to geographic variability and limited understanding of hydrogen uptake processes[23]. The remaining atmospheric hydrogen, as previously discussed, is oxidised via reactions with hydroxyl radicals, followed by subsequent reactions with peroxy radicals (•OOH) which leads to a diverse array of climate adverse effects, such as the ones mentioned earlier in this section.

When evaluating the environmental impact of deploying hydrogen as a substitute for carbon-intensive technologies, it becomes clear that a well-controlled supply chain, optimised to minimise leakage, is essential.

Figure 2 illustrates how varying leakage rates can either contribute to achieving or, in some cases, significantly diminish—even negate—the intended climate benefits of reducing CO_2 emissions.

Figure 2: Comparative long-term warming effects of substituting fossil fuel technologies with green or blue hydrogen alternatives



Source: Adapted from [2]

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[23] Derwent, R. G. Hydrogen for heating: atmospheric impacts – a literature review. BEIS: London, UK. 2018

[24] Novelli, P. C., Lang, P. M., Masarie, K. A., Hurst, D. F., Myers, R., & Elkins, J. W. (1999). Molecular hydrogen in the troposphere: Global distribution and budget. *Journal of Geophysical Research: Atmospheres*, *104*(D23), 30427-30444.

[25] Ehhalt, D. H.; Rohrer, F. The tropospheric cycle of H_2: a critical review. *Tellus B* 2022, *61* (3), 500– 535, DOI: 10.1111/j.1600-0889.2009.00416.x

[26] International Energy Agency. Methane and climate change. 2023. https://www.iea.org/reports/global-methane-tracker-2023

Figure 2 compares the range of potential climate impacts between best- and worst-case scenarios for hydrogen deployment, based on differing levels of leakage control in supply chains. In the worst-case scenario, involving blue hydrogen produced from natural gas with CCS—with a 10% hydrogen leakage rate and a 3% methane leakage rate—the initial climate impact could exceed that of the fossil fuel technologies it is intended to replace, potentially causing up to 60% more warming in the first decade of deployment. Under these conditions, it could take approximately 50 years to surpass statistical uncertainty and for the climate benefits of transitioning to hydrogen to become evident. Conversely, in the best-case scenario, with hydrogen produced from renewable energy sources (i.e., green hydrogen) and a well-controlled supply chain that minimises hydrogen leakage to 1%, the climate impact would be nearly eliminated relative to the carbon-intensive applications it replaces[2].

Moreover, it is crucial to differentiate between short- and long-term climate impacts when assessing hydrogen's warming potential. For short-lived gases like hydrogen, using metrics such as GWP-100 may not adequately reflect their immediate warming effects. Unlike CO_2, which accumulates in the atmosphere and causes prolonged warming, hydrogen and methane are short-lived gases whose warming impacts dissipate relatively quickly. This characteristic means that hydrogen, by avoiding CO_2 build-up, may offer greater climate benefits over the long term. However, relying solely on long-term metrics risks underestimating the short- and medium-term climate impacts of hydrogen and methane leakage, potentially leading to overly optimistic assessments of hydrogen's immediate benefits[2].

2.3 Assessments of the Impacts of Potential Fugitive Hydrogen Emissions

The integration of hydrogen into future energy systems offers numerous environmental benefits; however, as discussed in previous sections, it also presents challenges, especially regarding leakage risks throughout the supply chain. Recent studies have evaluated hydrogen emissions across various stages in the supply chain to estimate their global warming impact, though uncertainties remain due to limited data availability[8], as accurate assessment of emissions at each stage requires capabilities which do not exist today. With that in mind, in the uncertainty models utilized by the Intergovernmental Panel on Climate Change (IPCC), the average hydrogen emissions across the amalgamation of the different supply chain configurations are estimated at approximately 1.5%, with a statistical 99% confidence level[27].

Among the main stages in the hydrogen supply chain: Production, transport and storage, and consumption—transport and storage are cited to contribute the most to fugitive emissions, accounting for roughly 50% of total leakage. The primary sources of leakage are usually facilitated through faulty seals or gaskets, venting and purging processes, misaligned valves, and equipment malfunctions[28].

Leakage rates for hydrogen from vessels during production and storage, as well as from pipelines in transport and use, under the same conditions, are estimated to be about 1.3–2.8 times higher than those for methane gas and approximately four times those of air. This is mainly due to hydrogen's diffusivity: while methane is only 1.8 times lighter than air, hydrogen is 14.5 times lighter, allowing it to diffuse more rapidly through turbulent convection and rapid diffusion[28]. This characteristic highlights that systems designed as 'airtight' may not be 'hydrogen-tight'. Additionally, hydrogen's ability to permeate certain types of materials, discussed later, raises issues with the concept of retrofitting existing energy infrastructure[21].

To address uncertainties on hydrogen leakage, there is an increasing focus on refined assessments. For example on the global scale, UK authorities have evaluated lower boundary concentrations of hydrogen in model simulations using the UK Earth System Model (UKESM1) to understand how incremental hydrogen levels may affect atmospheric composition[29]. In the 'vide supra' scenario, with an

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[27] IPCC. (2014). Synthesis Report. Contribution of working groups I. *II and III to the fifth assessment report of the intergovernmental panel on climate change*, *151*(10.1017).

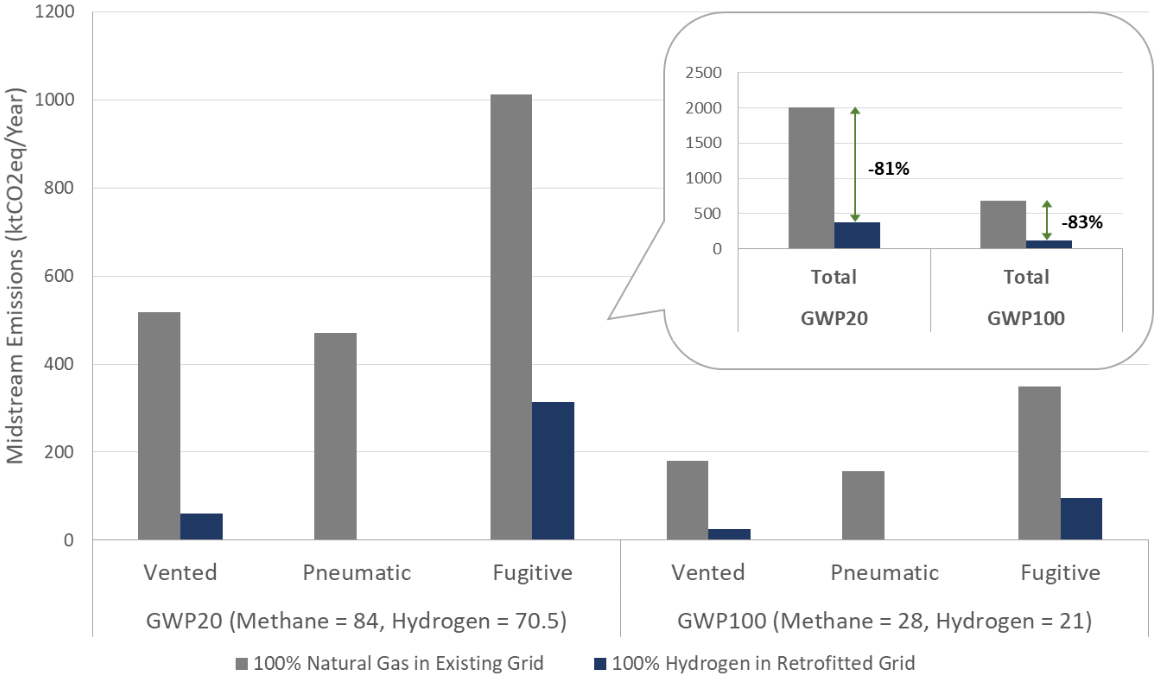
[28] Rigas, F., & Amyotte, P. (2013). Myths and facts about hydrogen hazards. *Chemical Engineering Transactions*, *31*.

[29] Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., & Shine, K. (2022). Atmospheric implications of increased hydrogen use. *Policy Paper*.

estimated global annual demand of 859 Mt of hydrogen to meet energy needs, and assuming leakage rates between 1–10%, annual fugitive hydrogen emissions could range from 9 to 96 Mt per year[30]. To put this in context, in a future where high leakage rates are allowed, hydrogen leakage at these levels could result in emissions equivalent to today's entire hydrogen demand being vented into the atmosphere on an annual basis[9].

Still, It is important to recognise that hydrogen does not exist in isolation; even if delayed benefits, its deployment yields a notably better environmental performance than today's carbon-based energy carriers. Figure 3 illustrates this by comparing the GWP impacts of methane versus hydrogen leakage in retrofitted SNAM pipelines over 20-year and 100-year timeframes. The GWP-20 values used in this assessment are 84 for methane and 70.5 for hydrogen, while the GWP-100 values are 28 for methane and 21 for hydrogen[18]. From the numbers seen, we can observe a significant reduction in global warming impact when transitioning from natural gas to hydrogen.

