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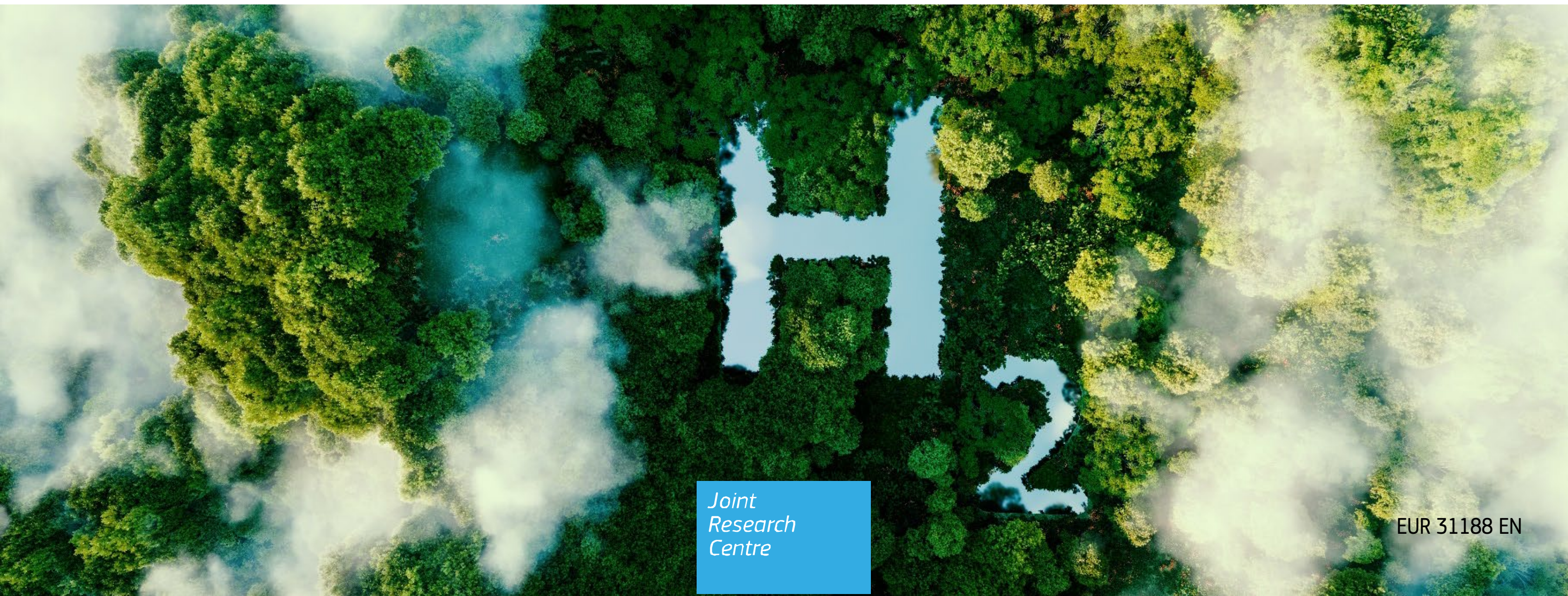
Hydrogen emissions from a hydrogen economy and their potential global warming impact

Summary report of the Clean Hydrogen Joint Undertaking Expert Workshop on the Environmental Impacts of Hydrogen

Arrigoni, A., Bravo Diaz, L.

2022



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Disclaimer

This report is not an opinion paper. It is the honest and balanced summary of the data, models, and viewpoints presented at the workshop, some of which may conflict with each other. The views expressed are purely those of the writers and contributors and may not in any circumstances be regarded as stating an official position of the European Commission, the Clean Hydrogen Joint Undertaking, the U.S. Department of Energy or the U.S. Government.

