Literature review on climate effects and leakage rates in a hydrogen economy

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Preface

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Acronyms and abbreviations

LCA	Life cycle assessment
GHG	Greenhouse gas
GWP	Global warming potential
ppb	Parts per billion
NMHC	Non-methane hydrocarbons
HCHO	Formaldehyde
OH	Hydroxyl radical
IPCC	Intergovernmental Panel on Climate Change
GWP100	Global warming potential for a time horizon of 100 years
GWP20	Global warming potential for a time horizon of 20 years
GTP	Global temperature potential
IEA	International Energy Agency

Executive summary

While hydrogen is widely recognized as an important future energy carrier because of its potential benefits through reduced pollutant and greenhouse gas (GHG) emissions, several studies in the last 20 years have raised the issue that a hydrogen economy would potentially lead to impacts on the global climate system. This report provides an overview of the latest technical and scientific knowledge on leakage rates in current and future hydrogen supply chains, as well as on the carbon dioxide equivalence of these emissions, expressed with the global warming potential (GWP) metric. The outcome of this report is expected to provide useful input data for 2.-0 LCA consultants to build a life cycle model of ammonia and e-methanol.

Even though hydrogen itself is not a radiative forcer, it can still be considered an 'indirect' GHG, given that once emitted to the atmosphere, its subsequent oxidation by hydroxyl radicals leads to increasing concentrations of GHG, namely methane, tropospheric ozone and stratospheric water vapor.

In the last 20 years, a few studies have attempted to determine a GWP for hydrogen, most of them focusing on GWP100. Studies published between 2001 and 2021 suggested GWP100 values that range between 3 and 6 kg CO_2-eq/kg hydrogen. However, several studies published in 2021-2022 led to a substantial increase in the GWP100 values, up to 11-13 kg CO_2-eq/kg hydrogen. This increase is the result of including in the models the effects of hydrogen in the stratosphere, namely the increase in stratospheric water vapor. For this reason, we propose the use of these higher GWP100 values for LCA/carbon footprint purposes.

As expected for a gas with a relatively short atmospheric lifetime of around 2 years, the value of GWP increases when a shorter time horizon is considered. The GWP20 for hydrogen is approximately three times higher than the corresponding GWP100 value.

Regarding hydrogen losses or leakage, the main conclusion is that quantitative data on these losses in current hydrogen systems are scarce. The existing data in the literature originate from theoretical assessments, simulation, or extrapolation rather than measures from operations. We have nevertheless found assumed or calculated leakage rates for several activities involved in current and hypothetical hydrogen supply chains, namely for:

- Production
- Distribution
- Final use

Values are extremely variable from source to source, although some patterns are consistent, such as the higher leakage rates expected for liquid hydrogen supply chains, compared to compressed hydrogen. Regarding the use of published leakage rates for LCA/carbon footprint purposes, care must be taken if data from different sources are used, given that they might overlap (a hypothetical example would be a study providing leakage values for production and compression, while another could provide values for compression and transport). This can be avoided if all values are taken from the same source.

When a full supply chain or even a global hydrogen economy is considered, some authors suggest that overall leakage could reach up to 10% or more, however these values are usually used as worst-case assumptions, rather than the most likely outcome. Studies assessing leakages with a higher level of detail tend to come up with upper limits of 5% or below.

Regarding potential impacts of hydrogen emissions on stratospheric ozone depletion, the existing evidence from models is that that there is no discernible impact as a result of adopting a global hydrogen economy.

1 Background and goal

2.-0 LCA consultants is interested in determining the life-cycle environmental impact of ammonia and e-methanol. Both fuels can in turn be produced from so-called “green, blue and grey” hydrogen (see Box 1), and therefore the life-cycle impact of ammonia and e-methanol is closely linked to that of hydrogen.

Box 1. Grey, blue and green hydrogen.

Grey hydrogen:
The most common form of hydrogen production currently. Grey hydrogen is created from natural gas or methane using steam methane reformation but without capturing the carbon dioxide generated by the process as a by-product.

Blue hydrogen:
Blue hydrogen is produced following the same process as in grey hydrogen, with the main difference that carbon dioxide is captured and stored permanently underground, thus avoiding its emission to the atmosphere.

Green hydrogen:
Green hydrogen is produced using electricity from renewable energy sources, such as solar or wind power, to electrolyze water. In this process an electrochemical reaction splits water into its components of hydrogen and oxygen. The production process does not directly emit any carbon dioxide.

While hydrogen is widely recognized as an important future energy carrier because of its potential benefits through reduced pollutant and greenhouse gas (GHG) emissions, several studies in the last 20 years have raised the issue that a hydrogen economy would potentially lead to impacts on the global climate system, through increased atmospheric hydrogen levels as a result from leakage during hydrogen production, storage, transmission and distribution (see section 3), and given that hydrogen has been found to be an “indirect” GHG (see section 2). This prompts the questions whether a global hydrogen economy would have consequences for global warming and ultimately whether a hydrogen economy would be better or worse than the fossil-fuel economy that it replaces (Derwent et al. 2006).