Figure 3: Global warming implications of substituting natural gas with hydrogen



Source: Adapted from [18]

Figure 3 displays midstream emissions from three sources: vented, pneumatic, and fugitive emissions. Across all emission types, hydrogen's GWP impact is consistently lower than methane's, with particularly pronounced reductions in fugitive emissions. The findings indicate an 81% reduction in total CO_2-equivalent emissions over 20 years and an 83% reduction over 100 years when transitioning from natural gas to hydrogen in the pipeline system, even accounting for hydrogen's higher leakage rates.

Also of note, when interpreting the results of Figure 3, it is important to note that the scope for generating the results reflects only those generated during gas transmission, storage, and regasification, excluding any variations in emissions from natural gas production and distribution. Furthermore, GWP-20 and GWP-100 for hydrogen may be represented at a higher level here than is generally accepted in existing literature. Nonetheless, these figures provide a highly conservative estimate, and adopting to the average values commonly cited in the literature would imply even greater emission reductions with hydrogen when compared to methane.

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[30] Pieterse, G., Krol, M. C., Batenburg, A. M., M. Brenninkmeijer, C. A., Popa, M. E., O'doherty, S., ... & Röckmann, T. (2013). Reassessing the variability in atmospheric H2 using the two-way nested TM5 model. *Journal of Geophysical Research: Atmospheres*, *118*(9), 3764-3780.

3. Hydrogen Leakage

While hydrogen is free from carbon, it presents unique environmental challenges, as explained earlier in this paper, with leakage being a significant yet often overlooked contributor. In this regard, other than venting and boil-off gas, hydrogen containment in today's common steel alloys presents a considerable challenge due to the high pressure required and hydrogen's ability to permeate and weaken materials over time. Hydrogen's small molecular size and high diffusivity mean that it can seep into materials, a process known as hydrogen embrittlement. As hydrogen gradually infiltrates the metal structure, reducing its strength and making it more susceptible to cracks and leaks. Over time, this deterioration not only compromises the safety of the pipelines but also increases the potential for hydrogen leakage, which could result in both environmental and economic consequences[31].

While this paper will not delve deeply into the next two concepts, it is important to note that leakage contributes not only to environmental impacts but also to economic losses and localised safety risk.

- Firstly, from an economics point of view, as hydrogen becomes an internationally traded energy commodity, competitive with other globally traded fuels, losses from leakage across the supply chain—whether during production, storage, or transport—become even more economically significant. Such inefficiencies and added costs can undermine hydrogen's viability as a clean energy alternative, especially in comparison to traditional energy sources that are readily available and cost-effective[32].
- Secondly, from a site safety point of view, in the event of a leak, hydrogen's rapid diffusion combined with wind dynamics can lead to the formation of an "explosion cloud" that could extend well beyond the immediate vicinity of the leak[33].

When looking at today's available literature, studies show that hydrogen can impact different components within the hydrogen supply chain, frequently leading to substantial leakage. These studies also highlight that leak rates and detection capabilities vary widely, influenced by factors such as infrastructure design and environmental conditions. In this section, we will examine a generalized version of the hydrogen supply chain, highlighting the ways in which hydrogen can leak at each stage and providing a generalized estimate of said leakage rates. Figure 4 presents a comprehensive overview of the hydrogen supply chain, illustrating the different stages and pathways from production to utilization. The supply chain begins with three primary sources for hydrogen production: fossil fuels, biomass, and water, each with distinct production methods.

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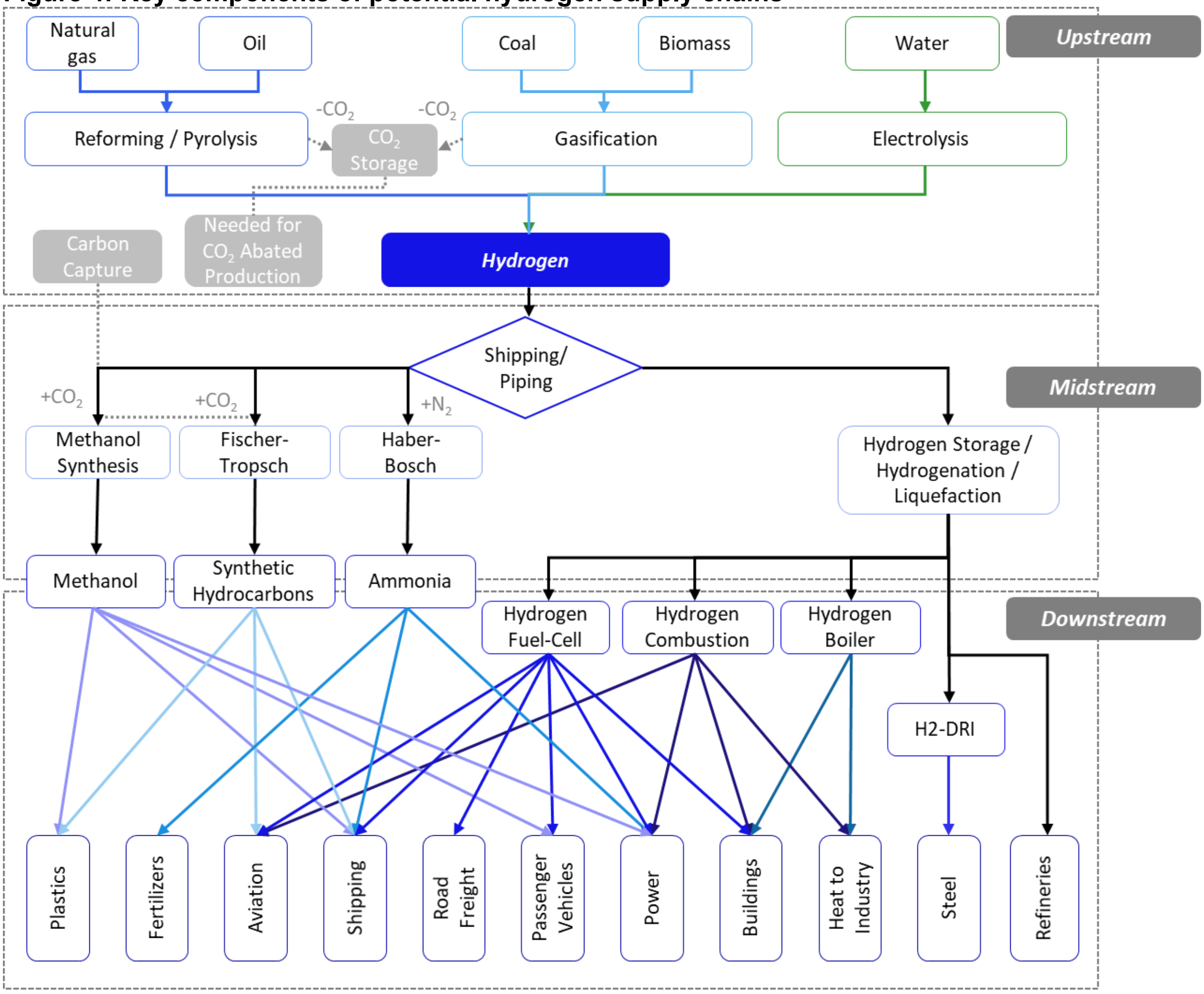
[31] Li, F., Liu, D., Sun, K., Yang, S., Peng, F., Zhang, K., ... & Si, Y. (2024). Towards a Future Hydrogen Supply Chain: A Review of Technologies and Challenges. *Sustainability*, *16*(5), 1890.
[32] IEA. (2019). The Future of Hydrogen, Report Prepared by the IEA for the G20, Japan. *Seizing Today's Opportunities*.
[33] Fu, X., Li, G., Chen, S., Song, C., Xiao, Z., Luo, H., ... & Xiao, J. (2024). Study on Liquid Hydrogen Leakage and Diffusion Behavior in a Hydrogen Production Station. *Fire*, *7*(7), 217.

Figure 4: Key components of potential hydrogen supply chains



Source: Adapted from [34,35]

At different stages within the hydrogen supply chain, the risk of leaks varies due to the specific requirements of each phase. For instance, production, storage, and end-use each present unique containment challenges based on the physical state of the hydrogen—whether it is gaseous, compressed, or liquefied. Storage of hydrogen in liquid form, especially cryogenic liquid hydrogen, carries particularly high leakage risks. This is as liquid hydrogen must be maintained at extremely low temperatures (-253°C) to stay in a liquid state, making containment challenging and increasing the likelihood of "boil-off" losses. These losses occur as small amounts of hydrogen revert to a gaseous state to relieve pressure in storage tanks, which can lead to fugitive emissions if not carefully managed[36].

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[34] Frankowska, M., & Błoński, K. (2023). Mapping the research landscape of hydrogen supply chains: A bibliometric analysis of citations and co-citations. *Journal of Sustainable Development of Transport and Logistics*, *8*(2), 360-374.

