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Hydrogen leakages across the supply chain: Current estimates and future scenarios

Davide Trapani, Paolo Marocco *, Marta Gandiglio, Massimo Santarelli

Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

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A B S T R A C T

Low-carbon hydrogen is widely acknowledged as a key pillar of the global energy transition. However, because hydrogen acts as an indirect greenhouse gas, estimating its atmospheric leakages across the supply chain is necessary for an accurate evaluation of its overall environmental benefits. As part of the European HYDRA project, this study presents a thorough assessment of hydrogen leakages across the entire supply chain – encompassing production, handling, storage, transport, and end-uses – under current conditions (2023) and projected scenarios for 2030 and 2050. For this purpose, a detailed dataset of hydrogen leakage rates is compiled from the literature, offering both average and minimum–maximum estimates to reflect the inherent uncertainties and provide ready-to-use values for emissions assessments. Results indicate that electrolysis is potentially the most leakage-prone production pathway, owing to processes such as purging and stack venting. Moreover, as hydrogen infrastructure develops over the coming decades, liquid hydrogen is expected to become a major contributor to losses, mainly due to boil-off during handling, transport, and refueling operations. By 2050, overall leakage rates across the supply chain could range from below 2% in optimistic projections to nearly 20% in worst-case scenarios. These findings highlight the importance of accurately quantifying hydrogen emissions and implementing mitigation measures to fully harness the climate benefits of a possible future hydrogen-based economy. By identifying the processes most susceptible to leaks, this analysis offers valuable insights for policymakers, researchers, and industry stakeholders aiming to reduce hydrogen losses and maximize hydrogen-related environmental benefits.

1. Introduction

Low-carbon hydrogen (H_2) and its derivatives are widely recognized as key pillars of future energy scenarios, as they can be effectively adopted in sectors where mitigating carbon dioxide (CO_2) emissions is particularly challenging, such as heavy industry [1], long-haul transport [2], aviation [3,4] and shipping [5]. In particular, hydrogen and hydrogen-based fuels are expected to contribute to reducing CO_2 emissions by 10 gigatonnes (Gt) between 2030 and 2050 [6]. The growing focus on hydrogen is also reflected in the increasing number of initiatives and funding programs aimed at accelerating its adoption worldwide [7]. However, at present hydrogen is far from being a clean solution for the energy transition as nearly 90% of the hydrogen demand (i.e., 97 million tonnes (Mt) consumed in chemical industry, oil refining and steelmaking) is produced from unabated steam methane reforming (SMR) and coal gasification processes, resulting in the emission of more than 900 Mt_{CO2} [8]. It is thus evident that a substantial transformation in hydrogen production routes is required to meet the ambitious goal of carbon neutrality by 2050.

1.1. Climate implications of hydrogen

While transitioning to low-carbon hydrogen is essential for achieving climate goals, it is equally important to consider the potential environmental trade-offs associated with its deployment. One key concern is hydrogen leakage along the supply chain, which could offset some of its anticipated climate benefits. Indeed, hydrogen acts as an indirect greenhouse gas as it can cause atmosphere perturbations leading to the increase in the concentrations of methane, ozone and water vapor [9]. Recent analyses have highlighted how hydrogen's climate impact is driven by these indirect effects, in particular by reacting with the hydroxyl radical (OH^-) and extending methane's atmospheric lifetime [10, 11]. Hydrogen oxidation also serves as a precursor of tropospheric ozone and increases stratospheric water vapor, where moisture is typically low

* Corresponding author.
E-mail address: paolo.marocco@polito.it (P. Marocco).

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[12].

These pathways can substantially amplify hydrogen's warming footprint. The 100-year global warming potential (GWP_{100}) has been estimated at 11 ± 5 [13], 11.6 ± 2.8 [10], 12 ± 6 [14] and 12.8 ± 5.2 [15]. To complement the long-term GWP_{100} perspective, some studies have also reported GWP_{20} values, which capture short-term warming dynamics and are approximately two to four times higher than GWP_{100} [16]. While GWP_{20} does not fully represent the long-term effects of carbon dioxide and may overemphasize short-lived gases, it remains a useful complementary metric for assessing near-term climate impacts and trade-offs, particularly for gases like hydrogen with short atmospheric residence times.

Overall, if hydrogen demand continues to grow significantly without adequate leak mitigation, fugitive H_2 emissions could partially offset the expected climate benefits of hydrogen deployment [11,16]. These findings underscore the importance of robust monitoring, detection, and mitigation of hydrogen emissions throughout its production, storage, and transport, to safeguard the climate advantages envisioned for a hydrogen-based economy [17].

1.2. Literature review on hydrogen leakage estimation

In the existing literature, hydrogen emissions are classified as intentional and unintentional, with the latter further divided into fugitive or operational leakages [9]. Unintentional emissions may happen in case of unplanned safety venting, leakages due to component failures (e.g., pipelines, valves and joints) or material permeation, boil-off phenomena and releases of residual hydrogen in the exhaust streams [9,18]. Conversely, intentional hydrogen releases are mainly caused by venting and purging procedures during start-up and shutdown operations [19]. Hydrogen emissions may occur at various stages of the supply chain (i.e., production, storage, transport and use), with losses typically estimated below 10% of the transported hydrogen [20,21]. However, the exact quantity of hydrogen released into the atmosphere remains unknown due to the absence of accurate hydrogen sensors capable of detecting concentrations with high sensitivity (i.e., ppb level) and fast response time [9]. Indeed, hydrogen monitoring is currently performed for safety purposes only with detection limits of 30 ppm, thus leaving non-flammable hydrogen leakages undetected [15]. The International Energy Agency (IEA) confirmed that quantitative information on hydrogen leakages is still scarce because of limited experimental data and knowledge gaps regarding leakage phenomena in hydrogen components (e.g., pipes and compressors) [22,23]. Furthermore, the lack of data is further amplified by the early-stage deployment of the hydrogen infrastructure (e.g., large-scale electrolysis plant, transmission pipelines, hydrogen refueling station), thereby preventing the possibility of conducting experimental campaigns across several stages of the hydrogen supply chain [24].

Given the lack of direct measurements, in recent years numerous studies have tried to determine the hydrogen emissions based on assumptions, technical insights from experts, simulations and data extrapolations [25,26]. Bond et al. [27] reported leakage rates between 1.1% and 4.5% when serving exclusively industrial users and Colella et al. [28] indicated 1–3% as a reasonable estimate for leakages in a gaseous-based hydrogen economy. Cooper et al. [29] compared different hydrogen supply chains, considering multiple production pathways (e.g., electrolysis, biomass and coal gasification) and transport solutions (compressed or liquid hydrogen and ammonia), but excluding end-use applications. They concluded that green hydrogen experiences higher losses (especially if transported in liquid state) with leakage rate up to 8.5%. Arrigoni and Bravo Diaz [18] reported the hydrogen release fractions to the atmosphere along various supply chains, but still neglecting the losses in end-use stages. Specifically, the compressed hydrogen supply chain is characterized by a leakage rate of approximately 4.2%, while the liquid hydrogen and the pipeline supply chains exhibit values of 10–20% and 1.2%, respectively. Finally, a study by Frazer-Nash Consultancy [19] considered a detailed value chain scheme, estimating an overall loss rate between 0.96% and 1.50%, though the analysis remained confined to a specific country-scale scenario.

1.3. Aim and novelty of this study

The reviewed studies highlight the lack of a comprehensive investigation and quantification of hydrogen emissions covering the entire hydrogen supply chain, from production to various end-uses. Given the expected increase in hydrogen demand, a thorough assessment of hydrogen leakages along the value chain is crucial for environmental, climate, economic and technical reasons.

This study aims to fill this gap by developing a dedicated framework to estimate hydrogen leakages at each stage of the supply chain under various scenarios, including:

- Production (e.g., SMR, SMR with carbon capture and storage, electrolysis and coal gasification),
- Handling (e.g., compression, liquefaction),
- Storage and transport (e.g., pipelines, compressed and liquid hydrogen by truck),
- End-uses (e.g., industry, mobility, aviation and shipping, residential, power generation).