Therefore, in order to perform a complete LCA of ammonia and e-methanol as shipping fuels, especially in terms of GHG emissions, it is crucial to include in such studies state-of-the-art information on the expected hydrogen leakage rates and on the carbon dioxide equivalence of these emissions.

The aim of this report is to provide an overview of the latest technical and scientific knowledge on leakage rates in current and future hydrogen supply chains, as well as on the carbon dioxide equivalence of these emissions, expressed with the global warming potential (GWP) metric. The study has been conducted as a literature review, mainly addressing peer-reviewed scientific articles as well as selected technical reports, which are cited throughout the report. The outcome of this report is expected to provide useful input data for 2.-0 LCA consultants to build a life cycle model of ammonia and e-methanol.

2 Global warming potential of hydrogen

2.1 Hydrogen in the atmosphere: sources and sinks

The presence of molecular hydrogen in the atmosphere has been recognized for a long-time, with the first reliable measurements being reported by Paneth (1937). Its major sources and sinks, however, were not identified before the early 1970s (Schmidt 1974). Currently, hydrogen has an average tropospheric mixing ratio[1] of about 530 ppb (Novelli et al. 1999). It is, thus, the second most abundant oxidizable trace gas in the troposphere (Ehhalt and Rohrer 2009) and it has an average atmospheric lifetime of approximately 2 years (1.4-2.5 years) (Arrigoni and Bravo Diaz 2022).

The current atmospheric hydrogen budget is subject to substantial uncertainty. It is presented in Table 1, combining the ranges for the different sources and sinks reported in Arrigoni and Bravo Diaz (2022).

Table 1. The global hydrogen budget (Arrigoni and Bravo Diaz 2022).

Sources and sinks	**Tg hydrogen/year**
Sources	
Nitrogen fixation in oceans	3-6
Photo-oxidation of methane and other hydrocarbons in the atmosphere	29-51
Nitrogen fixation in soils	3-6
Fossil fuel combustion	14-20
Biomass burning	9-20
Geological sources	0-31
Hydrogen industry	0-8
Sinks	
Soil uptake	40-90
Oxidation in the atmosphere	8-25

The dominant source of hydrogen in the atmosphere is not a direct emission, but the result of chemical oxidation reactions of other compounds released to the atmosphere. In particular, the photo-oxidation of methane and non-methane hydrocarbons (NMHC) generates approximately 40 Mt of hydrogen per year (29-51 Tg/year). Most NMHC form formaldehyde (HCHO) when they are oxidized in the atmosphere, and this in turn produces hydrogen when HCHO reacts with sunlight (photolysis):

$HCHO + h\nu \rightarrow H_2 + CO$

The main direct sources of hydrogen emissions to the atmosphere are fossil fuels (14-20 Tg/year), primarily from combustion processes associated with transportation, biomass burning (9-20 Tg/year), and nitrogen fixation both on land and oceans (6-12 Tg/year). Other sources that are currently not included in most models are geological sources (0-31 Tg/year), with the largest contribution likely arising from the seepage of hydrogen from underground reservoirs (Zgonnik, 2020), and industrial hydrogen losses. Assuming a 10% loss rate as a worst case for the current hydrogen industry, the contribution of the latter is a maximum of 8 Tg/year. Adding up all sources, total hydrogen production is believed to be 60-140 Tg/year, with the (direct) anthropogenic emissions accounting for approximately 15%.

Regarding sinks, they amount to 50-110 Tg/year, with the main one being soil uptake. The process is driven by bacteria, and it accounts for over 75% of total removals. The magnitude of the soil sink is modulated by soil

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[1] The mixing ratio is equivalent to the mole fraction, in this case the moles of hydrogen per mole of (dry) air.

temperature, soil moisture, and the activity of hydrogen consuming organisms (Leung et al. 2020). Although there has been recent progress in understanding the behavior of these hydrogen-consuming bacteria, current knowledge on this process is limited. It is well known, though, that the dominance of this soil sink is the reason why hydrogen is less abundant in the Northern Hemisphere than in the Southern Hemisphere, with about 3% more hydrogen in the latter (Novelli et al. 1999). This is due to the fact most of the land mass, and therefore the sink potential, is in the northern hemisphere. Hydrogen in the atmosphere not removed by soil bacteria is oxidized, mainly via reaction with the naturally occurring hydroxyl radical (OH) in the troposphere (see **¡Error! No se encuentra el origen de la referencia.**). This reaction is the driver for the indirect global warming impact of hydrogen, as described in the next section.

2.2 Hydrogen as an indirect greenhouse gas

Hydrogen is a homonuclear diatomic molecule with no dipole moment (a separation of electrical charge) and therefore it cannot not absorb infrared radiation and warm the Earth's atmosphere (Derwent et al. 2020). However, the oxidation of hydrogen in the atmosphere leads to increasing concentrations of greenhouse gases in both the troposphere and stratosphere.