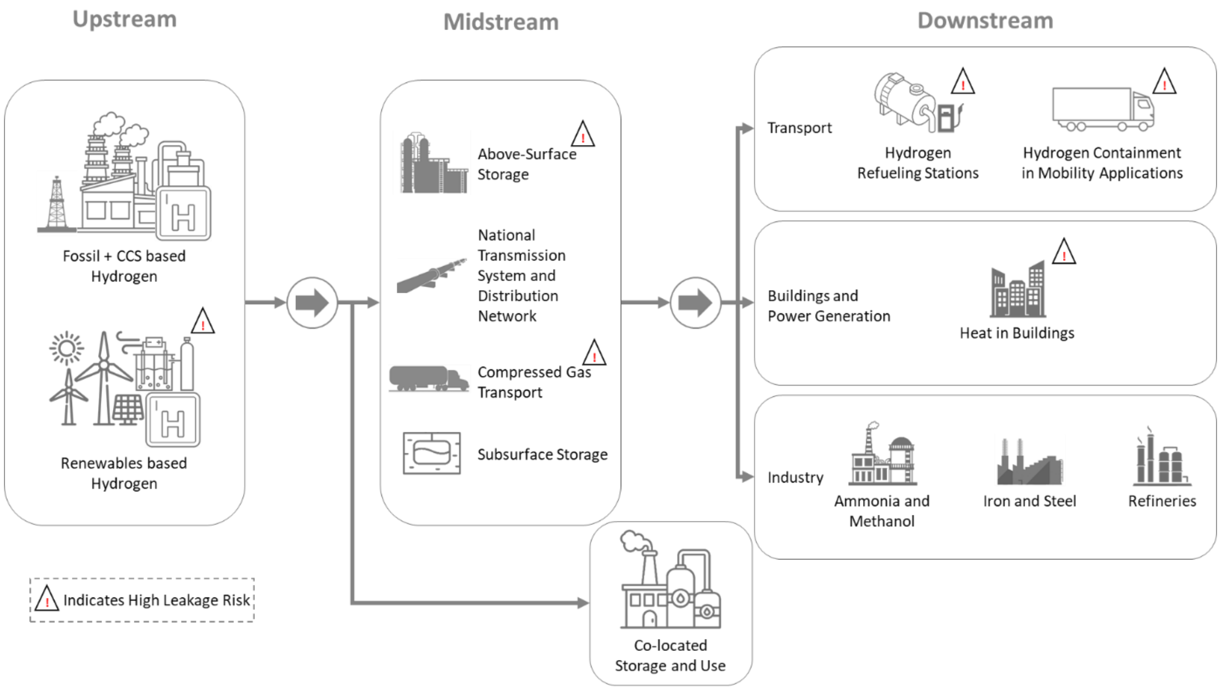
[35] Rystad Energy. (2022). Rystad Energy Week 2022: Americas Annual Summit. https://www.rystadenergy.com/events/offline-events/5050--Rystad-Energy-Week-2022-Americas-Annual-Summit-.

[36] Naquash, A., Agarwal, N., & Lee, M. (2024). A Review on Liquid Hydrogen Storage: Current Status, Challenges and Future Directions. *Sustainability*, *16*(18), 8270.

3.1 Supply Chain Configurations and Hydrogen Leakage

Figure 5 provides an overview of leakage risks along the hydrogen supply chain, covering the stages from low-carbon hydrogen production through storage, transmission, distribution, and end-use applications. The diagram identifies areas with high leakage risks using hazard icons, highlighting critical points within each segment where hydrogen leakage is most likely to occur.

Figure 5: Leakage risks along the Hydrogen supply chain



Source: Adapted from [37]

By examining the upstream, midstream, and downstream segments of the supply chain, we can identify the common concerns related to hydrogen leakage within each segment.

3.1.1 Low-Carbon Hydrogen Production

Hydrogen can be produced through low-carbon methods, including steam methane reforming CCS for blue hydrogen and water electrolysis powered by renewable energy for green hydrogen. While leakage risks are relatively controlled within these production facilities, some risk remains, particularly during the carbon capture and storage processes for blue hydrogen and within the electrolysers for green hydrogen. Potential sources of leakage at this stage include equipment failure, faulty seals, and venting during maintenance activities[37].

3.1.2 Storage, Transmission, and Distribution

The midstream segment, as mentioned earlier, would be responsible for the majority of hydrogen leakage with around 50% of the leakage of the supply chain[28]. Hydrogen's small molecular size and high diffusivity present significant containment challenges, as it can escape through even 'airtight' containment systems. This characteristic has substantial implications across the hydrogen supply chain, especially in pipelines and storage facilities. Mejia et al. (2020) found that hydrogen leaks approximately 2 to 3 times faster than natural gas in conventional low-pressure gas infrastructure[5]. This heightened leakage rate stems from hydrogen's unique properties, allowing it to permeate materials more readily

[37] Lacy, C. (2023). Reducing the cost impact of hydrogen leakage: Four ways to address fugitive emissions. *PA Consulting*. https://www.paconsulting.com/insights/reducing-the-cost-impact-of-hydrogen-leakage-four-ways-to-address-fugitive-emissions

than larger molecules like methane and propane. Supporting this, Swain & Swain (1992) demonstrated that even materials capable of containing methane or propane often struggle to retain hydrogen effectively[4]. These findings underscore the need for stringent containment protocols and specialized materials to minimize hydrogen leakage—a need that becomes even more critical as pressure increases or temperature decreases.

Co-located Storage and Use: Hydrogen storage is often set up near or within the same facilities where it will be used, in what is referred to as co-located storage and use. In these cases, hydrogen is commonly meant to be stored in above-ground tanks or underground facilities, such as salt caverns, close to the production or utilization site. Above-ground storage tanks present a high leakage risk due to factors like boil-off and required venting to prevent pressure build-up. Underground storage, while generally more stable, still requires careful monitoring to mitigate potential leakage over time. Co-locating storage with usage sites can streamline hydrogen supply and reduce transport needs, but it would also demand stringent safety protocols to manage the risks of storing hydrogen under high pressure or cryogenic conditions[37].

National Transmission and Distribution System: Pipelines transport hydrogen across long distances to distribution networks. Although pipelines typically have lower leakage rates than other transport modes, their extensive length and the number of joints and valves can contribute to overall leakage. Studies in the area estimate that pipelines, due to their scale, could lead to significant hydrogen fugitive emissions despite low individual leakage rates[37,38].

Compressed Transport: Compressed transport will play an integral role in hydrogen distribution, using high-pressure containers—sometimes combined with low-temperature cooling—to store hydrogen in compressed gas cylinders. These mobile containment systems carry a notable risk of leakage, particularly as high-pressure conditions increase the likelihood of leaks, and the frequent loading and unloading during transport create additional points of potential failure. In the liquefied natural gas (LNG) and compressed natural gas (CNG) industries, studies indicate that typical leakage rates during transport can range from 0.1% to 0.4% of total volume, depending on maintenance standards and handling frequency[39,40]. Given hydrogen's smaller molecular size and higher diffusivity relative to natural gas, comparable or potentially higher leakage rates can be expected in compressed hydrogen transport, especially in the absence of rigorous inspection and maintenance protocols.

Hydrogen Transported in Other Forms: Hydrogen can also be transported in the form of chemical carriers like ammonia, methanol, or liquid organic hydrogen carriers (LOHCs). These carriers are often preferred for long-distance transport or storage due to their higher energy density and reduced need for extreme pressure or cryogenic conditions, making them comparatively stable in transport. However, these carriers introduce a different set of leakage risks, as the conversion and handling processes associated with them can lead to emissions of other gases or compounds. For instance, ammonia (NH_3)—promoted for wide use as a hydrogen carrier, under certain conditions, can release nitrogen-based compounds into the atmosphere due to leakage or incomplete conversion. Methanol, another potential hydrogen carrier, poses risks associated with methanol vapor emissions, particularly during transfer or processing. Similarly, LOHCs, which absorb and release hydrogen through chemical bonding, are susceptible to degradation and small emissions of volatile organic compounds (VOCs)

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[38] Frazer-Nash Consultancy. (2022). *Fugitive hydrogen emissions in a future hydrogen economy*. Department for Business, Energy & Industrial Strategy.

[39] Yuan, Z., Ou, X., Peng, T., & Yan, X. (2019). Life cycle greenhouse gas emissions of multi-pathways natural gas vehicles in china considering methane leakage. *Applied Energy*, *253*, 113472.

[40] Xunmin, O. (2019). Life cycle analysis on liquefied natural gas and compressed natural gas in heavy-duty trucks with methane leakage emphasized. *Energy Procedia*, *158*, 3652-3657.

during cycling and handling. While hydrogen itself is not directly leaked in these forms, the potential emissions associated with ammonia, methanol, and LOHCs do pose cause for concern[41,42,43].