To the best of our knowledge, this work is the first to offer a disaggregated, process-level quantification of hydrogen emissions under current and future scenarios (current, 2030, 2050). The results are systematically presented as ranges to reflect data variability and uncertainty, including minimum values (representing optimistic assumptions), maximum values (pessimistic cases), and average estimates (plausible scenarios based on current knowledge and available evidence). Based on data from existing literature, including peer-reviewed papers and technical reports, this study evaluates the average leakage rate for each stage of the supply chain and identifies a minimum-maximum variation range. Unlike previous studies that typically adopt single leakage rate values for each stage of the value chain to assess overall hydrogen emissions, this study utilizes a complete dataset of hydrogen leakage rates and derived statistical values. It accounts for uncertainties and variability in the available data, enabling the definition of multiple scenarios (i.e., pessimistic, plausible and optimistic).

Building on this dataset of hydrogen leakage rates, several hydrogen-based scenarios are explored, considering projections from IEA, Hydrogen Council (HC) and International Renewable Energy Agency (IRENA) for 2030 and 2050. Ultimately, hydrogen emissions and overall supply chain leakage rates are evaluated, with a detailed process-level breakdown computed to identify the most critical phases within the hydrogen infrastructure.

The main contributions of this work are as follows:

- Proposing a process-based framework to quantify hydrogen emissions along the full supply chain.
- Providing a detailed and flexible dataset of leakage rates, including average values and minimum-maximum ranges for each stage of the supply chain, to support emissions assessments with ready-to-use data.
- Performing scenario analysis to reflect current and projected hydrogen demand in 2030 and 2050.
- Identifying high-leakage processes to support targeted mitigation strategies.

This work is conducted as part of the European project HYDRA (HYDrogen economy benefits and Risks: tools development and policies implementation to mitigate possible climAte impacts). The project focuses on assessing the climate and environmental implications of large-scale hydrogen deployment. It integrates market analysis, atmospheric modeling and the development of a hydrogen leakage monitoring tool

[30].

The structure of the work is as follows: Section 2 describes the methodology developed to estimate hydrogen leakages across different hydrogen-based scenarios, detailing each stage of the supply chain, Section 3 shows the main findings of the study, while Section 4 discusses the implications and significance of these results. Finally, Section 5 summarizes the key conclusions.

2. Methodology

The hydrogen leakage estimation framework consists of the following steps: first, the key stages of the hydrogen supply chain are presented (Section 2.1), followed by the analysis of hydrogen leakage rates for each stage (Section 2.2). Then, both short-term and long-term scenarios are defined (Section 2.3) with the aim of assessing the hydrogen leakages associated with each scenario and the most impactful stages. To achieve this, each scenario must be defined based on the amount of hydrogen processed across all stages of the supply chain.

2.1. Hydrogen supply chain

The hydrogen supply chain shown in Fig. 1 consists of five main stages: production, handling, storage, transport and end-uses. The following production pathways are considered: electrolysis, SMR, SMR equipped with solutions for carbon capture utilization and storage (CCUS) and coal gasification. The handling stage involves hydrogen compression and liquefaction processes, which enable subsequent hydrogen storage as compressed gas (CH_2) or in liquid form (LH_2). Hydrogen can be then transported from production to consumption sites via transmission and distribution pipelines and by trucks, delivering compressed or liquid hydrogen based on the specific market routes (domestic or international trade). Finally, hydrogen can be used as a fuel, feedstock or process gas (e.g., reducing agent) in multiple end-use applications, including industry, mobility, aviation and shipping, residential and power generation.

2.2. Hydrogen leakage rates

The main leakage phenomena occurring in each stage of the supply chain are briefly discussed below. For a comprehensive overview of the hydrogen leakage processes and a review of the quantification assessments available in literature, the reader can refer to the study from Esquivel-Elizondo et al [9].

In hydrogen production via electrolysis, the primary leakage mechanisms include venting during electrolyzer start-up and shutdown procedures, purging during the regeneration of the hydrogen purification system and hydrogen crossover [19]. Conversely, in SMR process the hydrogen leakages phenomena are limited as any losses from the SMR are currently flared [18]. Hydrogen production from SMR with CCUS technology is expected to have higher hydrogen leakages due to additional separation processes, which increase system complexity compared to conventional SMR [25].

In hydrogen compression and storage, the main leakage sources are the permeation through seals in the compressor and the fugitive emissions from the pressurized storage tank, which depend on the storage pressure, the valve material and the tank size [19]. In hydrogen liquefaction and storage, boil-off and losses in loading and unloading the cryogenic tanks represent the most severe hydrogen leakage phenomena. Geological storage options include salt caverns, which, despite their higher cost per unit of capacity, are suitable where geologically available. Lined hard rock caverns, which are more widely available, may serve a similar function, although they remain at the demonstration stage. Porous reservoirs, such as depleted gas fields and saline aquifers, also represent potential storage solutions, but their operational flexibility – in terms of fast injection and withdrawal cycles – and the risk of hydrogen losses are still unproven. Although geological storage has significant potential for long-term hydrogen storage – and therefore also poses associated emission risks – it was not considered in this study due to current technological limitations and the need for further research [8].

In hydrogen transport via transmission and distribution pipelines, leakages in pipework (e.g., pipes, joints and valves) are the main cause of hydrogen losses [18,19]. In truck-based hydrogen delivery (i.e., tube trailers), the most common sources of leakage are the fittings and venting of the trailer hose [18]. Currently, liquid hydrogen delivery is particularly susceptible to leakages, primarily due to boil-off effects [9].

Hydrogen is expected to be adopted in a wide range of industrial processes, including both existing uses (e.g., refining and chemical industry) and new applications (e.g., direct reduction of iron in steelmaking and high-temperature heat production for glass and ceramics

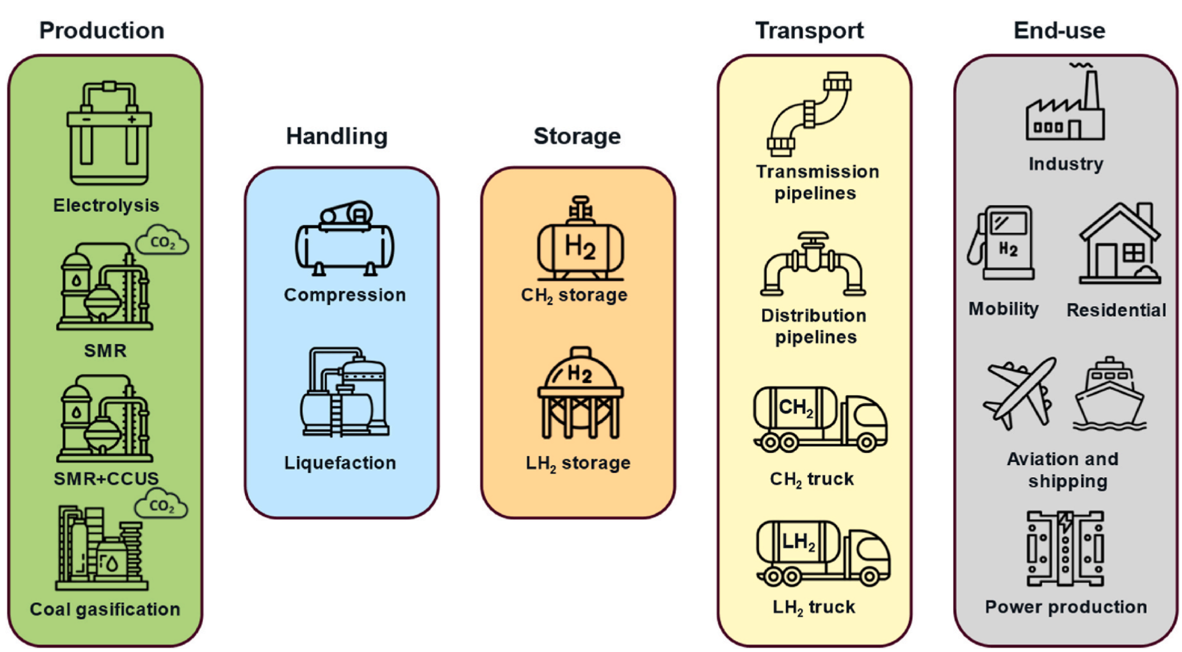

Fig. 1. Hydrogen supply chain.

manufacturing). The risk of hydrogen leakage in industries is considered moderate to high, with valves, flanges and seals identified as critical components, especially under elevated temperature and pressure conditions [20]. In the case of high-temperature heat production, leakages from the furnace and unburnt exhausts are classified as potential hydrogen emission sources. However, the information on hydrogen leakages in new industrial uses remains scarce as hydrogen-based technologies have yet to be widely implemented.