As a result of the oxidation of hydrogen in the atmosphere (Ocko and Hamburg (2022):

- Less OH is available in the troposphere to react with methane. Since methane's reaction with OH is its primary sink, this leads to a longer atmospheric lifetime for methane, increasing the warming effect of the latter.
- The production of atomic hydrogen from hydrogen oxidation in the troposphere leads to a series of reactions that ultimately form tropospheric ozone, the third most important man-made greenhouse gas after carbon dioxide and methane (IPCC 2013).
- In the stratosphere, the oxidation of hydrogen increases water vapor, which, in turn, increases the infrared radiative capacity of the stratosphere, leading to stratospheric cooling and an overall warming effect on the climate because energy emitted out to space is now from a cooler temperature.

These indirect effects were raised for the first time around 20 years ago (see Prather 2003). Since then, several attempts have been made at quantifying the indirect warming impact of hydrogen using different metrics, most notably with the GWP. A review on the calculated GWP values found in the literature is provided in the next section.

2.3 Published Global warming potentials for hydrogen

The GWP was presented in the First IPCC Assessment report (Houghton et al. 1990) as a metric for transferring emissions of different greenhouse gases (GHG) to a common scale. In particular, the GWP for a time horizon of 100 years (GWP100) was later adopted as metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change and made operational in the 1997 Kyoto Protocol and COP21. Despite its serious limitations (see Shine 2009), the GWP100 remains to this date the most popular metric to assess GHG emissions, not only in the context of national GHG inventories, but also in LCA and carbon footprinting.

The GWP of a forcing agent depends on the time horizon over which the potential is calculated: gases which are quickly removed from the atmosphere (such as hydrogen) may initially have a large effect, but for longer time periods they become less important than gases such as CO_2, which have a much longer atmospheric lifetime. In this review we show, whenever they are available, the published GWP values for hydrogen in two time horizons: 100 years and 20 years.

To date, only a handful of studies have attempted to determine a GWP for hydrogen, most of them focusing on GWP100, even though other metrics, such as the global temperature potential (GTP) have also been addressed (see Hauglustaine et al. 2022). Table 2 lists all studies calculating GWP values for hydrogen, classified into two groups, namely those that did not include effects on the stratosphere (increased water vapor), published between 2001 and 2021, and those addressing the stratospheric effects, published in last two years. As it can be seen, there is a clear difference between these two groups of studies. The first group resulted in published GWP100 values focused on the tropospheric effects on methane and ozone, leading to mean GWP100 values that range between 3 and 6 kg CO_2-eq/kg hydrogen. However, once stratospheric effects have been addressed by the latest studies in 2021-2022, this has led to a substantial increase in the mean GWP100 values, up to 11-13 kg CO_2-eq/kg hydrogen.

Table 2. Published GWP100 and GWP20 values for hydrogen emissions.

Reference	GWP100	GWP20	Comments
Studies excluding effects on the stratosphere			
Derwent et al. (2001) Derwent et al. (2006)	5.8		Approximately 59% of the GWP value is associated to the methane response and 41% to the tropospheric ozone response. Effects on the stratosphere were not included.
Derwent (2018)	4.3 (0-9.8)		Provides a 95% confidence range. The GWP excludes effects on the stratosphere.
Derwent et al. (2020)	4.6 (4.4-4.9)		Approximately 50% of the GWP value is associated to the methane response and 50% to the tropospheric ozone response. Effects on the stratosphere were not included.
Field and Derwent (2021)	3.3±1.4		Approximately 75% of the GWP value is associated to the methane response and 25% to the tropospheric ozone response. Effects on the stratosphere were not included.
Studies including effects on the stratosphere			
Warwick et al. (2022)	10.9 (6.4-15.3)	33 (20-44)	Approximately one third of the GWP arises due to the stratospheric response, which was not considered in previous studies.
Hauglustaine et al. (2022)	12.8 ± 5.2	40.1 ± 24.1	The higher GWP100 compared to previous studies can be attributed to a higher methane radiative efficiency, and to stratospheric effects not included in the previous estimates, and to the longer hydrogen tropospheric lifetime (2.1 years) compared to earlier estimates (1.6 years).
Paulot et al. (2021); Arrigoni and Bravo Diaz (2022)	11±5		Value reported by Arrigoni and Bravo based on work by Paulot et al. (2021). One third of the forcing is due to the increased production of water vapour in the stratosphere.

Regarding the variability of hydrogen's GWP to the time horizon, only two studies do address GWP for both 100 years and 20 years (Warwick et al. 2022; Hauglustaine et al. 2022). As expected for a gas with a relatively short atmospheric lifetime, GWP increases when a shorter time horizon is considered. Both studies agree in determining that the GWP20 for hydrogen is approximately three times higher than the corresponding GWP100 value. According to Ocko and Hamburg (2022), the sensitivity of GWP to the time horizon is such that hydrogen's maximum GWP occurs for a time horizon of 7 years, with a mean value of 40 and a range of 25 to 60 based on the model uncertainties. The authors also show that the uncertainty is much larger for GWP20 than for GWP100.