3.1.3 End-Use Applications

Transport: Hydrogen is increasingly used as a fuel across diverse transport modes—including road vehicles, aviation, rail, and shipping—each with unique requirements for storage, handling, and safety. This widespread application necessitates a robust infrastructure of hydrogen refueling stations, which are crucial yet vulnerable points in the supply chain. Due to the frequent handling of high-pressure hydrogen, the numerous valve connections, and the potential for human error during refueling, these stations are often identified as high-leakage risk areas. Transport applications would typically employ compressed hydrogen tanks, which must withstand high pressures (often up to 700 bar) to ensure adequate fuel storage. However, these tanks are at risk of leakage if not meticulously sealed and routinely inspected. For example, studies show that even minor imperfections in sealing can lead to gradual leakage over time, particularly under the mechanical stress of travel, impacting both safety and fuel efficiency. The need for durable tank materials and rigorous maintenance is particularly acute in high-stakes applications like aviation and rail, where hydrogen's low energy density requires frequent refueling or larger tanks, thus increasing the risk of leakage and storage challenges. In addition to these technical requirements, effective training for operators is essential. Human error remains a significant factor in hydrogen handling, with studies indicating that proper protocols and routine inspections can reduce leakage rates by as much as 30% in refueling stations[37,44,45].

Buildings and Power: In buildings, one use of hydrogen would be for heating and combined heat and power (CHP) applications, but the sector faces notable leakage risks. Hydrogen's high diffusivity and small molecular size allow it to escape from appliance connections, pipe joints, and burner systems, where even minor leaks could disperse rapidly and accumulate, posing significant safety hazards. Additionally, variations in pressure and the mechanical stress of frequent on-off cycles in heating systems can exacerbate leakage potential, especially in older infrastructure or systems not originally designed for hydrogen. In the power sector, co-firing hydrogen introduces another layer of complexity. The combustion process for hydrogen requires careful handling due to its high reactivity, and any unintended leaks or inconsistencies in hydrogen flow can disrupt combustion stability, leading to efficiency losses and unplanned emissions[37,38].

Industrial Applications: Hydrogen is set to play a substantial role across various industries, including iron and steel production, refining, and the synthesis of ammonia and methanol. These applications present moderate to high leakage risks, largely due to the high volumes of hydrogen handled under elevated pressures and temperatures in these processes. In large-scale industrial plants, fugitive emissions are a common concern, with hydrogen leakage likely to occur at points of vulnerability such as valves, flanges, and seals. At these points, especially under repeated mechanical stress and thermal cycling, can exacerbate leakage rates over time if not properly maintained[37,38].

3.2 Supply Chain Hydrogen Leakage Rates

Figure 6 illustrates hydrogen release fractions across various stages of the hydrogen supply chain, from production to end-use, along with target design goals for reducing these release rates by 2030, as estimated by Air Liquide. The graphic highlights different hydrogen loss rates associated with production,

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[41] Chen, X., Zhang, Y., & Zhang, X. (2024). Hydrogen production from renewable energy sources for a sustainable hydrogen economy: Challenges and solutions. *Energy Environment and Green Hydrogen Journal, 15*(2), 198-214.

[42] Methanol Institute. (2020). *Renewable methanol to green hydrogen: Pathways to sustainable energy*.

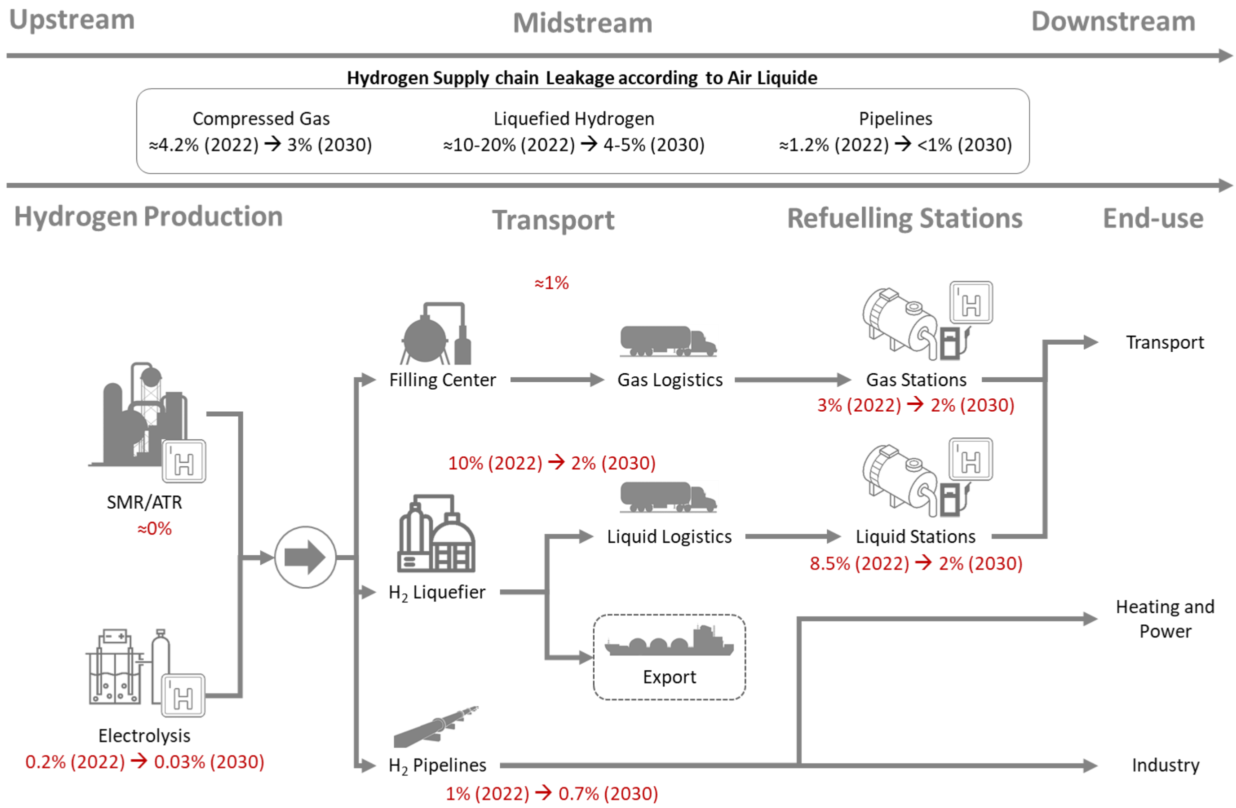
[43] Manoharan, Y., Thangavelu, L., Rahman, M. M., Alshehri, A., & Alkahtani, R. (2023). Environmental and operational considerations of LOHCs in hydrogen storage and transportation systems. *RSC Energy & Environmental Science, 14*(4), 789–801.

[44] Genovese M, Blekhman D, Fragiacomo P. An Exploration of Safety Measures in Hydrogen Refueling Stations: Delving into Hydrogen Equipment and Technical Performance. *Hydrogen*. 2024; 5(1):102-122.

[45] Magliano A, Perez Carrera C, Pappalardo CM, Guida D, Berardi VP. A Comprehensive Literature Review on Hydrogen Tanks: Storage, Safety, and Structural Integrity. *Applied Sciences*. 2024; 14(20):9348.

transportation, storage, refuelling, and end-use applications, providing a snapshot of the specific points in the supply chain where leakage is most prevalent.

Figure 6: Hydrogen release fractions to the atmosphere along the hydrogen supply chain and design goals for 2030



Source: Adapted from [18]

In hydrogen production, centralized electrolysis exhibits a relatively low leakage rate of 0.2% while Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR) shows negligible leakage (0%). After the production of hydrogen, the supply chain is divided into three main pathways:

- The compressed gas supply chain,
- The liquefied gas supply chain, and
- The piped hydrogen supply chain.

Currently, the compressed gas supply chain has a leakage rate of approximately 4.2%, with distribution stations being the main contributors, accounting for an average of 3% of these losses. Efforts are targeted to bring the overall compressed gas leakage down to 3% by 2030. In the liquefied gas supply chain, leakage rates are significantly higher, ranging from 10% to 20% today. The primary sources of these losses are the liquefaction process, which incurs around 10% leakage, and distribution, which contributes an additional 8.5%. Targeted improvements aim to reduce these liquefied gas losses to between 4% and 5% by 2030. For piped hydrogen, the current leakage rate stands at about 1.2%, with plans to lower it to below 1% by 2030 as pipeline infrastructure improves.

Moving beyond 2030 and looking further ahead to 2050 estimates, Table 2 compiles a generalised estimate of hydrogen leakage rates for 2050 across different categories in the hydrogen supply chain.