When using hydrogen in fuel cell systems, similar considerations to those made for electrolyzers operation are valid (i.e., venting, purging and hydrogen crossover are the main leakage causes). Moreover, in mobility applications, in addition to hydrogen losses in fuel cells, leakages during refueling operations and from the on-board pressurized storage tank have to be considered [19].

Hydrogen use in residential applications (i.e., heat and combined heat and power production) exhibits high leakage risk, especially in appliance connectors, pipes, joints and burners. Moreover, the frequent on-off cycles can intensify the risk of leakages, particularly in old infrastructure and retrofitted systems [20].

In the case of hydrogen use as a fuel in turbines (e.g., in aviation or maritime applications), venting when turning on and off the system and hydrogen losses in exhaust during idle state are widely recognized as the main leakage factors.

In the present study, a comprehensive dataset of hydrogen leakage rates for each stage of the supply chain is provided, considering both peer-reviewed articles and technical reports. Based on the dataset originally compiled by Esquivel-Elizondo et al. [9], Table 1 reports the leakage rate values according to the process-level disaggregation of the supply chain shown in Fig. 1. These values are expressed in percentage (% mass) of the total hydrogen quantity that undergoes a specific process (e.g., production via electrolysis or compression) or application (e.g., use in industrial processes, use in fuel cell for mobility or stationary applications). The data in Table 1 are then processed to compute the average leakage rate for each stage of the supply chain and identify the minimum-maximum variation range. More in detail, for each stage of the supply chain, the minimum leakage rate is identified as the lowest value among those listed in Table 1. A similar methodology is applied to determine the maximum leakage rate. Conversely, the evaluation of the average leakage rate requires an additional step, as most of the references provide ranges of values. First, the average value of each range is computed, and then these values are used to determine the average leakage rate for each step of the supply chain. Minimum, average and maximum values will be used to represent, in the Results section, pessimistic, plausible and optimistic scenarios respectively.

It is necessary to highlight that aviation and shipping have distinct leakage rates. However, in the literature, hydrogen demand for these two sectors is usually reported as an aggregated value. In this analysis, an average leakage rate is thus computed for the “aviation and shipping” end-use. For analogous reasons, the same methodology is also applied for power generation using fuel cells or other stationary devices (e.g., gas turbines). For an in-depth discussion of the assumptions underlying hydrogen leakage estimation and the quantitative assessment procedure, the reader can refer to Ref. [19], where input data are reported and the estimation methodology is presented.

2.3. Hydrogen scenarios

The present analysis focuses on the hydrogen supply chain and related hydrogen leakages across three distinct scenarios:

- **Current scenario**, representing the situation as of 2023
- **2030 scenario**, a short-term projection of hydrogen demand and supply
- **2050 scenario**, a long-term projection of hydrogen demand and supply

Table 1
Hydrogen leakage rates (% mass). The dataset was originally compiled and synthesized by Esquivel-Elizondo et al. [9], who reviewed leakage estimates across the hydrogen value chain.

	Fan et al. [25]	Cooper et al. [29]	Frazer-Nash [19]	Arrigoni and Bravo Diaz [18]	Van Rujiven et al. [21]	Petitpas et al. [31]
Production						
Electrolysis	2%–4%	0.1%–4%	0.24%–3.32% 0.52%–9.2%	0.2% 0.03%		
SMR + CCUS	1%–1.5%	0.1%–1%	0.25%–0.5%			
SMR	0.5%–1%					
Coal gasification		0.1%–1%				
Handling						
Compression		0.14%–0.27%	0.05%–0.25%			
Liquefaction		0.15%–2.21%		10% 2%		
Storage						
Compressed			2.77%–6.52%			
Liquid		0.05%–0.54%			0.3%–1%	
Transport						
Transmission pipelines	1%–2%	0.02%–0.06%	0.04%–0.48%	1.2%	0.1%–5%	
Distribution pipelines	0.2%–0.4%	0.0003%–0.16%	0.26%–0.53%		0.1%–5%	
Compressed hydrogen truck	1%–2.3%		0.3–0.66%	1%		
Liquid hydrogen truck	2.5%–5%		3.76%–13.2%		2%–5.5%	
End-use						
Industry	0.2%–0.5%		0.25%–0.5%			
Refueling CH_2			0.25%–0.89%	3%; 2%		
Refueling LH_2				8.5%; 2%		2%–15%
Fuel cell vehicle			0.56%–2.64%			
Aviation	3%					
Shipping	1%–2.3%					
Residential	0.5%–0.8%		0.3%–0.69%			
Power generation (in fuel cell)			0.56%–2.64%		0.1%–1%	
Power generation (not in fuel cell)	1.5%–3%		0.01%–0.66%			

When transitioning from the current scenario to 2030 and 2050 scenarios, the supply chain evolves, reflecting changes driven by the expected increase in hydrogen penetration and the adoption of novel technologies in production, transport, and end-use sectors.

2.3.1. Hydrogen supply chain in the current scenario

In the current scenario, referred to as the IEA2023 scenario, most hydrogen is locally produced and consumed, primarily in refineries and large chemical plants, with only limited quantities destined for the market. More in detail, IEA reports that around 85% of the hydrogen demand is captive (i.e. produced on-site at end-user facilities), while the remaining 15% is merchant (i.e., produced in a centralized plant and delivered to consumption sites by trucks or pipelines) [32]. In addition, IEA clearly states that currently hydrogen is not a globally traded commodity [8], although some minor imports and exports between neighboring countries are registered, especially in large petrochemical hubs in Europe [33]. Merchant hydrogen is currently delivered by trucks (with compressed or liquid hydrogen) and by short-distance and privately owned pipelines [8]. Compressed hydrogen delivery via tube trailers is assumed to be adopted for specialized industrial applications requiring limited hydrogen quantities, amounting to 1 Mt [8]. Conversely, liquid hydrogen delivery is considered for larger-scale transport over longer distances. To estimate the hydrogen delivered in liquid form, the current global liquefaction capacity (350 t/day) is assumed to work with an annual capacity factor of 90% [34]. Based on these hypotheses, the amount of merchant hydrogen transported by pipelines is then evaluated by difference.

Information on global hydrogen demand, supply and end-users are sourced from Ref. [8]. In this scenario, hydrogen consumption is concentrated in industrial applications, with fossil-based production pathways meeting nearly all of the demand and low-carbon solutions contributing to less than 1%.

2.3.2. Hydrogen supply chain in 2030 scenarios

By 2030, the main transformations in the hydrogen supply chain involve the partial transition to low-carbon production pathways and the emergence of new end-uses, such as road mobility, aviation and maritime applications. Captive and merchant hydrogen shares are projected to remain relatively stable in the near future, therefore, this analysis assumes the same values as in 2023. International hydrogen trade is unlikely to be fully established in 2030, as most of the export-oriented announced projects are still in the early stages of development [8]. The liquefaction capacity is projected to reach 495 t/day (with annual capacity factor of 90%), according to data from planned and under-construction plants, and is assumed to meet part of the road mobility demand [35]. Compressed hydrogen delivery is assumed to serve specialized industries and the remaining road mobility demand not covered by liquid hydrogen. Based on these assumptions, the quantity of merchant hydrogen transported via pipelines is determined by difference.