3 Leakages in the hydrogen supply chain

Hydrogen can be produced from a wide variety of sources and used in a wide variety of applications, with supply chains containing different combinations of supply, handling and demand technologies. Being a tiny molecule, hydrogen is hard to contain and some losses to the atmosphere are to be expected. These losses can occur at many steps of the chain, including from electrolyzers, compressors, liquefiers, storage tanks, geologic storage, pipelines, trucks, trains, ships, and fueling stations (Ocko and Hamburg 2022).

In general, quantitative data on these losses in current hydrogen systems are scarce. This is because measurement efforts to date have been concentrated on safety concerns, regulations, and risk assessment, which are focused on larger leaks (Ocko and Hamburg 2022). Commercially available sensing technologies able to detect smaller leaks – that would impact the climate but not safety – are unavailable (Mejia et al. 2020). As a result, the existing data in the literature originate from theoretical assessments, simulation, or extrapolation rather than measures from operations (Fan et al. 2022). As Wuebbles et al. (2009) put it, “measurements of H_2 leaks in realistic conditions are badly needed”.

In this chapter we review the currently available data on hydrogen losses (referred to with the generic term “leakage”) in the supply chain. We were able to identify a total of 20 studies reporting values, although the quality and level of detail of the data vary widely. While some studies only take a single mean value for leakage in a hydrogen supply chain or for the whole global economy, others provide leakage rates for specific steps in the chain. In sections 3.1 to 3.3 we first review the data for each step of the supply chain, while in section 3.4 we provide an overview of the reported data for the entire supply chain.

3.1 Leakages during production

Hydrogen losses associated to different hydrogen production routes are shown in Table 3 and they range from 0 to 9.2%, depending on the authors and on the production process. There seems to be agreement among different authors in the fact that green hydrogen involves higher leakage rates than blue and grey hydrogen.

Table 3. Leakage rates for hydrogen production.

Reference	Process	Value
Cooper et al. (2022)	Hydrogen production from Biomass gasification	0.55% (0.1-1%)
	Blue Hydrogen production from coal	0.55% (0.1-1%)
	Blue Hydrogen production from natural gas	0.55% (0.1-1%)
	Green Hydrogen production	2.05% (0.1-4%)
Frazer-Nash Consultancy (2022)	Green hydrogen with venting and purging	3.32-9.2%
	Green hydrogen with full recombination of hydrogen from purging and crossover venting	0.24-0.52%
	Blue Hydrogen production and from biomass	0.25-0.5%
Fan et al. (2022)	Grey hydrogen	0.5-1%
	Blue hydrogen	1-1.5%
	Green hydrogen	2-4%
Arrigoni and Bravo Diaz (2022)	Green hydrogen, today	0.2%
	Blue hydrogen	0%
	Green hydrogen, 2030	0.03%

According to Frazer-Nash Consultancy (2022), Leakage in electrolyzers can occur through:

- Through casing and pipework;
- Through venting during start-up and shutdown;
- Contamination of the vented oxygen (hydrogen crossover);
- Purging or bleeding processes during operation to remove impurities.

According to the authors, leakage through the electrolyzer casing is likely to be negligible, while operational purging is the most significant mechanism. However, as they point out, it would be relatively easy to incorporate technology in the electolyzer to recombine the hydrogen purged and vented due to cross-over back into water. As it can be seen in Table 3, in such a scenario, leakage would most likely be below 1%, just like for blue hydrogen production.

It is also worth commenting on the leakage rates reported by Arrigoni and Bravo Diaz (2022), which were communicated by Air Liquide, based on operation feedback and know-how. The figures are substantially lower than those from the other two sources in Table 3, although no specific arguments are provided. The company expects that current leakage rates will decrease even further by 2030.

3.2 Leakages during distribution

3.2.1 Compression and liquefaction

Hydrogen can be transported in gaseous or in liquid form. The former typically involves compression, while the latter requires liquefaction. Only one of the reviewed studies (Cooper et al. 2022) does provide figures on these specific processes, as well as for the regasification process needed after transport in a liquid form. The proposed values by these authors are shown in Table 4. In the particular case of liquefaction, the authors provide three different values with approximately the same mean, but different range. We did not find the reason for these differences.

Table 4. Leakage rates for hydrogen compression, liquefaction and regasification.