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Abstract

Hydrogen (H_2) is expected to be a key instrument to meet the European Union (EU) Green Deal main objective: i.e., climate neutrality by 2050. Renewable hydrogen deployment is expected to significantly reduce EU greenhouse gas (GHG) emissions by displacing carbon-intensive sources of energy. However, concerns have been raised recently regarding the potential global warming impact caused by hydrogen emissions. Although hydrogen is neither intentionally emitted to the atmosphere when used nor a direct greenhouse gas, hydrogen losses affect atmospheric chemistry, indirectly contributing to global warming. To better understand the potential environmental impact of a hydrogen economy and to assess the need for action in this respect, the Clean Hydrogen Joint Undertaking and the U.S. Department of Energy jointly organised, with the support of the European Commission, Hydrogen Europe, Hydrogen Europe Research, the Hydrogen Council, and the International Partnership for Hydrogen and Fuel Cells in the Economy, a 2-day expert workshop. Experts agreed that a low-carbon and, in particular, a renewable hydrogen economy would significantly reduce the global warming impact compared to a fossil fuel economy. However, hydrogen losses to the atmosphere will impact the lifetime of other greenhouse gases, namely methane, ozone, and water vapour, indirectly contributing to the increase of the Earth's temperature in the near-term. To minimise the climate impact of a hydrogen economy, losses should therefore be minimised, prevented, and monitored. Unfortunately, current loss rates along the hydrogen supply chain are not well constrained and are currently estimated to go from few percents for compressed hydrogen (1-4%), up to 10-20% for liquefied hydrogen. Both the global warming impact of hydrogen emissions and the leakage rates from a developed hydrogen economy are subject to a high level of uncertainty. It is therefore of paramount importance to invest in developing the ability to accurately quantify hydrogen emissions, as well as engage in more research on hydrogen leakage prevention and monitoring systems. More data from the hydrogen industry and improved observational capacity are needed to improve the accuracy of the global hydrogen budget. Finally, it is recommended to always report the amount and location of hydrogen emissions when environmental assessments are performed. There is a range of emission metrics and time scales that are designed to evaluate the climate impacts of short-lived GHG emissions compared to CO_2 (i.e., CO_2 equivalents). The metric choice must depend on the specific policy goal, as they can provide very different perspectives on the relative importance of H_2 emissions on the climate depending on the time horizon of concern. These differences need to be viewed in the context of the specific policy objectives.

1 Introduction

Hydrogen is expected to be a key instrument to meet the European Union (EU) Green Deal main objective: i.e., climate neutrality by 2050 (European Commission, 2019). To align with that objective, the EU is planning to ramp up its renewable hydrogen production: the initial target of 10 Mt per year of renewable hydrogen production by 2030 set out in the hydrogen strategy for a climate-neutral Europe (European Commission, 2020) has been recently raised to 20 Mt in the framework of the REPowerEU strategy for more affordable, secure and sustainable energy (European Commission, 2022). By 2050, hydrogen could provide more than 20% of the total energy demand in Europe (Fuel Cells and Hydrogen Joint Undertaking, 2019) and globally (Hydrogen Council and McKinsey & Company, 2021).

Renewable hydrogen deployment is expected to significantly reduce EU greenhouse gas (GHG) emissions by displacing carbon-intensive sources of energy. On average, the Hydrogen Council (2017) estimated that the production of each kilogram of renewable hydrogen would allow the saving of 10.9 kg of CO_2 equivalents (CO_2e). A hydrogen economy could hence abate some 80 Gt of CO_2e by mid-century and some 730 Mt of CO_2e by 2030 (Hydrogen Council and McKinsey & Company, 2021). However, concerns have been raised regarding the potential greenhouse gas effect caused by hydrogen emissions (Derwent et al., 2001; Warwick et al., 2022). Although hydrogen is neither intentionally emitted to the atmosphere when used nor a direct greenhouse gas (i.e., the hydrogen molecule does not interact with the incoming solar radiation, nor with the infrared radiation emitted back by our planet), hydrogen losses (and natural emissions) affect the atmospheric chemistry, contributing to global warming.

To better understand the potential climate impact of a hydrogen economy and to assess the need for action in this respect, the Clean Hydrogen Joint Undertaking (JU)[1] and the U.S. Department of Energy organised jointly, with the support of the European Commission, Hydrogen Europe, Hydrogen Europe Research, the Hydrogen Council, and the International Partnership for Hydrogen and Fuel Cells in the Economy, a 2-days expert workshop.