Two different forecasts are considered for 2030, referred to as IEA scenario (IEA2030) and Hydrogen Council scenario (HC2030):

- For the IEA2030 scenario, data on global hydrogen demand and end-users are obtained from Ref. [36], while the shares of low-carbon and unabated hydrogen production is derived from Ref. [37]. In this scenario, the unabated fossil-based hydrogen production portfolio is assumed to remain the same as in 2023. More in detail, reforming processes of hydrocarbons (i.e. primarily natural gas, but also naphtha in refineries) will account for approximately 80% while coal gasification will contribute 20% [8]. The IEA identifies several industrial applications as end-users, including refining, chemical industry, steel production, and other industrial sectors. For the purposes of this work, these processes are collectively categorized as "industry".
- For the HC2030 scenario, global hydrogen consumption and its segmentation among end-users are sourced from Ref. [38]. Based on the data reported in Ref. [38], grey hydrogen is anticipated to cover 46.4% of the demand, while electrolysis and SMR with CCUS are expected to contribute to 17.9% and 35.7%, respectively. The HC2030 scenario foresees hydrogen use in multiple industrial sectors, such as chemical and refining, steelmaking and industries requiring high-temperature heat. In the framework of this work, these industrial applications are grouped under the general classification of "industry".

2.3.3. Hydrogen supply chain in 2050 scenarios

By 2050, it is assumed that 21.6% of the hydrogen produced will be captive, while the remaining 78.4% will be merchant [6]. Additionally, two-thirds of the global hydrogen demand is supposed to be produced and consumed domestically, while the remaining one-third will come from international trade [39]. Among internationally traded hydrogen, 55% is anticipated to be transported by pipeline, 40% in the form of ammonia and 5% as liquid hydrogen [39], with the latter assumed to be transported by land. Hydrogen converted into ammonia is expected to be used directly as ammonia, without reconversion to its original form [40]. The contribution of liquid organic hydrogen carriers (LOHC) is considered negligible, as they are expected to cover less than 0.2% of the hydrogen demand [39]. According to projections by Arrigoni and Bravo Diaz [18], by 2050, all end-use applications will be supplied via pipelines, except for road mobility, which will rely on merchant hydrogen delivered by trucks, specifically 70% as liquid hydrogen and 30% as compressed gas. Residential users are supposed to be served by distribution pipelines, while all other users (e.g., industry, aviation and shipping) are assumed to be directly connected to the hydrogen transmission network.

Three distinct projections are analyzed for 2050, namely the IEA scenario (IEA2050), Hydrogen Council scenario (HC2050) and IRENA scenario (IRENA2050):

- The same methodology and sources described for the IEA2030 scenario are applied for the IEA 2050 scenario. However, in this case the unabated fossil-based hydrogen production in 2050 is assumed to rely on SMR technology only, with no contribution from coal gasification.
- For the HC2050 scenario, data on global hydrogen demand, end-users and production pathways are sourced from Ref. [38]. In this case, hydrogen demand is assumed to be met only by low-carbon production pathways, with electrolysis and SMR with CCUS covering 70% and 30%, respectively. Moreover, this scenario adopts the same classification of industrial applications presented for the HC2030 scenario.
- For the IRENA2050 scenario, global hydrogen demand is sourced from Ref. [41] and its breakdown among end-users is extracted from Ref. [39]. Moreover, according to IRENA projections, hydrogen production portfolio includes only electrolysis and SMR with CCUS technology, accounting for 94% and 6%, respectively [41]. It is noteworthy that in the IRENA2050 scenario, hydrogen is expected to serve multiple industrial applications, namely oil refining, steelmaking, ammonia, methanol and other chemicals synthesis, and other industries. For the scope of this work, these different industrial uses are grouped under the broader category of "industry". IRENA also differentiates between road and rail transport; however, these applications are included here under the wider "mobility" category.

3. Results

This study presents a generalized model of the hydrogen supply chain, highlighting potential leakage pathways at each stage and providing estimated leakage rates. The results include the hydrogen leakage rates (expressed as average, minimum and maximum values) for the different stages of the supply chain (Section 3.1), as well as the evaluation of global hydrogen emissions across the aforementioned scenarios (current, 2030, and 2050) in Section 3.2. Additionally, the impact of each stage on the overall emission levels is examined (Section 3.3).

3.1. Hydrogen leakage rates

Based on the data presented in Table 1, the average hydrogen leakage rates and their minimum-maximum variation ranges are derived. The resulting values are illustrated in Fig. 2 for the key stages of the hydrogen supply chain. For the sake of clarity, these values are also reported in table format in the Supplementary Material. Fig. 2 reveals that hydrogen leakage rates may exhibit significant minimum-maximum variability arising from heterogeneous quantification approaches (e.g., simulations, data extrapolations and assumptions) and incomplete understanding of hydrogen leakage phenomena. These factors thus result in substantial epistemic uncertainties.

Hydrogen production through electrolysis exhibits the highest leakage rate and the largest variation range (0.03%–9.2%) among the different production routes. This may be influenced by the presence in the dataset of measurements from outdated electrolyzers (e.g., 3.5% reported by Peters et al. [42]) and the uncertainty related to the impact of purging during the regeneration of hydrogen purification systems. SMR with CCUS is generally considered more susceptible to hydrogen leakage compared to conventional SMR; however, the higher uncertainty associated with the former leads to a wide variability (0.1%–1.5%). As a result, the average leakage rates for SMR-based solutions are nearly comparable: 0.73% for SMR with CCUS and 0.75% for conventional SMR.

Hydrogen liquefaction represents one of the most critical stages in the supply chain, with an average leakage rate of 4.4% and a maximum of 10%, which are considerably higher than the leakage values of compression. Conversely, liquid hydrogen storage shows a lower leakage rate compared to compressed hydrogen as proper insulated cryogenic tanks (e.g., double-jacketed tanks and multilayer insulated tanks) are used and mitigation solutions (e.g., re-liquefaction and on-site use of boiled-off hydrogen) are usually adopted [43]. Moreover, hydrogen leakages from pressurized tanks are clearly affected by the storage duration, which is typically assumed between 2 and 30 days when seasonal applications are not considered [19].

Transmission and distribution pipelines exhibit similar variation bands with average values of 1.09% and 0.83%, respectively. The broad variability (with minimum values that are almost negligible and maximum values up to 5%) is primarily attributed to the significant uncertainties related to the hydrogen behavior in existing pipelines, as well as the complexity of adapting current leakage models to account for the differences between hydrogen and natural gas.

The leakage rate of hydrogen delivery by pressurized tube trailers (CH_2 trucks) results in 1.04%. Similarly to compressed hydrogen storage, this leakage rate is strongly influenced by the time required for the delivery, which is usually considered to be between 0.5 and 3 days [19]. Liquid hydrogen delivery by trucks (LH_2 trucks) emerges as the most leakage-prone solution for hydrogen transport, with an average leakage rate of 5.33%, which can increase up to 13.2%.

The average hydrogen leakage rate in industrial applications is equal to 0.36%, with a variation range from 0.2 to 0.5%. This value refers to multiple industrial uses and it does not differentiate between industrial processes and hydrogen role (e.g., feedstock, reducing agent or high-temperature heat source). Industry is typically considered as one of the main hydrogen end-users in the future, making hydrogen emissions at this stage relevant. However, based on the available literature these leakage rates are deemed solid and robust enough to carry out the subsequent analysis.

Refueling operations in hydrogen refiling stations (HRS) are critical, particularly in the case of liquid hydrogen-based stations. During hydrogen transfer between tanks, boil-off losses can result in an average leakage rate of 6.33%, which can potentially increase to 15%.