Reference	Process	Value
Cooper et al. (2022)	Compression	0.18% (0.15-0.27%)
	Liquefaction	0.34% (0.15-2.21%)
	Liquefaction	0.33% (0.14-0.98%)
	Liquefaction	0.33% (0.01-2.04%)
	Regasification	0.002%

3.2.2 Transport by pipeline

Pipelines, including both dedicated hydrogen pipelines and natural gas blending systems, are the most important systems for hydrogen delivery and according to Fan et al. (2022) they demonstrate a low risk of leakage. Table 5 shows the leakage values found in the literature for this activity, even though some sources include not only the transport but also some form of storage. According to Fan et al. (2022), pipeline losses can be as low as 0.4%, but this increases when including storage in pressurized tanks, liquefaction tanks and salt caverns, that will incur mechanical loss (e.g., from pressurization, depressurization, permeation leakage, and accidents). For this reason, their loss of hydrogen from integrated pipeline-storage systems is estimated to be between 1-2% percent. Van Ruijven et al. (2011) suggests an even upper limit for pipeline transport, although storage is not included in their figures. They suggest a maximum of 5% leakage, but this is in a scenario where retrofitted natural gas pipelines are used to distribute hydrogen. Otherwise, all authors suggest pipeline leakage rates typically below 1%.

Table 5. Leakage rates for hydrogen transport by pipeline.

Reference	Process	Value
Cooper et al. (2022)	Transmission and storage	0.03% (0.02-0.05%)
	Transmission and storage	0.05% (0.04-0.06%)
	Distribution	0.08% (0.05%-0.12%)
	Distribution	0.08% (0.05%-0.16%)
	Distribution	0.02% (0.0003%-0.03%)
Frazer-Nash Consultancy (2022)	National Transmission System	0.04-0.48%
	Distribution Network	0.26-0.53%
Ramsden et al. (2013)	Pipelines	0.8%
Fan et al. (2022)	Pipeline transport and storage	1-2%
	Pipeline local distribution	0.2-0.4%
van Ruijven et al. (2011)	Pipeline	0.1-5%
Arrigoni and Bravo Diaz (2022)	Pipelines, today	1%
	Pipelines, 2030	0.7%

3.2.3 Transport by truck

Another hydrogen delivery method is by truck to fueling stations. Compared with pipeline systems, this method is both less important in terms of scale and leakier, mostly due to boil-off losses (Fan et al. 2022). Such losses occur when gaseous hydrogen has to be released from a cryogenic tank due to liquid hydrogen evaporating, in order to limit pressure rising in the tank (Ghaffari-Tabrizi et al. 2022). Table 6 displays the leakage values found in five different studies. It must be highlighted that in some cases values are not comparable to one another, as they include not only the transport activity per se, but also additional activities, such as liquefaction, compression, or storage once delivered to fueling stations. There seems to be agreement, though, on the fact that leakage is expected to be higher when transporting liquid hydrogen as opposed to compressed hydrogen. This is due to the above-mentioned boil-off losses. In spite of this, Arrigoni and Bravo (2022), based on data from Air Liquide, suggest that in the future (by 2030), these losses are expected to be reduced, from 10% to 2%. The reduction is expected to arise from improvements in the supply chain and from the recycling of the boil-off. Moreover, some of the hydrogen that is currently vented is expected to be flared in the future, so that only water vapor will be emitted to the atmosphere.

Table 6. Leakage rates for hydrogen transport by truck.

Reference	Process	Value
Frazer-Nash Consultancy (2022)	Road Trailering (gas)	0.3-0.66%
	Road Trailering (liquid)	3.76-13.2%
Ramsden et al. (2013)	Gas Trucks for Delivery	1%
	Liquefaction and truck delivery	2.8%
Fan et al. (2022)	Truck[a] transport and storage in fueling stations	2.5-5%
van Ruijven et al. (2011)	Truck[b]	2-5.5%
Arrigoni and Bravo Diaz (2022)	Compression and truck transport	1%
	Liquefier and truck transport, today	10%
	Liquefier and truck transport, 2030	2%

[a] Unspecified hydrogen format (gas/liquid).

[b] Interpreted from the source as transporting liquid hydrogen.

3.2.4 Transport by ship

Only two reviewed studies do report figures on hydrogen leakages associated to maritime transport. On the one hand, Cooper et al. (2022) provided a total of four figures, which correspond to four specific case studies for different hydrogen supply chains. It is not explicitly stated why maritime transport in each supply chain leads to a different leakage rate. A possible reason is that the duration of the transport is different and thus slip emissions from the engine, fueled by hydrogen, end up being different. On the other hand, van Ruijven et al. (2011) suggest higher leakage figures. According to the authors, the boil-off losses in hydrogen-fueled ships can be used as fuel and would not necessarily be emitted to the atmosphere, however, the amount of evaporated hydrogen is expected to be greater than the required amount of energy for the ship so that some losses to the atmosphere should be expected.

Table 7. Leakage rates for hydrogen transport by ship.