1.1 Workshop objectives and speakers

The workshop took place on the 31st of March and the 1st of April 2022, and was divided into two main sub-topics: the global warming impact of hydrogen, and detection methods and quantification of hydrogen losses. The workshop was chaired by Alberto Garcia Hombrados, project officer of the Clean Hydrogen JU. Welcoming remarks were given by the executive director of the Clean Hydrogen JU (Bart Biebuyck), the head of unit of Directorate-General for Climate Action of the European Commission (Willem Van Ierland), and the director of the Hydrogen and Fuel Cell Technologies Office of the U.S. Department of Energy (Sunita Satyapal).

The three main objectives of the workshop were:

1. Provide insights on the current knowledge on the global warming impact of hydrogen;
2. Share evidence-based information on human-made hydrogen emissions (sources, quantities, etc.);
3. Support reaching a better understanding of the climate impact of hydrogen, and assessing the need for action.

The list of speakers for day 1 and 2 of the workshop is reported in Table 1 and Table 2, respectively. After the presentations, joint discussions took place on both days. The discussion was moderated by the Clean Hydrogen JU, and also saw input from Hydrogen Europe (Grzegorz Pawelec and Jorgo Chatzimarkakis), Hydrogen Europe Research (Laurent Antoni and Louis Mazurkiewicz), Hydrogen Council (Andrei V. Tchouvelev), European Commission (Pietro Moretto from the Joint Research Centre), U.S. Department of Energy (Sunita Satyapal and Christine Watson), and International Partnership for Hydrogen and Fuel Cells in the Economy (Tim Karlsson).

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[1] The Clean Hydrogen JU is a unique public private partnership supporting research and innovation activities in hydrogen technologies in Europe, with the goal of contributing to the European climate neutrality. The three members of the JU are the European Commission, Hydrogen Europe and Hydrogen Europe Research.

Table 1. Day 1 presentations

Presenter	**Organisation**	**Title**
Maria Sand	Centre for International Climate Research (CICERO)	Climate and environmental impacts of hydrogen emissions
Fabien Paulot	National Oceanic and Atmospheric Administration (NOAA)	Atmospheric budget of hydrogen: implications for assessing the environmental impact of a hydrogen transition
David Stevenson	University of Edinburgh	Modelling atmospheric H_2 and estimating its Global Warming Potential
Steven Hamburg	Environmental Defense Fund (EDF)	Future hydrogen economy: Leakage can undermine climate benefits of decarbonisation
Didier Hauglustaine	Laboratory for Sciences of Climate and Environment (LSCE)	Climate benefit of a future hydrogen economy
Volker Grewe	German Aerospace Center (DLR)	AHEAD results in terms of CO_2 and H_2O atmospheric impact
Cathy Clerbaux	National Centre for Scientific Research (CNRS)	Environmental impacts of hydrogen: Ammonia (NH3) - impact on air quality and climate and detection from space

Table 2. Day 2 presentations

Presenter	**Organisation**	**Title**
Stephen Bradley	European Industrial Gas Association (EIGA)	Hydrogen fugitive emissions
Guy de Reals	Air Liquide	Hydrogen release: a supply chain overview
Pere Margalef and Davide Scrocchi	SNAM	Hydrogen leakage climate impact in the gas midstream
William Buttner and Kevin Hartmann	National Renewable Energy Laboratory (NREL)	Hydrogen releases quantification: I) Sensors and detection tools; II) Leak rate quantification
Ethan S. Hecht and Austin M. Glover	Sandia National Laboratories	Detection and monitoring tools for quantification of hydrogen releases, benchmark against methane
Didier Jamois and Christophe Proust	MultHyFuel project; French National Institute for Industrial Environment and Risks (INERIS)	Hydrogen release: detection, monitoring tools for quantification; Industrial compatible techniques for detection and flowrate estimates
Rod Robinson	National Physical Laboratory (NPL); European Association of National Metrology Institutes (EURAMET)	EURAMET Project Decarb and metrology aspects of hydrogen emission measurement