When comparing the leakage rates in fuel cells for mobility and stationary applications (i.e., power generation), it is evident that fuel

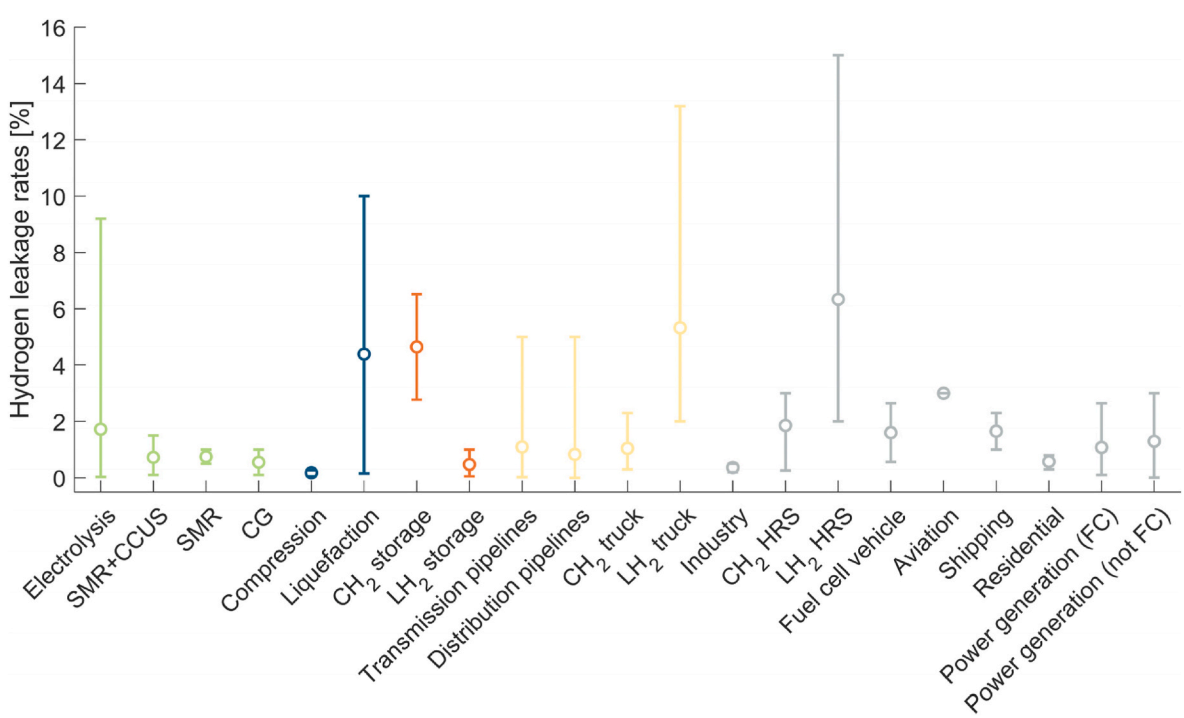

Fig. 2. Hydrogen leakage rates (% mass) of the different stages in the hydrogen supply chain. Average values (depicted as circles) and minimum-maximum variation ranges are shown. The supply chain includes the following stages: production (green color), handling (blue color), storage (orange color), transport (yellow color) and end-uses (grey color). For a complete graphical representation of the hydrogen leakage dataset, the reader is referred to [9]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

cell electric vehicles experience higher hydrogen leakages as losses from the on-board storage tank have to be considered.

3.2. Hydrogen scenarios

Resulting information for the current, short-term and long-term scenarios are summarized below. Fig. 3 also shows overall hydrogen demand and details on how it is distributed among main end-users (industry, mobility, aviation and shipping, residential, power production).

- **IEA2023 scenario:** In 2023, more than 97 Mt of were consumed at global level, mainly in oil refining, chemical industry, steelmaking and specialized industrial processes. Fossil-based production routes covered almost completely the demand (more than 99%), with reforming processes and coal gasification accounting for 80% and 20%, respectively.
- **IEA2030 scenario:** According to IEA, global hydrogen consumption is projected to reach 143 Mt in 2030, with the majority concentrated in industrial applications (74.1%). Hydrogen-based power production is forecast to grow considerably, accounting for 15.4% of the total demand. Moreover, road mobility will consume 4 Mt (2.8%), while 11 Mt (7.7%) will be required by aviation and shipping. Hydrocarbons reforming and coal gasification are expected to cover more than half of the demand, contributing for 44.8% and 11.2%, respectively. Conversely, electrolysis and SMR with CCUS will account for 32.1% and 11.3%, respectively.
- **HC2030 scenario:** The Hydrogen Council foresees that 143 Mt of hydrogen will be consumed globally in 2030. Industries will represent the largest hydrogen consumers (77%), followed by power generation, aviation and shipping, and mobility, accounting approximately for 10 Mt each. The Hydrogen Council considers also hydrogen use in the residential sectors, which is expected to require around 2 Mt. Hydrogen production will be still dominated by SMR (66.4 Mt), followed by SMR with CCUS (51.1 Mt) and finally by electrolysis (25.5 Mt).
- **IEA2050 scenario:** According to IEA, global hydrogen demand is projected to reach 402 Mt by 2050, primarily driven by industrial uses (37.3%) and aviation and shipping (28.9%). Road transport and power production are expected to account for 15.2% and 18.7%, respectively. Hydrogen production is predicted to rely only marginally on conventional SMR (3.5%), while low-carbon production pathways will cover more than 95% of the demand. Specifically, renewable-powered electrolysis will account for 75.1% while SMR equipped with CCUS solutions will contribute 20.5%.
- **HC2050 scenario:** The Hydrogen Council anticipates that hydrogen consumption can reach 660 Mt on a global scale by 2050. Industries will demand 263 Mt, mobility will require 180 Mt, while aviation and shipping will need 110 Mt. Additionally, power production is expected to consume 67 Mt, and residential applications are projected to account for 40 Mt. On the production side, renewable-based electrolysis will produce 462 Mt, while 198 Mt will be sourced from SMR with CCUS plants.
- **IRENA2050 scenario:** IRENA projections for 2050 foresee a global hydrogen demand of 523 Mt, which is mostly covered by electrolytic hydrogen (491.6 Mt) and only marginally by SMR with CCUS (31.4 Mt). Industrial applications will represent the largest hydrogen consumers, accounting for 48.6%. In contrast to other scenarios, hydrogen is expected to play a relatively minor role in road mobility (9.7%), and aviation and shipping sectors (10.9%). However, a significant demand is forecasted for hydrogen-based power generation (26.9%).

3.3. Hydrogen leakages

In the scenarios analyzed, hydrogen leakages are determined based on the hydrogen leakage rate and the hydrogen amount associated with each stage of the supply chain. Details regarding the distribution between captive and merchant hydrogen, and for the latter, between domestic and international trade, can be found in the Supplementary Material. Once the total hydrogen emissions across the supply chain are calculated, the hydrogen leakage rate for the entire supply chain can also be determined. The results are displayed in Fig. 4, which highlights the contributions of the main stages of the supply chain across the six scenarios under analysis.

As shown Fig. 4, in the IEA2023 scenario, the hydrogen losses are estimated at 1.3 Mt, resulting in a total leakage rate of 1.3% along the supply chain. This result is in line with the value reported by Arrigoni and Bravo Diaz [18] for 2020, who estimated a leakage rate of 1.2%. Most of the hydrogen losses take place in the production phases (53.3%), followed by the use in the industrial processes (27.2%). Hydrogen handling and storage contribute around 3% each, while hydrogen transport causes 12.6% of the hydrogen emissions.