Reference	Process	Value
Cooper et al. (2022)	Shipping	0.03% (0-0.1%)
	Shipping	0.06% (0.01-0.17%)
	Shipping	0.03% (0.003-0.1%)
	Shipping	0.06% (0.01-0.17%)
van Ruijven et al. (2011)	Shipping	0-2%

3.2.5 Storage

Only two reviewed studies report specific values on leakages during hydrogen storage. As we have seen in previous sections, sometimes storage leakage is put together with that from other activities such as transport. Van Ruijven et al. (2011) reported leakage from liquid hydrogen tanks. They report that boil-off from these tanks is estimated at between 0.3 and 0.5% (de Wit and Faaij 2007; Sherif et al. 1997) and 2-3% per day (Amos 1998). They calculate an average leakage of 0.1-3% assuming a storage time of 7 days.

Table 8. Leakage rates for hydrogen storage.

Reference	Process	Value
Frazer-Nash Consultancy (2022)	Underground Storage (gas)	0.02-0.06%
	Above Ground Storage (gas)	2.8-6.8%
van Ruijven et al. (2011)	Storage of liquid hydrogen	0.1-3%

Frazer-Nash consultancy (2022) provides leakage figures for two alternative storage strategies for gaseous hydrogen, namely above-ground in tanks and in underground salt caverns. Such caverns have been used to store hydrogen for use in industrial processes over several decades. They are artificially generated cavities in underground rock salt (halite) formations created by the solution mining process, where halite is dissolved and removed in a controlled manner by injection of water (Williams et al. 2022). According to Frazer-Nash consultancy (2022), leakage from these formations is predicted to be negligible. The main leakage will be from the accompanying surface processing plants and includes deliberate releases from scheduled annual whole plant shutdown, annual component maintenance releases and emergency shutdown. Overall, losses are expected in the 0.02-0.06% range. Regarding above-ground storage, leakage rate is very dependent on the storage pressure, cylinder and valve material, the size of the cylinder, and most notably, of storage time. For an assumed leakage rate of 0.12 – 0.24 % per day and a duration of 30 days, the authors estimate a leakage range of 2.8-6.8%.

3.2.6 Fueling stations

The reviewed literature (see Table 10) provides leakage figures for fueling stations dispensing hydrogen in three formats: as compressed gas, as liquid, and cryo-compressed. According to Langmi et al. (2022) cryo-compressed hydrogen storage is a combination of the attributes of compressed hydrogen storage and cryogenic (i.e. liquid) hydrogen storage. One of the disadvantages of compressed hydrogen storage is the large volumes and high pressures required, while for cryogenic hydrogen storage the disadvantage is the inevitable boil-off losses. Cryo-compressed storage serves to curtail these challenges, by withstanding cryogenic temperatures and high pressures, thus improving the volumetric hydrogen storage capacity and safety over that of compressed hydrogen or liquid hydrogen.

According to Arrigoni and Bravo (2022), The dispensing of liquid hydrogen is expected to lead to higher losses than when dispensing compressed hydrogen, due to boil-off. However, their data, provided by Air Liquide, suggests that improvements are expected by 2030, especially regarding liquid hydrogen. Concerning cryo-compressed hydrogen, losses reported by Ramsden et al. (2013) seem to be somewhere in between those for compressed and liquid hydrogen.

Table 9. Leakage rates for hydrogen fueling stations.

Reference	Process	Value
Ramsden et al. (2013)	Forecourt dispensing, gas	0.5%-1.1%
	Cryo-Compressed Dispensing	3.1%
Arrigoni and Bravo Diaz (2022)	Fuelling station, gas, today	3%
	Fuelling station, gas, 2030	2%
	Fuelling station, liquid, today	8.5%
	Fuelling station, liquid, 2030	2%
Frazer-Nash Consultancy (2022)	Refuelling Stations, gas	0.25-0.89%

3.3 Leakages during use

According to Fan et al. (2022) End-use leakage risks are less understood than those from production and distribution, especially since there are future hydrogen end uses that do not exist today. They suggest the largest consumers of hydrogen by scale are and will remain within the industrial sector, namely chemical plants, refineries, and iron and steel producers. Based on the International Energy Agency's net-zero scenario (IEA 2021), these end users are expected to consume around 200 million tonnes of hydrogen by 2050, constituting close to 40% of the forecasted production in that year.

Table 10. Leakage rates for hydrogen by end use.

Reference	Process	Value
Frazer-Nash Consultancy (2022)	Residential	0.3-0.69%
	Gas Turbines	0.01-0.01%
	Fuel Cells with venting and purging	1.36-2.64%
	Fuel cell with full recombination of hydrogen from purging and crossover venting	0.56-1.02%
	Combustion Engines	0.3-0.66%
	Process Industry	0.25-0.5%
Fan et al. (2022)	Natural gas blending	0.5-0.9%
	Chemical synthetic fuel production	0.2-0.5%
	Iron and steel production	0.2-0.5%
	Electricity generation	1.5-3%
	Road transport	1-2.3%
	Aviation	3%
	Shipping	1-2.9%
	Refineries	0.2-0.5%
	Buildings	0.5-0.8%
	Other industries	0.2-0.5%
	Miscellaneous	0.5%
	Direct use onsite	0.2%
van Ruijven et al. (2011)	Fuel cell	0.1-1%

Based on the reviewed literature (Table 10), the highest leakage risk seems to be identified for aviation, shipping, electricity generation and road transport, as reported by Fan et al. (2022). Frazer-Nash consultancy also highlights potentially high leakage for fuel cells, if these do not recombine hydrogen from purging and crossover venting into water (similarly as explained in section 3.1 for electrolyzers).