Table 2: Compiled hydrogen leakage rate estimates

Leakage Source	*Category*	*2050 Leakage Rates*	
		Low Case	High Case
Blue Hydrogen	Production	1.0%	1.5%
Green (electrolytic) Hydrogen	Production	2.0%	4.0%
National Transmission System	Storage, transmission, and distribution	0.1%	0.5%
Distribution Network	Storage, transmission, and distribution	0.2%	0.5%
Compressed Gas Road Transport	Storage, transmission, and distribution	0.3%	0.7%
Geological Storage	Storage, transmission, and distribution	0.0%	0.1%
Above-ground Tank Storage	Storage, transmission, and distribution	1.8%	6.5%
Industrial Applications	End-use	0.2%	0.5%
Hydrogen Refuelling Stations	End-use	0.3%	0.9%
Fuel Cell Electric Road Vehicles	End-use	1.0%	2.3%
Heat in Buildings	End-use	0.5%	0.8%

Source: Adapted from [38]

By 2050 under an optimistic case, general values for total hydrogen leakage are as follows, blue hydrogen production is estimated to have a leakage rate of 1.0%, while green (electrolytic) hydrogen production is projected to have a slightly higher rate at 2.0%. Within storage, transmission, and distribution, the national transmission system and distribution networks are expected to have very low leakage rates of 0.1% and 0.2%, respectively, while above-ground tank storage shows a significantly higher rate of 1.8%. Compressed gas road transport and hydrogen refuelling stations have projected leakage rates of 0.3%, reflecting the emphasis on minimizing loss during transport and refuelling. In end-use applications, fuel cell electric vehicles are estimated to have a leakage rate of 1.0%, indicating that mobile hydrogen storage still presents containment challenges. In heating applications within buildings, the expected leakage rate is 0.5%, while industrial applications show a relatively low rate of 0.2%.

4. Factors Influencing Hydrogen Leakage

Hydrogen leakage through the supply chains is governed by many factors at production, storage, transportation and end-use stage. Without understanding these factors, it is difficult to design good containment solutions and limit any environmental impact. Main influences on hydrogen leakage are material compatibility, storage conditions, infrastructure design, and operational parameters.

4.1 Material Compatibility and Hydrogen Embrittlement

Hydrogen has an affinity to embrittle metals, resulting in the failure of certain materials over time and therefore material selection for use in hydrogen infrastructure is critical. Hydrogen embrittlement happens when hydrogen atoms enter the material lattice, with loss of ductility combined increase in brittleness leading to cracking under stress. In high-pressure applications, pipelines and storage tanks are typically constructed from steel or other alloys, which are susceptible to weakening and acid stress corrosion cracks. These cracks can lead to tearing, especially when hydrogen-induced embrittlement further reduces the material's strength. According to Ahad et al. (2023), materials most susceptible to hydrogen embrittlement include high-strength steels and certain non-metallic components[46].

[46] Ahad, M. T., Bhuiyan, M. M. H., Sakib, A. N., Becerril Corral, A., & Siddique, Z. (2023). An overview of challenges for the future of hydrogen. *Materials*, *16*(20), 6680

Table 3: Hydrogen permeability of selected membranes

Metal	*Extremely Embrittled*	*Severely Embrittled*	*Slightly Embrittled*	*Negligible Embrittled*
Aluminum Alloys				
1100				Yes
6061-T6				Yes
7075-T73				Yes
Be-Cu Alloy 25				Yes
Copper, OFHC				Yes
Nickel 270				Yes
Titanium and Titanium Alloys				
Titanium		Yes		
Ti-5Al-2.5Sn (ELI)		Yes		
Ti-6Al-4V (annealed)		Yes		
Ti-6Al-4V (STA)		Yes		
Steel				
Alloy Steel, 4140	Yes			
Carbon Steel				
1020		Yes		
1042 (normalized)		Yes		
1042 (quenched and tempered)		Yes		
Maraging Steel, 18Ni-250		Yes		
X42		Yes		
X52		Yes		
X60		Yes		
X65		Yes		
X70		Yes		
X80		Yes		
X100		Yes		
Stainless Steel				
A286		Yes		
17-7PH		Yes		
304 ELC		Yes		
305		Yes		
310		Yes		
316				Yes
410		Yes		
440C		Yes		
Inconel 718		Yes		

Source: Adapted from [48,47]

[47] Degtyareva, V. F., & Smirnov, P. M. (2023). *Aluminum alloys and hydrogen embrittlement: A review of recent advances*.; Shi, L., & Smith, R. (2023). *Beryllium-copper alloys and resistance to hydrogen embrittlement. Current Engineering*.; Anderson, P., &

Table 3 illustrates the embrittlement effects on different materials, with a comparison of embrittlement susceptibility across commonly used pipeline metals[46].In case of pipelines, the risk of embrittlement means that materials must have low hydrogen permeability (through improving microstructure and by choice e.g. special steels or composite polymers). While metals such as stainless steel alloys containing chromium and nickel exhibit greater resistance to the entry of hydrogen, creating this material make them thus more favourable for a certain applications[48].

4.2 Environmental Factors

Leakage rates are significantly influenced by hydrogen's behaviour under varying pressures and temperatures, especially in conditions of high pressure or cryogenic storage. Storing hydrogen at pressures exceeding 700 bar, as is common for fuel cell vehicle applications (FCVA), increases the likelihood of leakage through microscopic cracks and joints in containment materials. These conditions raise concerns about the long-term integrity and safety of storage systems, as maintaining containment at such extremes can be challenging and may have implications for both environmental and human health[49]. Also, liquid hydrogen is stored at cryogenic temperatures (-253C) and has a boil-off hazard that demands subsequent venting of the tanks in order to prevent pressure escalation inside.

Fu et al. (2024) demonstrated through CFD simulations that ambient wind speed and temperature significantly affect the dispersion of hydrogen gas following a release. At higher wind speeds, hydrogen disperses over a greater distance, requiring an expanded safety perimeter around storage and handling sites to prevent accidental exposure and ignition risks[33]. This dispersion behaviour is critical to safety, as hydrogen is highly flammable and, when mixed with air, can form an explosive mixture. The hydrogen gas dispersion patterns—often referred to as 'clouds'—show varied spread and concentration under different wind conditions, indicating that atmospheric interactions can influence the path and reach of leaked hydrogen. This makes understanding local wind patterns and environmental factors essential for establishing effective safety protocols and containment zones at hydrogen storage facilities.

4.3 Design and Infrastructure Integrity

Both the propensity and consequence of leakage can be impacted by design (e.g., pipelines, storage tanks & refuelling stations) of hydrogen containment systems. This includes lengths of pipelines, number of connections or joints and components such as valves, compressors and flanges that are often weak points in a system. Zhang et al. (2022) carried out a full risk analysis of hydrogen refuelling plants, but notably identified individual components like valves and compressors as the most likely sources for leaks. In particular, their study showed that frequent checking for leaks using gas detection devices was key to detecting and preventing leaks early on, particularly in areas which are common sites of hydrogen transfer[49].

This integrity of infrastructure is almost always compromised by the long-term effect hydrogen has on materials and therefore requires immediate attention in any prospective designs as well as continued maintenance once established. Reducing the number of joints can also minimize cumulative leak risks, but every joint adds a potential for failure. Li et al. (2024) recommend the use of safety barriers, venting systems, and sensor networks to contain and manage accidental releases[31].

Gupta, S. (2023). *The hydrogen embrittlement resistance of high-purity copper and nickel alloys*. *Current Engineering*.; Koul, A., & Leonard, D. (2023). *Hydrogen-induced embrittlement in titanium and titanium alloys: A metallurgical perspective*. *Journal of Metals*, 47(2), 12-23.; Robertson, M., & Zhang, H. (2023). *Effects of hydrogen on the mechanical properties of Ti-6Al-4V alloys*. *Metallurgical Transactions A*, 32(7), 1523-1535.; Chen, Q., & Tan, R. (2023). *The susceptibility of alloy steels to hydrogen embrittlement: Implications for high-strength applications*. *Current Engineering*.; Patel, S., & Oran, J. (2023). *Hydrogen embrittlement in carbon steels: Mechanisms and mitigation strategies*. *Current Engineering*.; Wilson, T., & Barrett, F. (2023). *Hydrogen embrittlement and structural integrity of maraging steels*. *Current Engineering*.; Ruiz, P., & Thompson, E. (2023). *Pipeline steels and hydrogen embrittlement in high-pressure environments*. *Current Engineering*.; Taylor, G., & Park, S. (2023). *Hydrogen embrittlement resistance in austenitic and martensitic stainless steels*. *Current Engineering*.; Collins, M., & Singh, J. (2023). *Nickel-based superalloys in hydrogen-rich environments: Inconel 718 performance*. *Current Engineering*.

[48] Pişkin, F. (2013). *Deposition and testing of thin film hydrogen separation membranes* (Master's thesis, Middle East Technical University).

[49] Zhang, X., Qiu, G., Wang, S., Wu, J., & Peng, Y. (2022). Hydrogen leakage simulation and risk analysis of hydrogen fueling station in China. *Sustainability*, *14*(19), 12420.