1.2 Report structure

This report aims to provide an overview of the presentations and discussions that took place during the 2-day workshop, and to summarise the main outcomes. Instead of summarising each individual presentation, the report combines the information provided by the different speakers. First, an overview of the hydrogen budget in the atmosphere is provided (chapter 2), highlighting the main sources and sinks of hydrogen to the atmosphere and the resulting role in warming the planet. Chapter 3 presents an overview of the potential implications for climate change of a future hydrogen economy, including the potential replacement of fossil fuels and the impact of hydrogen losses. In Chapter 4 the state of the art and current challenges for hydrogen leakage prevention, monitoring, and quantification are presented. Finally, conclusions and recommendations based on the presentations and discussions sparked during the workshop are provided in chapter 5.

In the report the terms “source”, “emission”, “loss”, “release”, and “leak” (or “leakage”) will be used related to hydrogen with the following meaning:

- Source: any activity adding hydrogen to the atmosphere (anthropogenic or natural, including H_2 indirect production via chemical reactions in the atmosphere);

- Emission: any activity adding hydrogen to the atmosphere directly (anthropogenic or natural, excluding H_2 production in the atmosphere resulting from chemical reactions);

- Loss: any H_2 addition to the atmosphere from anthropogenic activities, including releases and leaks;

- Release: any planned, foreseen, and/or necessary H_2 addition to the atmosphere from anthropogenic activities (e.g., for safety reasons, depressurisation events);

- Leak or leakage: any unexpected, accidental, and/or unintended H_2 addition to the atmosphere from anthropogenic activities.

2 Global warming impact of hydrogen emissions to the atmosphere

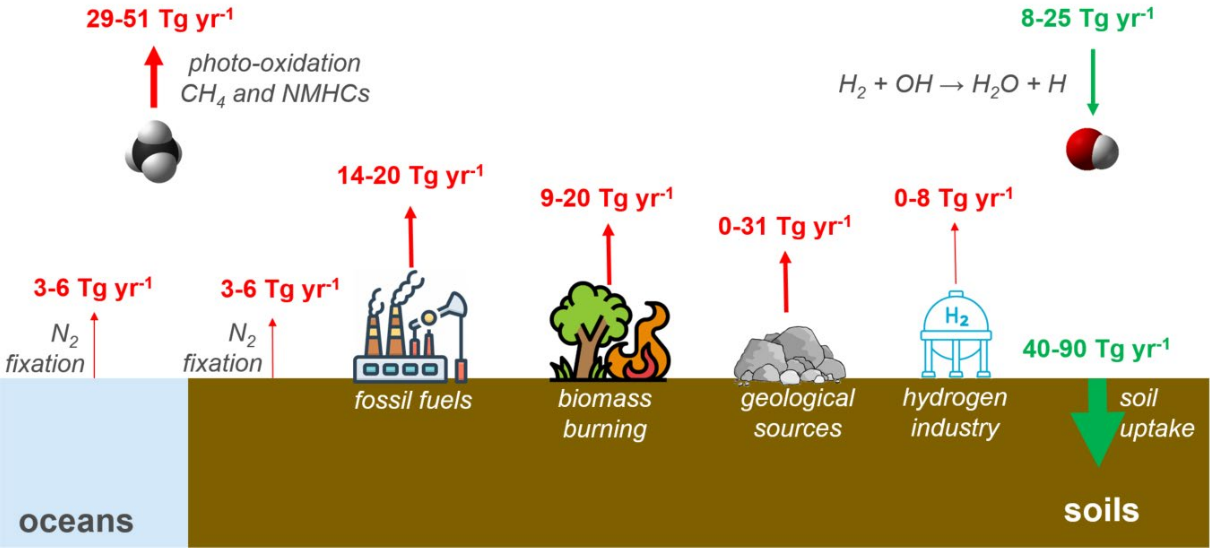
In this section the potential global warming impact from hydrogen emissions is presented, first introducing the hydrogen atmospheric budget (2.1), then presenting the current best estimates for the different global warming metrics (2.2).