3.4 Overall supply-chain leakage

In this section we provide an overview of leakage rates over the entire supply chain, as reported by several studies. As it can be seen in Table 11, we differentiate between two types of studies: those which assume a certain leakage rate, and those that calculate it. It appears that there is a certain tendency to find higher leakage values whenever these are assumed, than when they are the result of a calculation or a more detailed study. Eight out of 19 studies assuming a leakage rate expect it to reach (as an upper limit) 10% or above, while only two out of 14 studies calculating a leakage rate expect it to reach those levels. It must be borne in mind, though, that the values given by different studies are not necessarily comparable, as they assess completely different scenarios: some of them address specific supply chains (liquid hydrogen only, or hydrogen produced in a particular country with a particular technology and exported to another particular country), while others address the whole global economy, constituted by a mix of current or forecasted production, distribution and end-use options, which vary from study to study. Last but not least, some look at the current situation, while others address scenarios as far in the future as 2100.

The highest leakage rates, predicted for the overall hydrogen economy, are those suggested by Tromp et al. (2003) in their article published in the Science journal, namely from 10 to 20%. These figures were subsequently highly contested by several authors in a series of letters to the journal (Kammen and Lipman 2003; Lovins 2003; Lehman 2003). Disagreement with such high leakage rates are also found in several of the reviewed articles, for example:

- Warwick et al. (2022) points out that “…a leakage rate of 10% would be likely to be both unsafe and expensive”.
- Colella et al. (2005) states that “…a 10% leakage rate is an unlikely overestimate of the hydrogen leakage in a future hydrogen economy based on gaseous hydrogen transport and storage. Higher leakage would be expected in a liquid hydrogen economy, but it is not feasible due to the high energy consumption of liquefaction”.
- Finally, Schultz et al. (2003) states that “…in extreme cases, leak rates of 10 to 20% are possible… such losses are, however, very unlikely to occur on a large scale because of safety and economic considerations”.

From those studies in Table 11 that calculated leakage rates, only one suggests values as high as 10-20% (Arrigoni and Bravo 2022). This, however, is suggested by the company Air liquide specifically for liquid hydrogen supply chains operating today, which have high losses due to boil-off. The authors however suggest that by 2030 these losses will be reduced to 4-5%.

In summary, while some authors suggest overall leakage could reach up to 10% or more, these values are usually used as worst-case assumptions, rather than the most likely outcome. Authors assessing leakages with a higher level of detail, tend to come up with upper limits of 5% or below. Also, authors predicting leakages in future systems tend to be optimistic, generally claiming or forecasting lower values than those estimated for current systems. Whether or not such improvements become reality, it remains to be seen in the coming decades.

Table 11. Leakage rates for the overall hydrogen supply chain.

Reference	Value	Comments
Studies assuming leakage rates		
Warwick et al. (2022)	1-10%	Assumes a higher leakage than for natural gas supply chains
Derwent et al. (2020)	1-10%	Taken only as illustrative lower and upper bounds
Wuebbles et al. (2010)	2.5%	Future scenario for hydrogen applied for energy and transportation
Colella et al. (2005)	1-3%	For a gaseous-based hydrogen economy
Jacobson (2008)	3%	For wind-powered hydrogen fuel cell vehicles
Derwent et al. (2006)	1-10%	Taken only as illustrative lower and upper bounds
Hauglustaine et al. (2022)	1-10%	Assumed based on previous studies
Bond et al. (2011)	1-4%	In 2010
	0.5-4%	In 2020
	0.1-2%	In 2050
	0.01-0.5%	In 2100
Zittel and Altmann (1996)	<1%	For gaseous hydrogen
	1-10%	For liquid hydrogen
Kammen and Lipman (2003)	1-2%	the lower-end estimates corresponding to gaseous hydrogen delivery systems, and the higher end to liquid hydrogen
Ocko and Hamburg (2022)	1-10%	Stated as plausible best-case and worst-case leak rates
Warwick et al. (2004)	1-12%	Assumed lower and upper leakage rates, however the authors state that the upper limit is unlikely to occur on a large scale
Schultz et al. (2003)	3%	10% is also mentioned, but only as an unlikely, extreme case
Tromp et al. (2003)	10-20%	These values are rebutted by Kammen and Lipman (2003), Lovins (2003) and Lehman (2003)
Kammen and Lipman (2003)	1-2%	Mature systems, lower-end corresponding to gaseous hydrogen and the higher end to liquid hydrogen
Studies calculating leakage rates		
Fan et al. (2022)	2.7%	In 2020
	2.9-5.6%	In 2050
van Ruijven et al. (2011)	0.3-10%	For a low- and high-leakage supply chain. The latter involves more liquid hydrogen, more trucks and more transfuses between transport modes
Arrigoni and Bravo Diaz (2022)	4.2%	Compressed gas, today
	3%	Compressed gas, 2030
	10-20%	Liquid gas, today
	4-5%	Liquid gas, 2030
	1.2%	Distributed through pipeline, today
	<1%	Distributed through pipeline, 2030
	1.2%	In 2020
	0.8%	In 2030
	2%	In 2050
Cooper et al. (2022)	0.63-4.09%	Calculated for seven different supply chains
Frazer-Nash Consultancy (2022)	0.96-1.5%	In 2050