4.4 Operational Practices and Real-Time Monitoring

Leak detection and monitoring systems are critical to help owners of hydrogen infrastructure in identifying small leaks early before they become large costly ones. Qanbar & Hong (2024) noted that real-time monitoring technology is becoming more advanced, with electrochemical and catalytic sensors improvements in providing on the spot readings of H 2 concentration. The sensors are distributed over the hydrogen infrastructure depending on location of measurement requirement, from production to refuelling[50].

Contemporary hydrogen systems are also forced to use mechanical shutdown protocols, which in about one second will automatically isolate the sector of gas delivery and therefore avoid large-scale leaks. Sensor are, however, a significant challenge for both placement and calibration especially in places affected by high humidity or temperature differences that can affect sensibility. According to Li et al. For hydrogen detection, sensors must provide reliable operation in a variable environment to enable active leak management under different climate conditions[31].

5. Mitigating Hydrogen Leakage

As hydrogen technology is developed to scale up for commercial use, reducing leakage becomes an important factor in economics and environmental sustainability of the downstream hydrogen supply chains. Leakage mitigation really requires some combined best practices — technology, design of the infrastructure we are building and a good regulatory support system. This part goes into state-of-the-art technologies and methodologies that have been developed to tackle hydrogen leaks, as well as the implications on policy effectiveness and the economics behind prevention rather than compensation for any hydrogen leakage.

5.1 Review of Potential Solutions and Technologies Aimed at Reducing Hydrogen Leakage

The development of effective solutions for managing hydrogen leakage is essential for the safe and sustainable deployment of hydrogen as a clean energy carrier. Due to hydrogen's unique characteristics—its small molecular size, high diffusivity, and tendency to embrittle materials—conventional containment and leak detection methods often fall short. Recent advancements have focused on innovative materials, advanced containment design, and enhanced leak detection and monitoring systems to improve hydrogen containment throughout its supply chain. However, the implementation of these technologies is not without challenges. Beyond the technical complexities, the costs associated with these advanced solutions pose significant economic barriers, particularly as the industry seeks to scale up hydrogen infrastructure. While each technology offers specific benefits for mitigating leakage risks—from storage tanks and pipelines to distribution systems and end-use applications—the financial viability of large-scale adoption remains a critical issue.

5.1.1 Advanced Containment Materials and Coatings

Hydrogen is known to embrittle and permeate traditional containment materials, posing a significant challenge for safe and durable storage and transportation. Consequently, material innovations have become a primary focus for addressing hydrogen leakage. High-strength steel alloys, polymer linings, and nanocomposite coatings are being developed to mitigate both permeation and embrittlement in hydrogen containment structures. As shown in Table 3 certain metals, including various types of stainless steel and nickel alloys, demonstrate minimal or negligible embrittlement, making them among the most commonly used materials in high-pressure hydrogen applications. For example, alloys like stainless steel 316 and certain aluminium alloys resist hydrogen-induced cracking, which is crucial for maintaining structural integrity over time. In addition to metal alloys, hybrid materials, such as polymer-

[50] Qanbar, M. W., & Hong, Z. (2024). A Review of Hydrogen Leak Detection Regulations and Technologies. Energies, 17(16), 4059.

lined metallic pipelines, are increasingly explored for hydrogen transport. These pipelines combine the structural strength of metal with the impermeability of polymer linings, effectively reducing hydrogen diffusion rates. Arrigoni & Diaz (2022) suggest that using embrittlement-resistant materials and polymer linings can extend infrastructure lifetimes and reduce maintenance costs by limiting hydrogen permeation and the associated material degradation. Furthermore, advanced nanocoatings, including graphene-based coatings, are being tested to enhance resistance against hydrogen embrittlement without compromising material flexibility, especially in high-pressure and variable-temperature applications. These innovations promise to improve the safety and cost-effectiveness of hydrogen containment systems across the supply chain[18].

Also, recent works suggest that nanocoatings such as graphene or carbon based composite can provide almost a complete retardation for hydrogen molecules. Fu et al. (2024) observed that these two coatings were the most effective in slowing down hydrogen diffusion, while avoiding a significant decrease in material flexibility for applications using pressure variation[33]. These materials are undergoing testing for applications in pipelines and storage, which could be key to future containment strategies.

5.1.2 Leak Detection and Monitoring Systems

Hydrogen leak detection technologies are critical in managing the risks associated with hydrogen's unique properties: it is colorless, odorless, and has low viscosity, making it difficult to detect with conventional systems designed for natural gas. Accordingly, new sensor technologies have been developed to achieve highly sensitive and rapid hydrogen leak detection.

There are three principal types of hydrogen sensors: electrochemical, catalytic, and optical[50]. Electrochemical sensors are highly sensitive with fast response times and low power requirements, making them ideal for applications requiring frequent, precise readings. However, they need regular calibration and have a limited lifespan. Catalytic sensors are more stable over time and are thus suited for long-term, static environments, such as warehouses and storage facilities, although they respond more slowly to hydrogen than electrochemical sensors. Optical sensors, on the other hand, offer high precision and can detect hydrogen concentration changes by measuring light wavelength variations, providing durability in harsh conditions. Their environmental resistance makes them particularly suitable for monitoring large areas, high-humidity environments, temperature-fluctuating zones, and outdoor pipeline networks.

The European Union's Joint Research Centre (JRC) emphasizes that consistent and reliable hydrogen monitoring along the supply chain—from production facilities to storage locations and transport vehicles—is essential to minimize emissions and ensure safety. Detection methods are chosen based on specific application areas, taking into account the range, response time, and environmental conditions. Additionally, advanced systems such as real-time drone monitoring and satellite surveillance are being explored to enhance spatial coverage and enable rapid response capabilities, thus improving overall leak management along extensive hydrogen infrastructure[18].

5.1.3 Improved Infrastructure Design and Sealant Technologies

Effective infrastructure design plays a vital role in reducing hydrogen leakage, with specific attention to minimizing joints and potential failure points. Hydrogen containment systems are now being developed with modular designs that require fewer connection points, thus reducing the risk of leaks. For example, continuous-length pipelines constructed from high-strength materials offer fewer potential leak points than traditional segmented systems. According to Ahad et al. (2023), these modular designs not only reduce the chances of leakage but also simplify maintenance, as fewer connections require routine inspection[46].

Sealant technology has also advanced significantly, as traditional seals are often ineffective against hydrogen. Innovations in sealant materials include elastomeric polymers and fluoropolymer-based compounds that provide a more durable, hydrogen-resistant seal. A study by Li et al. (2024) demonstrated that fluoropolymer seals, used in high-pressure applications, withstand prolonged hydrogen exposure without significant degradation, reducing maintenance costs and improving safety[31].

5.2 Analysis of Policy Implications and Economic Considerations Related to Hydrogen Leakage Mitigation Strategies

Technical solutions are essential for mitigating hydrogen leakage, the success of these measures heavily depends on supportive policy frameworks and economic incentives. Policies must carefully balance economic feasibility with safety and environmental goals, creating conditions that encourage industries to invest in advanced containment and leak-detection technologies. Whilst addressing the economic challenges associated with hydrogen leak prevention calls for a strategic blend of targeted incentives and innovative financing models.

Effective policy incentives and financial support mechanisms play a critical role in making hydrogen production and infrastructure investments economically viable, particularly in the nascent stages of industry development. Without substantial government support, the growth of the hydrogen supply chain could be constrained by high initial costs and competition with existing solutions. This section explores the types of incentives that have proven effective, draws on relevant case studies from other energy sectors, and considers potential cost-sharing models that could help reduce financial barriers to upgrading hydrogen infrastructure.

Countries around the world are beginning to establish regulatory frameworks specifically targeting hydrogen leakage. In the United States, the Department of Energy's (DOE) "Hydrogen Shot" initiative emphasizes cost-effective hydrogen production while prioritizing safety standards that address leakage prevention[51]. Similarly, the European Union has implemented guidelines under its Clean Hydrogen Partnership, which mandates regular leak monitoring and the use of certified containment materials[52].

Regulatory frameworks often set permissible leakage rates and outline containment standards for hydrogen production, storage, and transport facilities. The International Organization for Standardization (ISO) and the American Society of Mechanical Engineers (ASME) have both introduced guidelines (e.g., ISO/TR 15916 and ASME B31.12) that provide industry standards for hydrogen handling, including material selection, safety protocols, and leak testing procedures[53]. Compliance with these standards not only reduces the likelihood of hydrogen leakage but also encourages uniformity in containment practices across the industry, promoting widespread adoption of best practices.

Of note here is that currently, hydrogen leakage is not addressed in policy, as most political initiatives focus on stimulating hydrogen supply and demand. Nevertheless, It can be anticipated that leakage will emerge as a regulatory and safety concern, potentially leading to market reforms once supply and demand are more firmly established.