For the IEA2030 scenario, the hydrogen losses amount to 3.2 Mt, which corresponds to a supply chain leakage rate of 2.2%. As evident in the bar plot of Fig. 4, the main hydrogen leakages occur during production (green area) and end-use (grey area), which account for 46.6% and 33% of the total losses, respectively. The contribution of hydrogen handling is almost negligible, while storage and transport (mainly as compressed gas via pipelines and tube trailers) cause 19% of the

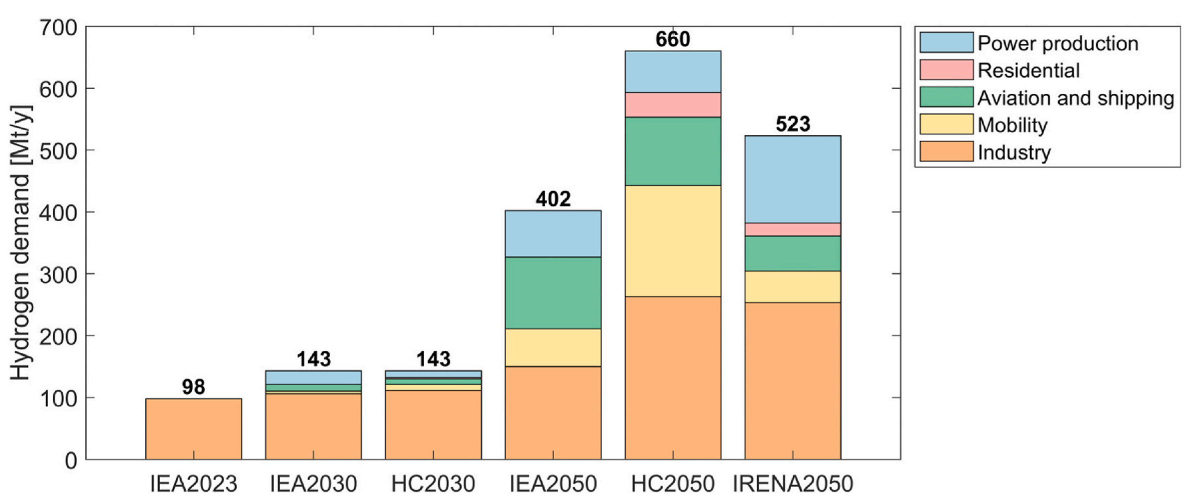

Fig. 3. Hydrogen demand and details on how it is distributed in the different scenarios.

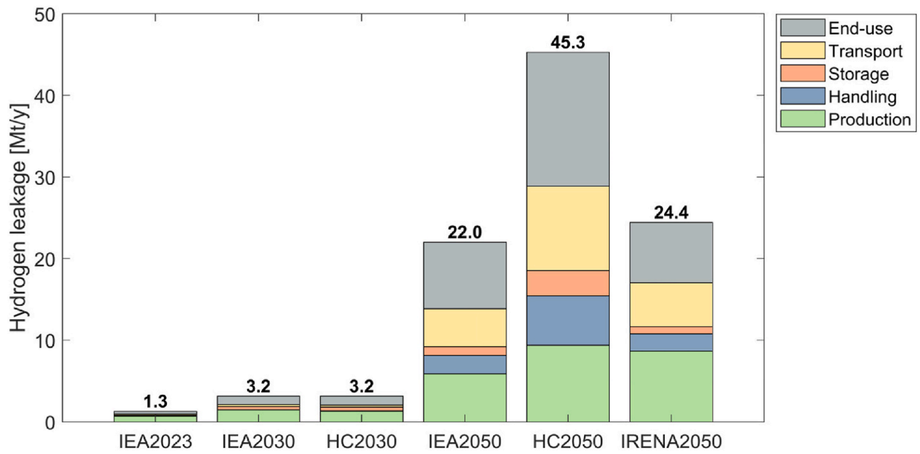

Fig. 4. Comparison of hydrogen leakages in the different scenarios. The results are based on the average leakage rates shown in Fig. 2.

leakages. Similar considerations are valid for the HC2030 scenario, in which the total leakage rate of the supply chain is again equal to 2.2%, with a slightly lower contribution from the production stage due to different hydrogen production pathways.

In the IEA2050 scenario, the hydrogen leakage is estimated at 22 Mt, corresponding to a 5.5% leakage rate along the value chain. More than one-third (37%) of the hydrogen losses are expected to occur in the end-use stage, while hydrogen production contributes to 26.8%. Hydrogen handling and transport account for 31.4%, while hydrogen storage has a minor impact, representing less than 5% of the total losses.

In the HC2050 scenario, the hydrogen losses along the supply chain are estimated at 45.3 Mt, which results in a total leakage rate of 6.9%. The largest leakages are observed in the end-uses, which account for 36.2% of the total losses. As a direct result of the hydrogen flows in the supply chain, in this scenario the handling and transport phases have a larger impact, contributing to 36.2%. The contribution of hydrogen production stands at around 21% of the total losses, corresponding to 9.4 Mt.

In the IRENA2050 scenario, a total of 24.4 Mt of hydrogen is lost along the supply chain, corresponding to a 4.7% leakage rate. In this scenario, the main leakage phenomena take place in the production phase, which generates 35.5% of the total hydrogen emissions. End-use applications are confirmed to be one of the major sources of hydrogen leakages, contributing to one-third of the total hydrogen losses.

These results are consistent with the values reported by Fan et al. in Ref. [25] and the Hydrogen Council in Ref. [38], which indicated leakage rates of 5.6% and 4.5% for the hydrogen supply chain in 2050.

To clearly identify the most critical processes within the future hydrogen supply chain, the leakage breakdowns are shown in Fig. 5 (for 2030 scenarios) and Fig. 6 (for 2050 scenarios).

Analyzing the IEA2030 scenario, it is evident that hydrogen generation through electrolysis is the cause of more than 50% of the total leakages occurring in the production stage, although it covers only 32.1% of the hydrogen demand. This result emphasizes the potentially critical role of electrolysis in the 2030 hydrogen supply chain and underscores the importance of addressing and mitigating its leakage-related challenges. In the handling, storage and transport stages, the main source of leakage is represented by compressed hydrogen, as a direct result of the hydrogen flows in the supply chain. Despite the high leakage rates associated with refueling operations, road mobility has limited impact in 2030 because of the lower demand compared to the other end-uses.

The analysis of the HC2030 scenario reveals a significant contribution from hydrogen production through SMR with CCUS, which accounts for around one-third of the overall hydrogen leakages associated with the production stage. In the handling and storage stages, the

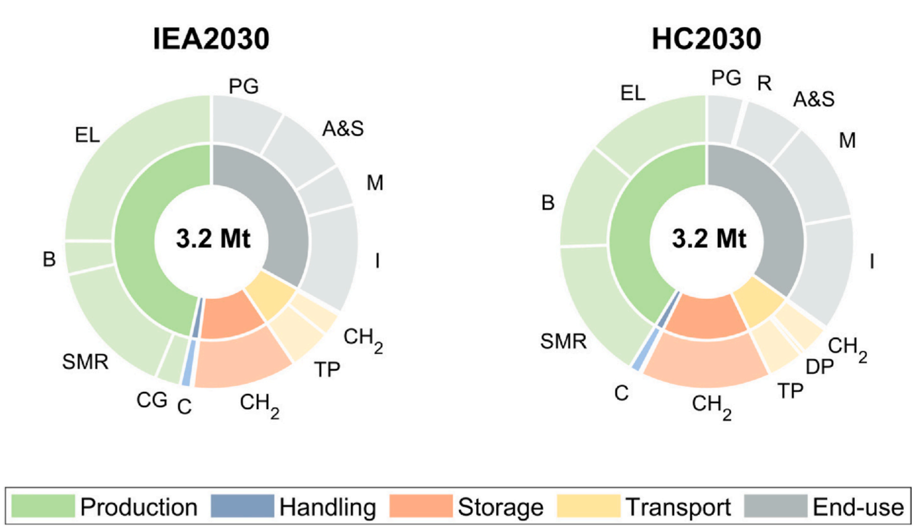

Fig. 5. Hydrogen leakage breakdown for the 2030 scenarios. The results are based on the average leakage rates shown in Fig. 2. The following acronyms are adopted in the figure: A&S = aviation and shipping, B = steam methane reforming with CCUS (blue hydrogen), C = compression, CG = coal gasification, CH_2 = compressed hydrogen, DP = distribution pipelines, EL = electrolysis, I = industry, M = mobility, SMR = steam methane reforming, PG = power generation, R = residential, TP = transmission pipelines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