4 Other relevant findings

4.1 Hydrogen emissions and stratospheric ozone

Besides potential impacts on the climate, potential impacts of hydrogen emissions on stratospheric ozone depletion are also a common subject that has been subject to parallel research. As it has been mentioned in section 2.2, hydrogen acts as a source of water vapor in the stratosphere, which will in turn lead to increased stratospheric cooling (Forster and Shine 2002). This cooling may change the distribution of polar stratospheric clouds which play an important role in the formation of ozone holes and hence may delay the recovery of the ozone layer (Tromp et al., 2003). A review of scientific literature on this topic, performed by Derwent (2018) concluded that even though the number of studies is limited, they all point to the impact of large hydrogen leakages on the stratospheric ozone layer as being small. This was also concluded by a more recent study (Warwick et al. 2022), stating that there is no discernible impact on ozone recovery as a result of adopting a global hydrogen economy.

4.2 Fossil fuels are not free from hydrogen emissions

While we have at length discussed the potential leakages associated to a future hydrogen economy, it should nevertheless not be forgotten that the current fossil fuel economy is not free from hydrogen emissions either. As we have shown in **¡Error! No se encuentra el origen de la referencia.**, fossil fuels are currently one of the main sources of direct hydrogen emissions to the atmosphere, being responsible for 14-20 Tg/year, primarily from combustion processes associated with road-based transportation (Ehhalt and Rohrer 2009). In fact, several studies (Colella et al. 2005; Jacobson (2008) looking specifically at the replacement of combustion vehicles by an equivalent fleet powered by hydrogen fuel cells, found that the latter would involve lower hydrogen emissions than the former, assuming a hydrogen leakage rate of around 3% or lower. Lovins (2003) goes even further, boldly suggesting that a hydrogen economy, rather than increasing anthropogenic hydrogen emissions, would instead reduce them to a level well below natural hydrogen releases.

5 Conclusions

Even though hydrogen is not a radiative forcer by itself, it can still be considered an ‘indirect’ GHG, given that its oxidation once emitted to the atmosphere leads to increasing concentrations of GHG, namely methane, tropospheric ozone and stratospheric water vapor.

In the last 20 years, a few studies have attempted to determine a GWP for hydrogen, most of them focusing on GWP100. Studies published between 2001 and 2021 suggested GWP100 values that range between 3 and 6 kg CO_2-eq/kg hydrogen. However, several studies published in 2021-2022 led to a substantial increase in the GWP100 values, up to 11-13 kg CO_2-eq/kg hydrogen. This increase is the result of including in the models the effects of hydrogen in the stratosphere, namely the increase in stratospheric water vapor. For this reason, we propose the use of these higher GWP100 values for LCA/carbon footprint purposes.

As expected for a gas with a relatively short atmospheric lifetime of around 2 years, the value of GWP increases when a shorter time horizon is considered. The GWP20 for hydrogen is approximately three times higher than the corresponding GWP100 value.

Regarding hydrogen losses or leakage, the main conclusion is that quantitative data on these losses in current hydrogen systems are scarce. The existing data in the literature originate from theoretical assessments, simulation, or extrapolation rather than measures from operations. We have nevertheless found assumed or calculated leakage rates for several activities involved in current and hypothetical hydrogen supply chains, namely for:

- Production
- Distribution
- Final use

Values are extremely variable from source to source, although some patterns are consistent, such as the higher leakage rates expected for liquid hydrogen supply chains compared to compressed hydrogen. Regarding the use of published leakage rates for LCA/carbon footprint purposes, care must be taken if data from different sources are used, given that they might overlap (a hypothetical example would be a study providing leakage values for production and compression, while another could provide values for compression and transport). This can be avoided if all values are taken from the same source.

When a full supply chain or even a global hydrogen economy is considered, some authors suggest that overall leakage could reach up to 10% or more, however these values are usually used as worst-case assumptions, rather than the most likely outcome. Studies assessing leakages with a higher level of detail tend to come up with upper limits of 5% or below.

Regarding potential impacts of hydrogen emissions on stratospheric ozone depletion, the existing evidence from models is that that there is no discernible impact as a result of adopting a global hydrogen economy.

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