5.2.1 Review of Cost-Benefit Analyses of Hydrogen Leakage Mitigation

Implementing hydrogen leakage mitigation technologies involves substantial upfront costs, especially for infrastructure upgrades, material procurement, and sensor deployment. A comprehensive cost-benefit analysis by Goita et al. (2024) highlights that while these initial costs are high, the long-term benefits—such as reduced maintenance, increased system longevity, and minimized environmental impact—outweigh the expenses[19]. The study suggests that leak-resistant materials and advanced detection systems can reduce overall operational costs by minimizing the need for frequent repairs and by preventing costly accident-related damages.

Economic modeling from Qanbar & Hong (2024) shows that industries investing in state-of-the-art hydrogen containment systems can expect returns in the form of reduced insurance premiums, as

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[51] McNaul, S., White, C., Wallace, R., Warner, T., Matthews, H. S., Ma, J. N., ... & Shultz, T. (2023). *Strategies for Achieving the DOE Hydrogen Shot Goal: Thermal Conversion Approaches* (No. DOE/NETL-2023/3824). National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States).

[52] Koneczna, R., & Cader, J. (2021). Hydrogen in the strategies of the european Union member states. *gospodarka surowcami mineralnymi*, *37*(3), 53-74.

[53] Moretto, P., & Quong, S. (2022). Legal requirements, technical regulations, codes, and standards for hydrogen safety. In *Hydrogen safety for energy applications* (pp. 345-396). Butterworth-Heinemann.

advanced leak mitigation measures lower the risks of high-cost incidents. Additionally, these systems can help companies comply with evolving regulatory requirements, avoiding potential penalties associated with non-compliance[50].

A recent top-down assessment of total hydrogen leakage from a future hydrogen grid was presented in a paper published by UK Department for Business, Energy and Industrial Strategy (BEIS) in April 2022[54]. Their model estimates that in a scenario where approximately 23% of global energy consumption is supplied by hydrogen—replacing 40% of current fossil fuel energy—859 million tonnes (Mt) of hydrogen would need to be produced each year. With the current US gas grid losing around 2.3% of natural gas as leakage[55], and studies indicating that hydrogen escapes approximately three times faster than natural gas[56] it's reasonable to assume a hydrogen escape rate of about 6.9% in an equivalent hydrogen supply chain. This would result in an estimated 59.3 million tonnes of hydrogen lost annually.

The economic impact of this hydrogen loss is significant. At an estimated production cost of $2-4 per kilogram[57] for hydrogen, the financial loss due to leakage could range between $118.6 billion and $237.2 billion each year, depending on production costs and market conditions. Preventing this loss could save billions annually, funds that could instead be invested back into improving infrastructure, advancing hydrogen technology, or expanding hydrogen production capacity to meet global energy needs.

In constructing hydrogen-specific infrastructure, material costs represent a substantial portion of total expenses. For example, pipeline construction materials account for about 26% of the overall cost, and hydrogen pipelines require thicker walls and more resilient materials than natural gas pipelines to resist hydrogen embrittlement and permeation[58]. While the thicker-walled pipelines and specialized materials increase the upfront cost—estimated to be up to 68% higher than for natural gas pipelines—the longer-term benefits include reduced maintenance costs, lower risk of hydrogen-related degradation, and a decrease in the frequency of repairs over the infrastructure's lifecycle. On the other hand, The BEIS report[54] suggests that implementing effective leakage prevention strategies could reduce hydrogen loss by up to 50%. This would result in the potential savings of $59.3 billion to $118.6 billion annually and prevent approximately 326 million tonnes CO_2-eq of emissions, underscoring the dual economic and environmental benefits of investing in robust hydrogen leak prevention strategies.

Furthermore, valve technology innovations, such as the Dragonfly valve, illustrate the potential for cost savings through reduced maintenance and prevention of lost hydrogen product. This valve technology has been shown to deliver annual savings equivalent to 240% of its purchase cost per valve, resulting in savings equivalent to 27 valve purchases over a 20-year lifespan. In the study proposing this valve technology, the adoption of such technologies is claimed to prevent more than $500 million in lost hydrogen value annually by 2050, underscoring the economic benefits of investing in reliable containment solutions[59].

Despite the economic advantages, the higher initial costs associated with hydrogen-specific materials and monitoring technologies can hinder widespread adoption. Financial incentives and policy support are essential to mitigate these barriers. For example, tax credits, grants, and subsidies could offset some of the costs of advanced leak prevention systems, making these technologies more accessible to a

[54] N. Warwick, "Atmospheric implications of increased hydrogen use," UK Government, London, 2022

[55] R. A. Alvarez, "Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain," Science, pp. 186 - 188, 2018

[56] NREL, "Blending Hydrogen into Natural Gas Pipeline Networks: Key Issues Review," National Renewable Energy Laboratory , 2013.

[57] PwC. (n.d.). The cost of green hydrogen production. https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html#:~:text=The%20most%20attractive%20production%20markets,3%20to%20%E2%82%AC8%2Fkg

[58] BEIS, UK Government. (2023). *Hydrogen transport and storage cost report*. https://assets.publishing.service.gov.uk/media/659e600b915e0b00135838a6/hydrogen-transport-and-storage-cost-report.pdf

[59] BEIS, UK Government. (2022). *HYS2154 Actuation Lab Final Feasibility Report*. https://assets.publishing.service.gov.uk/media/6467908a43fe01000cac65e6/HYS2154_Actuation_Lab_Final_Feasibility_Report__Public_.pdf

wider range of industries. Regulatory frameworks, such as those under the European Union's Clean Hydrogen Partnership and the U.S. Department of Energy's "Hydrogen Shot" initiative, aim to support hydrogen infrastructure development while prioritizing safety and emission standards.

5.2.2 Economic Challenges and Incentives for Widespread Adoption

Despite the potential environmental, safety, and economic benefits of investing in advanced mitigation infrastructure, certain challenges limit the widespread adoption of advanced hydrogen leakage mitigation technologies. High upfront costs and the requirement for specialized materials deter some companies from investing in upgraded systems. Furthermore, many existing natural gas infrastructures that are poised to be repurposed for hydrogen face compatibility issues, requiring expensive retrofitting to safely contain hydrogen.

To address these economic barriers, governments and organizations need to explore financial incentives and funding programs aimed at reducing the cost burden. In the United States, for example, the Infrastructure Investment and Jobs Act includes provisions for grants and tax incentives for hydrogen infrastructure projects, making it more economically feasible for companies to implement high-quality leak prevention systems. In the European Union, subsidies are available under the Horizon Europe framework, which supports innovation in hydrogen technology and includes funding for pilot projects focused on leak mitigation[52].

5.2.3 Government Incentives and Financial Support Mechanisms

Governments can foster the adoption of hydrogen leak prevention measures by providing targeted financial incentives to both hydrogen producers and industrial consumers. Effective examples include direct support schemes for clean hydrogen production, where funds are distributed through transparent, competitive tenders to provide immediate financial assistance and offset high production costs. Tax exemptions and fee waivers for electrolysers used in hydrogen production can also substantially reduce costs and boost competitiveness. Countries like Germany, Norway, France, and the Netherlands have adopted such policies, easing entry barriers for clean hydrogen producers[60]. Additionally, research and development grants, alongside low-interest loans specifically aimed at renewable energy projects and hydrogen infrastructure, support innovations in leak detection and containment technologies, as well as the creation of cost-effective, embrittlement-resistant materials[61]. Alternative financing models, such as build-operate-transfer (BOT), build-lease-transfer (BLT), and build-lease-operate-transfer (BLOT) schemes, offer further incentive by attracting private sector investment and allowing investors to share in profits before transferring ownership back to public entities. These models are particularly attractive for international investors, aligning financial returns with longer-term infrastructure goals[62]. Together, these financial mechanisms could create a supportive environment for hydrogen adoption and infrastructure development.

The European Hydrogen Alliance (ECHA) plays as a good example as its vital role in driving Europe's hydrogen strategy by coordinating investments and fostering collaborations between public and private stakeholders. Through identifying viable projects and facilitating partnerships, ECHA attracts investment and accelerates the rollout of hydrogen initiatives across Europe. Complementing these efforts, the European Union offers a range of financing facilities designed to support green hydrogen projects. The InvestEU Programme backs innovative green projects with investment support[63], while the European Regional Development Fund (ERDF) provides funding for regional hydrogen projects that deliver

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economic and environmental benefits[64]. For hydrogen initiatives in economically disadvantaged regions, the Cohesion Fund offers financial support[65], and the Just Transition Mechanism helps mitigate the social and economic impacts of shifting from fossil fuels to green energy, including hydrogen[66]. Infrastructure funding for hydrogen transport and storage networks is available through the Connecting Europe Facility[67], and further backing is offered by the EU Hydrogen Bank[68]. Together, these mechanisms form a robust financial framework to promote the adoption and development of green hydrogen across the EU.

5.2.4 Case Studies in Hydrogen and Broader Energy Sectors

Lessons in the hydrogen space and other energy sectors demonstrate that well-designed policy incentives can effectively drive the adoption of new technologies and support emissions reductions.