2.1 Hydrogen atmospheric budget

2.1.1 Current budget

Hydrogen is fairly abundant in the atmosphere, with a concentration of approximately 0.5 parts per million by volume (ppmv), and an average lifetime of approximately 2 years (1.4-2.5 years). The atmospheric hydrogen budget is presented in Figure 1, combining the ranges for the different sources and sinks presented during the workshop. Sources of hydrogen are depicted in red, while sinks are in green.

Figure 1. Global hydrogen budget



***Source:* JRC (2022) adapted from the figures presented by Sand, Paulot, and Stevenson**

The dominant source of hydrogen in the atmosphere is not a direct emission, but it is 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 yr^{-1}). Most NMHC form formaldehyde (HCHO) when they are oxidised, which in turn produces hydrogen when it photolyses ($HCHO + hv \rightarrow H_2 + CO$). The main direct sources of hydrogen emissions to the atmosphere are fossil fuels (14-20 Tg yr^{-1}), primarily from combustion processes associated with transportation, biomass burning (9-20 Tg yr^{-1}), and nitrogen fixation both on land and oceans (6-12 Tg yr^{-1}). Other sources that are currently not included in most models are geological sources (0-31 Tg yr^{-1}), 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, the current best estimate of the maximum potential average emission rate, the contribution of hydrogen emissions from the current hydrogen industry is 8 Tg yr^{-1}. Adding up all sources, total hydrogen production is believed to be 60-140 Tg yr^{-1}, with the direct anthropogenic emissions accounting for approximately 15%[2]. The main sink for hydrogen is soil uptake. The process is driven by

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[2] The figure includes only direct anthropogenic hydrogen emissions (i.e., from fossil fuels, biomass burning, and hydrogen industry), and does not include hydrogen production caused indirectly by anthropogenic activities

bacteria, and it accounts for over 75% of total removals. The magnitude of the soil sink is modulated by soil temperature, soil moisture, and the activity of hydrogen consuming organisms (Leung et al., 2020). Although there has been recent progress in understanding the behaviour of these hydrogen consuming bacteria, our knowledge is limited regarding their distribution and the effect of soil moisture on uptake rates. Current understanding is that too much soil water impedes hydrogen diffusion into the soil, while too little water (e.g., in deserts) impedes microbial activity. To better constrain the hydrogen uptake, it will be necessary to investigate the temporal dynamics of soil moisture and its relationship to hydrogen consumption across specific regions (Bertagni, Paulot, and Porporato, 2021). Hydrogen in the atmosphere not removed by bacteria is oxidised, mainly via reaction with the naturally-occurring hydroxyl radical (OH) in the troposphere (*R1*). This reaction is the driver for the indirect global warming impact of hydrogen. Total hydrogen sinks amount to 50-110 Tg yr^{-1}.

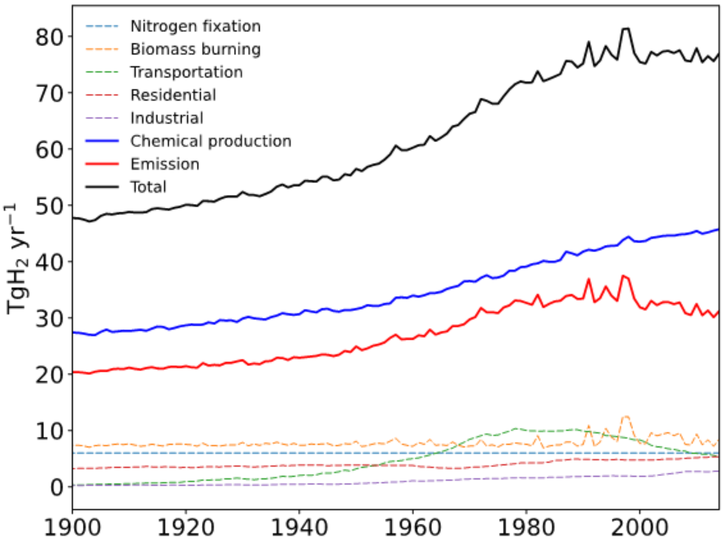
$$\text{R1: } H_2 + OH\ (+O_2) \rightarrow H_2O + HO_2$$

The magnitude of individual sources and sinks are subject to a high level of uncertainty. The main reason is the scarcity of extensive studies and observations, which constrains the ability to obtain robust bottom-up estimates of hydrogen concentration in the atmosphere. Starting with estimated hydrogen emissions, the global hydrogen budget is modelled by tuning the land sink to match the hydrogen concentration observations. This leads to large uncertainties, in the size of both the sources and sinks (approximately 30% on individual terms) as well as in the atmospheric lifetime of hydrogen.