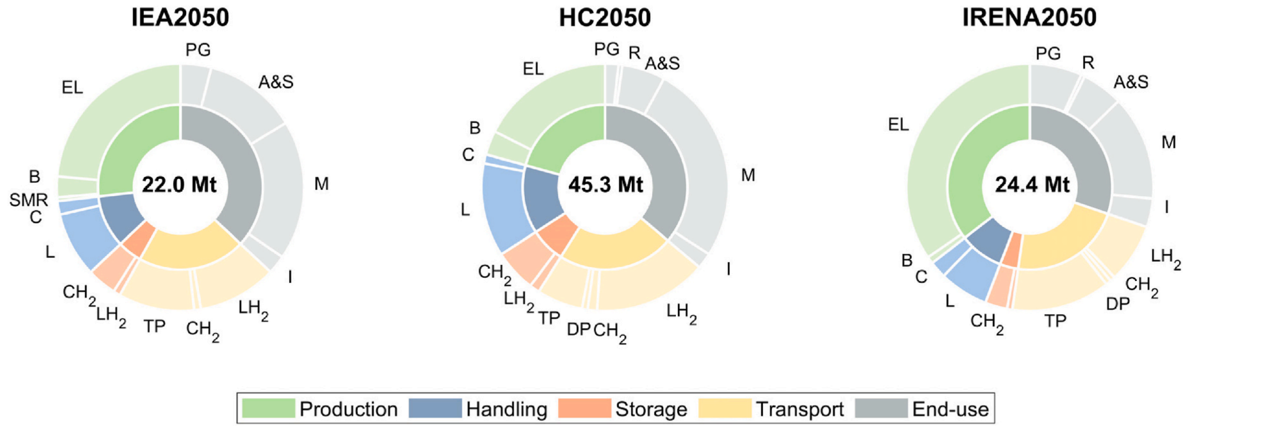

Fig. 6. Hydrogen leakage breakdown for the 2050 scenarios. The results are based on the average leakage rates shown in Fig. 2. The following acronyms are adopted in the figure: A&S = aviation and shipping, B = steam methane reforming with CCUS (blue hydrogen), C = compression, CG = coal gasification, CH_2 = compressed hydrogen, DP = distribution pipelines, EL = electrolysis, I = industry, L = liquefaction, LH_2 = liquid hydrogen, M = mobility, SMR = steam methane reforming, PG = power generation, R = residential, TP = transmission pipelines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

contribution of liquid hydrogen is almost negligible due to the limited adoption of this technology. Focusing on the transport stage, unlike in the IEA20230 scenario, distribution pipelines also contribute to hydrogen leakages, albeit to a small extent, as they are needed to serve residential applications. Among the end-users, industry and mobility are clearly the dominant leakage sources, accounting for 36% and 32%, respectively.

The emissions breakdowns for the 2050 scenarios share several common aspects. Firstly, liquid hydrogen emerges as a key contributor to hydrogen leakages in handling and transport phases. Additionally, it indirectly impacts end-user applications, which are dominated by road mobility that considers also the leakages taking place during the refueling operations. Moreover, electrolysis is confirmed as the major leakage source in the production stage. Specifically, it accounts for over one-third of the overall leakages across the entire supply chain in the IRENA2050 scenario. However, each scenario presents unique characteristics, with key factors shaping the variations in hydrogen leakage patterns. The IEA2050 scenario does not foresee hydrogen use in residential applications, which results in no leakages in the distribution network. Conversely, both HC2050 and IRENA2050 consider the residential sector as an end-user, with the resulting leakages in the transport and use phases that account for around 1%. In the IRENA2050 scenario, the hydrogen leakages in power generation account for more than double compared to the other scenarios, contributing to 6.8% of the total losses in the supply chain.

To investigate the impact of uncertainty on hydrogen leakage rates, the analysis is also conducted adopting the minimum and the maximum values reported in Fig. 2. As shown in Table 2, findings reveal great variability in the estimated hydrogen leakages. Specifically, a variation range between +166% and −61% can be observed for the IEA2030 scenario. In the HC2030 scenario, the leakages can increase or decrease by more than a factor two when adopting the maximum and minimum leakage rate, respectively. Larger variations can be noted for the IEA2050 scenario, in which leakages may rise by 200% or drop by 72%. Comparable results are obtained for the HC2050 scenario, with a potential increase of +182%. The IRENA2050 scenario exhibits the largest variability, with leakages potentially increasing by 252% or decreasing by 79%. These wide fluctuations arise from the significant reliance on electrolysis, which is one of the processes characterized by the highest uncertainties.

Table 2
Hydrogen leakages in the different scenarios, calculated using the minimum, average and maximum leakage rates reported in Fig. 2.

Scenario	Minimum [Mt]	Average [Mt]	Maximum [Mt]
IEA2023	0.7	1.3	2.3
IEA2030	1.2	3.2	8.4
HC2030	1.3	3.2	7.1
IEA2050	6.2	22.0	66.2
HC2050	11.9	45.3	127.7
IRENA2050	5.3	24.4	86.1

Finally, based on the current and projected hydrogen demand and the estimated hydrogen losses, the leakage rates along the supply chain can be computed for the various scenarios. As shown in Fig. 7, when considering the minimum leakage rate values, hydrogen losses impact less than 2%. Conversely, when maximum leakage rates are applied, hydrogen losses can reach approximately 20%.

4. Discussion

The results presented in the previous chapter quantify the magnitude of hydrogen losses (expressed in mass and as a percentage leakage rate along the supply chain) across multiple scenarios. In line with the recommendations of the Intergovernmental Panel on Climate Change (IPCC, [44,45]), emissions are reported in this study primarily as mass of hydrogen released, since the aggregation into CO_2-equivalent terms involves significant uncertainty [18]. Nevertheless, for contextual purposes, this section also provides indicative CO_2 equivalent values using GWP metrics to illustrate the potential climate relevance of these emissions.

Hydrogen is an indirect greenhouse gas, and its impact is predominantly mediated by its interference with the hydroxyl radical (OH), which leads to increased atmospheric concentrations of methane, ozone, and water vapor. These processes justify the need to assign GWP values to hydrogen. The global warming impact of hydrogen is presented using both GWP_{100} and GWP_{20} metrics. While GWP_{100} aligns with reporting conventions under the Paris Agreement, GWP_{20} provides additional insight into the short-term climate risks posed by hydrogen leakage, which are particularly relevant given its short atmospheric lifetime [46]. As stated in Section 1.1, recent literature suggests a GWP_{100} ranging from 11 ± 5 [13] to 12.8 ± 5.2 [15], while the GWP_{20} can reach values of about 33 ± 16 [16] (with a wide range due to both uncertainties in hydrogen lifetime and in radiative properties of indirect effect of CO_2), indicating a significantly stronger short-term climate impact.

When considering average values from Table 2 and applying a GWP_{100} of 11.6 [10], the hydrogen emission estimates for 2050 yields a global warming impact of approximately 255 Mt_{CO2eq}/year for the IEA2050 scenario and 525 Mt_{CO2eq}/year for the HC2050 scenario

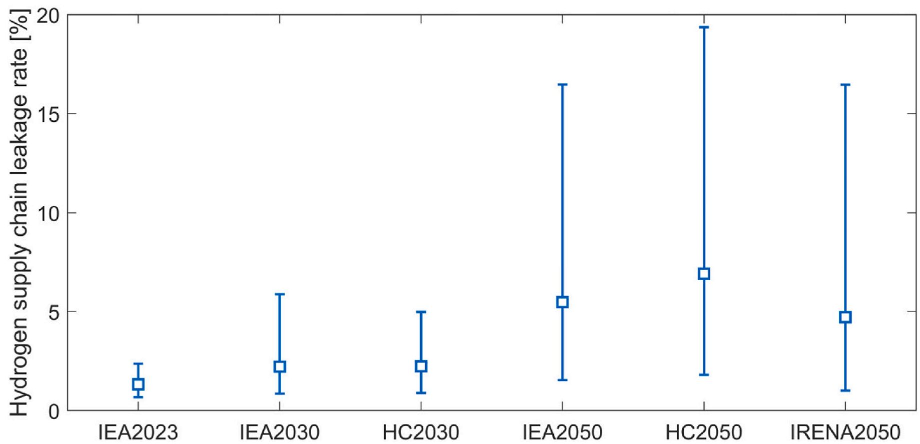

Fig. 7. Minimum-maximum variation in the leakage rates of the hydrogen supply chain.