One successful approach has been carbon pricing mechanisms, including cap-and-trade systems and carbon taxes. These tools have proven effective in reducing emissions and incentivizing cleaner technologies. For example, France's carbon tax on grey hydrogen, set to rise to €100 per tonne by 2030, encourages a shift toward decarbonized hydrogen by making it more cost-competitive[69].

Tax exemptions for electrolysers also illustrate the power of targeted financial incentives. Germany's policy exempting electrolysers used in clean hydrogen production from taxes and fees has significantly reduced production costs, improving green hydrogen's competitiveness[70]. Indeed, such tax policies can reduce the financial burden on hydrogen producers, making sustainable production methods more attractive to investors and companies alike.

5.2.5 Cost-Sharing Models

In addition to policy incentives, cost-sharing models can significantly reduce financial barriers by distributing the costs of hydrogen infrastructure upgrades across multiple stakeholders. While models specific to hydrogen leak prevention are still in development, there are several adaptable mechanisms from other sectors.

Public-Private Partnerships (PPPs) are a promising model. The European Clean Hydrogen Alliance (ECHA), for instance, could coordinate investments through PPPs to facilitate cost-sharing among public entities, private companies, and investors. By spreading financial risks, these partnerships make hydrogen infrastructure projects more feasible and attract broader investment[71].

Structured government incentives, such as grants and low-interest loans, can further promote collaborative investments. By requiring matching funds or co-investment from private stakeholders, governments ensure a shared responsibility for the costs and benefits of implementing leak prevention technologies. This structure supports both innovation and financial commitment across sectors[72].

Alternative financing models like build-operate-transfer (BOT) and build-lease-operate-transfer (BLOT) also present effective cost-sharing options. These models allow private companies to manage and profit from hydrogen infrastructure projects for a period before transferring ownership back to the government

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or public entities. Particularly beneficial for high-cost projects, they enable private investors to recoup expenses over time, reducing the burden on public resources and making these projects more financially accessible[62].

6. Future Directions in Hydrogen Leakage Mitigation

From a technical point of view, the future of hydrogen leakage mitigation lies in continued research and development, which aims to improve the durability, effectiveness, and cost-efficiency of containment and detection technologies. Key areas of focus include:

- **Material Science Advancements**: Developing new alloys and coatings that further resist hydrogen embrittlement and diffusion[73].
- **Automated Monitoring Systems**: Expanding the use of artificial intelligence (AI) and machine learning in leak detection to enhance predictive maintenance and real-time monitoring accuracy[74].
- **Integration of Distributed Sensors and IoT**: Leveraging the Internet of Things (IoT) to enable large-scale, interconnected leak monitoring networks for improved data analysis and rapid response[75].

As these technologies evolve, the cost of implementing robust hydrogen leak prevention systems is expected to decrease, making these systems more accessible to a broader range of industries.

From a more overarching perspective, strategic measures must be taken along the entire hydrogen supply chain in order to prevent losses and maximize the ecological as economic advantages of hydrogen use as a clean energy carrier. Based on what was stated earlier in the report, the following are some recommendations for technological advancement and infrastructure design guidance together with policy support, meant to bolster the support for the required industry standards that are needed to manage hydrogen leakage & shore up its credible role in achieving Net-Zero emissions.

Invest in Advanced Material Technologies and Containment Solutions: Due to its physical characteristics that lead leakage and material embrittlement, hydrogen requires specialized containment materials. Advanced materials such as high-strength steel alloys, polymer linings, and nanocoatings are essential for minimizing leakage from storage tanks, pipelines, and transport vessels. For example, nanocoatings provide almost impermeable barriers mitigating hydrogen diffusion into containment materials. Investing in leak reduction should also be concentrated for the high-pressure and cryogenic applications, where the risk of leakage is most pronounced.

Implement Rigorous Leak Detection and Monitoring Systems: Hydrogen leaks are challenging to detect as hydrogen is colourless and odourless. Implementing advanced leak detection with comprehensive, in-situ monitoring systems, such as optical and electrochemical sensors, across the supply chain—from production to storage and distribution—is essential. Deploying upgraded sensor networks at critical points, like refuelling stations and liquefaction facilities where fugitive emissions are most likely, can significantly reduce response times. Additionally, integrating leak detection with automated shutdown mechanisms can prevent minor leaks from escalating into major safety and environmental hazards.

Retrofit and Optimize the Assigned Natural Gas Infrastructure for Hydrogen Use: Retrofitting existing natural gas infrastructure for hydrogen transport provides economic and logistical benefits but

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requires substantial modifications to prevent leakage. Pipelines, storage facilities, and refuelling stations must be upgraded with hydrogen-compatible materials and seals to address the risks associated with hydrogen's small molecular size. Regular inspections and maintenance are also essential to ensure that leak prevention measures remain effective over time. Optimizing current infrastructure for hydrogen transport can accelerate the scale up of lower-cost hydrogen supply chains whilst supporting containment standards that minimize environmental impact.

Establish and Enforce Stringent Regulatory Standards: To ensure hydrogen leakage is minimized, governments and regulatory bodies must establish and enforce stringent standards for hydrogen containment and leak detection. Existing standards, such as ISO/TR 15916 and ASME B31.12, provide valuable guidelines but should be updated and expanded to address the unique challenges posed by hydrogen. Policymakers should work with industry stakeholders to set acceptable leakage limits and mandate routine monitoring and maintenance across the supply chain. Regulatory frameworks should include penalties for non-compliance and provide incentives for companies that demonstrate effective leak prevention practices.

Develop Incentives for Low-Leakage Technologies: Economic incentives can encourage the adoption of low-leakage technologies throughout the hydrogen supply chain. Governments and industry organizations should offer tax credits, grants, and subsidies for companies investing in advanced containment materials, leak detection technologies, and infrastructure upgrades. These incentives could help offset the high upfront costs of retrofitting or building hydrogen-specific infrastructure and support companies in meeting stringent regulatory requirements. Incentive programs could be part of broader national and international initiatives focused on promoting clean hydrogen, aligning with climate goals while ensuring hydrogen's sustainability.

Prioritize Research on Leakage Rates and Environmental Impacts: The current uncertainty in hydrogen leakage rates and environmental impacts necessitates further research. Detailed studies should be conducted to quantify leakage rates across different stages of the supply chain, especially in emerging areas like liquid hydrogen logistics and compressed gas transport. Research should also focus on understanding the indirect effects of hydrogen leakage on atmospheric chemistry, including interactions with methane and ozone. This information will provide a clearer picture of hydrogen's net environmental impact and inform future containment and leak prevention strategies.

Enhance Public Awareness and Industry Training on Hydrogen Safety: Public and industry awareness of hydrogen leakage risks and safety measures is crucial to safely integrating hydrogen into energy systems. Training programs for industry professionals on best practices in hydrogen handling, leak detection, and containment can reduce the likelihood of accidental releases. Additionally, public awareness campaigns on hydrogen safety, particularly regarding the installation and operation of facilities nearest to them, can help build public confidence and support for hydrogen adoption.

7. Conclusion

As a clean energy carrier poised to be produced and used in sectors such as industry, transport, and power generation and buildings, hydrogen has the potential to drive an accelerated global decarbonisation process. However, the effectiveness of hydrogen as a sustainable solution largely depends on addressing the environmental challenges posed by hydrogen leakage throughout its supply chain. This paper has examined the hydrogen supply chain, from production to end-use, highlighting the critical points of leakage and the potential impacts on climate and air quality due to indirect effects on methane and ozone levels.

The analysis reveals that hydrogen leakage, while often minor in terms of volume, can significantly influence global warming potential through its interactions with other atmospheric gases, notably methane. As hydrogen reacts with hydroxyl radicals, it extends the atmospheric lifetime of methane, a potent greenhouse gas. Additionally, hydrogen leakage contributes to changes in tropospheric and stratospheric ozone, with possible repercussions for both human health and ecosystem stability. These indirect effects underline the need for comprehensive leakage mitigation to preserve hydrogen's environmental benefits.

To realize hydrogen's potential as a clean energy carrier, a multi-faceted approach is essential. Technological innovations, such as advanced containment materials and real-time monitoring systems, will be critical to reducing leakage across production, storage, and distribution stages. Simultaneously, retrofitting existing infrastructure, establishing stringent regulatory standards, and providing economic incentives for low-leakage technologies are all crucial steps for minimizing fugitive emissions. Enhanced public awareness and industry training will further support the safe and effective integration of hydrogen into existing energy systems.

In conclusion, by addressing the challenges associated with hydrogen leakage and implementing targeted mitigation strategies, stakeholders can ensure that hydrogen contributes positively to climate goals. With coordinated efforts across technological, regulatory, and economic fronts, hydrogen can fulfil its potential as a sustainable energy solution, supporting global efforts to reduce greenhouse gas emissions and mitigate the impacts of climate change.