2.1.2 Historical changes

The model developed by Paulot et al. allowed historical changes in hydrogen sources to be modelled. The results are presented in Figure 2, where the black line represents total sources. The model predicts that hydrogen sources increased from 1900 to the present day by approximately 65% due to anthropogenic activities (not including potential hydrogen losses from the hydrogen industry). The rise in hydrogen sources is due both to direct emissions (red line) and indirect production (blue line). The model also predicts that hydrogen sources plateaued around 1980, due to a reduction in hydrogen emissions from transportation (while indirect sources kept increasing). This result of the modelling has not been corroborated by observations.

Figure 2. Historical changes of hydrogen sources. Chemical production refers to the natural chemical reactions in the atmosphere producing hydrogen.



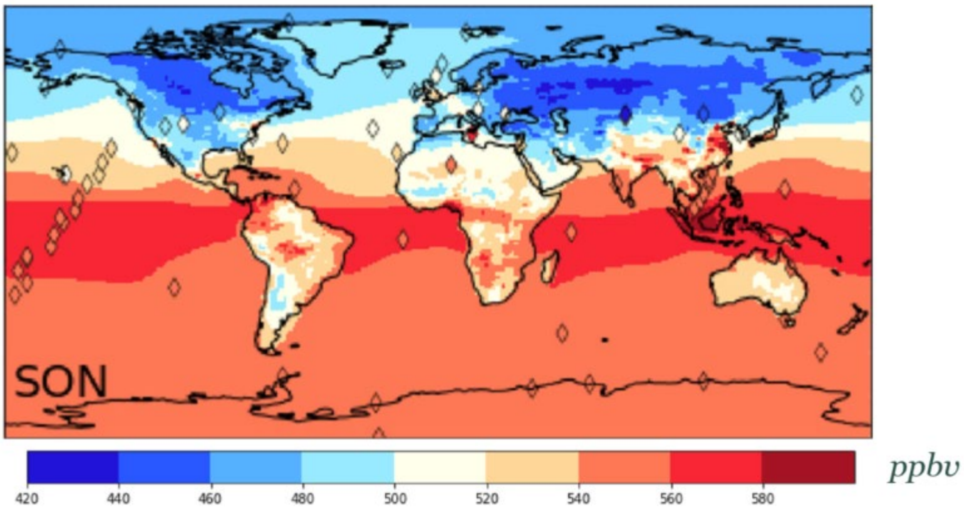
Source: **presentation by F. Paulot.**

(e.g., hydrogen from the oxidation of anthropogenic methane emissions, hydrogen from wildfires caused by anthropogenic climate change, etc.)

2.1.3 Hydrogen concentration

Hydrogen concentrations in the atmosphere are not uniform across the globe. As presented by Paulot et al. (Figure 3), concentrations over the continents in the northern hemisphere are much lower than the ones in the southern hemisphere. This is due to the larger land surface in the northern hemisphere, confirming the role of soils as the major hydrogen sink.

Figure 3. Hydrogen concentration. Diamonds in the figure show the observation points.