(calculated using average values for both scenarios). Under maximum leakage assumptions, the climate impact could reach nearly 1.5 Gt_{CO2eq}/year (HC2050, maximum value), equivalent to roughly 4% of today's CO_2 emissions (i.e., 37.8 Gt_{CO2eq} in 2024 [47]). However, minimum leakage projections (IRENA2050, minimum) correspond to less than 0.2% of current global CO_2 emissions. It must be emphasized that these estimates involve significant uncertainty. First, the hydrogen GWP itself varies considerably across sources and is influenced by multiple atmospheric processes that are still under active investigation. Second, the emission estimates rely on limited empirical data, often derived from theoretical models or laboratory measurements.

This highlights the need for improved climate modelling and direct measurement capabilities. In particular, advances in hydrogen detection technologies are essential for supporting more accurate quantification of emissions across the full supply chain. Despite the availability of multiple hydrogen sensing technologies (e.g., optical, thermal, electrochemical, acoustic, thermal and resistive) available on the market [24], none currently achieves detection at ppb sensitivity levels, which would be necessary to detect low but climatically relevant leakages [8]. Each sensing technology exhibits distinct advantages and limitations, and none consistently outperforms the others across the whole range of applications and operating conditions (e.g., humidity, temperature, hydrogen concentration) [48].

Research efforts are focused on identifying innovative detection solutions or improving the existing technologies to reach sensitivity in the ppb range [49]. More in detail, resistive-based sensors offer a promising approach, potentially combining simplicity, cost-effectiveness, high sensitivity and stability, and rapid response times [48]. Electrochemical sensors can rapidly detect low hydrogen concentrations (around 10 ppm within 2 s [49]) with limited power consumption and reliable operation at high temperatures, although their use is still limited by cross-sensitivity to other gases and relatively high costs [48,50]. In addition, plasmonic hydrogen detectors based on palladium nanoparticles are emerging as a viable option, with improved detection limit below 1 ppm and high selectivity [18]. Furthermore, a laser spectroscopy-based sensor with a sensitivity of 10 ppb and response time below 1 s was successfully developed in 2023, but its commercialization is hindered by the considerably high cost [23]. It is thus evident that further research is still required to achieve precise and cost-effective solutions for hydrogen leakage detection and quantification. In this context, the U.S. Department of Energy (DoE) has recently introduced a dedicated 20 M$ funding scheme to support the development of low-cost and accurate hydrogen detecting technologies [8]. Additionally, the DoE has established ambitious performance targets for hydrogen sensors (primarily intended for safety applications) defining the requirements for concentration range, response time, operating temperature, environmental conditions, lifetime and cost [51].

Beyond improving sensing capabilities, a broader effort is needed to enable consistent and actionable data collection. Future developments should prioritize the definition of standardized protocols for measuring and reporting leakage rates across technologies and operational contexts, and the development of clear standards and regulations aimed at managing and reducing hydrogen emissions while promoting transparency and accountability. Training and awareness programs will also be crucial to ensure that industry stakeholders adopt detection and mitigation strategies effectively. In parallel, mitigation strategies should be advanced, particularly in the most leakage-prone phases, such as liquid hydrogen refueling and pipeline distribution systems [52].

Taken together, these considerations emphasize the need for a multidisciplinary approach to managing hydrogen leakages. The comprehensive assessment presented in this study can serve as a foundational reference for further research. In particular, future works could integrate these leakage estimates into regional and global climate models, allowing for a more accurate evaluation of the systemic impacts associated with large-scale hydrogen deployment.

5. Conclusions

Low-carbon hydrogen is widely acknowledged as a key player in the ongoing energy transition. However, once released into the atmosphere, hydrogen can act as an indirect greenhouse gas. Therefore, quantifying hydrogen leakages throughout the hydrogen supply chain is crucial for an accurate estimation of its potential environmental impact.

In this analysis, a comprehensive dataset of hydrogen leakage rates is provided, covering all stages of the hydrogen supply chain, from production and handling to storage, transport and end-uses. Average values and minimum-maximum variation ranges are derived to account for uncertainties and facilitate emissions assessments with ready-to-use data. Current hydrogen scenario as well as future projections for 2030 and 2050 are examined, allowing for detailed estimation of the hydrogen flows associated with each stage of the supply chain. The hydrogen leakages are then evaluated for the different scenarios and the most leakage-prone stages are identified.

From a sectoral perspective, the analysis indicates that electrolysis is the most leakage-prone among the hydrogen production pathways, although its leakage rate is affected by high uncertainty. In the coming decades, liquid hydrogen is expected to emerge as a key contributor to hydrogen losses during handling, transport and refueling operations. End-use applications are also responsible for a significant share, potentially accounting for up to one-third of total hydrogen losses.

Based on the findings from average scenarios, annual hydrogen leakages currently amount to 1.3 Mt and are projected to nearly triple by 2030, followed by a sharp rise exceeding 22 Mt by 2050. The corresponding hydrogen leakage rates of the supply chain are estimated at

1.3% in 2023, rising to 2.2% in 2030, and reaching between 5% and 7% by 2050. However, it should be noted that these estimates may be subject to considerable variability (especially for the long-term scenarios), reflecting the challenges in accurately measuring hydrogen leakages rates at the various stages of the supply chain. This uncertainty arises from technical limitations in existing hydrogen sensors and the early-stage development of hydrogen infrastructure. Concerning 2050 scenarios, results indicate that the total supply chain leakage rates could range from below 2% under optimistic projections to nearly 20% in worst-case estimates, highlighting large uncertainties still inherent in hydrogen technologies.

To provide climate-relevant context, hydrogen emissions have also been expressed in terms of CO_2-equivalent impact using a GWP_{100} of 11–13, following current scientific recommendations. As for the 2050 scenarios, considering a GWP_{100} of 11.6, these emissions could represent between less than 0.2% and up to 4% of today's global CO_2 emissions. However, this must be interpreted within the broader context of a full climate model, which would also account for the substantial CO_2 reductions enabled by replacing fossil fuels with low-carbon hydrogen.

These findings emphasize the importance of precise emissions quantification and effective mitigation strategies to ensure that hydrogen can achieve its intended climate benefits. By identifying the processes most susceptible to leaks, this analysis offers valuable insights for policymakers, researchers, and industry stakeholders aiming to minimize hydrogen losses and fully realize the environmental advantages of a hydrogen-based economy.

CRediT authorship contribution statement

Davide Trapani: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Marocco:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Massimo Santarelli:** Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.06.103.

Acronyms

A&S	Aviation and shipping
B	Blue hydrogen (steam methane reforming with CCUS)
C	Compression
CCUS	Carbon capture utilization and storage
CG	Coal gasification
CGS	Combustible gas sensor
CH2	Compressed hydrogen
DoE	Department of energy
DP	Distribution pipelines
EC	Electrical conductivity
EL	Electrolysis
FC	Fuel cell
GWP	Global warming potential
HC	Hydrogen council
HRS	Hydrogen refiling station
I	Industry
IEA	International energy agency
IPCC	Intergovernmental panel on climate change
IRENA	International renewable energy agency
L	Liquefaction
LH2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
M	Mobility
MS	Mass spectrometry
PG	Power generation
R	Residential
SMR	Steam methane reforming

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