Source: **Paulot al. (2021)**

2.2 Global Warming Potential (GWP) and other metrics

The hydrogen molecule is not a direct greenhouse gas since the lack of a dipole moment prevents absorption of infrared radiation. However, hydrogen acts as an indirect greenhouse gas. All of the indirect greenhouse gas effects of hydrogen are driven by its oxidation in the atmosphere (R1), which affects the lifetime of other greenhouse gases in the atmosphere. In this section, the latest scientific understanding of the potential global warming caused by an increase of hydrogen concentration in the atmosphere is presented. The estimations do not include potential global warming effects which are not fully understood nor assessed, such as the impact of hydrogen emissions on aerosols and nitrous oxide[3]. Moreover, the estimates do not include all of the global warming consequences that a hydrogen economy might entail. In addition to direct hydrogen emissions, non-H_2 greenhouse gases may be emitted throughout the renewable hydrogen value chain: from the CO_2 emissions to produce the concrete and steel used in the infrastructure, through the electricity to power the electrolysers, to the emissions associated with transport and use the hydrogen. At the same time, a hydrogen economy may reduce methane emissions thanks to a lower demand for fossil fuels. These aspects are not taken into account in the models presented in this section, focused only on the global warming potentially caused by hydrogen emissions, but they are presented in more detail in section 3.

The scientific community agrees that an increase in the concentration of hydrogen in the atmosphere indirectly leads to a warming of the planet. Overall, Paulot et al. estimated via the NOAA's GFDL-AM4 model an effective radiative forcing (ERF) for hydrogen of 0.13 mW/m^2/ppbv (Paulot et al., 2021). This means that an instantaneous increase in hydrogen concentration in the atmosphere by 1 part per billion by volume (ppbv) leads to a change[4] in the energy balance of the Earth system, increasing the energy flux directed towards

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[3] Although not assessed yet, the direct impact of hydrogen emissions on aerosols and nitrous oxide is expected to be small. Nevertheless, the transition from fossil fuels to hydrogen will affect their concentrations.

[4] The change in radiative forcing is not instantaneous, as the hydrogen molecule does not directly absorb infrared radiation. The change happens when hydrogen is oxidised, indirectly affecting the radiative forcing of methane.

Earth by 0.13 mW/m^2. This additional energy flux will lead to a variation in the Earth's temperature to reach a new radiative equilibrium (i.e., incoming radiation equal to the outgoing radiation at the top of the atmosphere). Due to the lifetimes of the different species involved in the process (i.e., hydrogen, methane, water vapour, ozone), it takes at least a decade for the atmospheric radiative forcing to equilibrate after the perturbation caused by hydrogen emissions. Different processes related to hydrogen oxidation in the atmosphere contribute to the ERF. In the model developed by Paulot et al., 46% of hydrogen's radiative forcing is due to longer lifetime of methane caused by the hydrogen emission. Overall, the reaction of H_2 with OH leads to a feedback mechanism where less OH is available to react with methane. Since the reaction with the hydroxyl radical is the primary sink for methane ($CH_4 + OH (+O_2) \rightarrow CH_3O_2 + H_2O$), its lifespan in the atmosphere is extended and its concentration increases when OH concentrations decline. The remaining radiative forcing of hydrogen is attributed by Paulot et al. to the increased production of water vapour in the stratosphere (28%), and to the increased ozone in the troposphere (21%) and in the stratosphere (5%). The increased production of ozone is due to the fact that both the hydroperoxyl radicals (HO_2) formed via oxidation and the extra methane available in the atmosphere are tropospheric ozone precursors.

In the following sections, metrics to estimate the potential global warming impact of hydrogen emissions are presented. First, the Global Warming Potential over 100 and 20 years of a pulse emissions is presented (2.2.1 and 2.2.2, respectively). Then, the potential global warming impact arising from continuous hydrogen emissions is discussed (2.2.3). Finally, some discussion regarding the metric to adopt when assessing the climate impact of hydrogen emissions are provided (2.2.4).

2.2.1 GWP$_{100}$

To better grasp the climate effects of hydrogen, its radiative forcing is compared against CO_2 (i.e., the reference climate forcing agent). A widely used approach to appreciate the effect on climate of emissions is to integrate the radiative forcing over time, taking into account the lifetime of the species involved. The most adopted metric based on this approach is the global warming potential (GWP). This metric compares the effects of an idealised pulse over 1 year of 1 kg of some climate forcing agent (e.g., H_2) against the effects of a pulse of 1 kg of CO_2. This allows one to describe the different greenhouse gases in terms of CO_2 equivalent emissions (CO_2e), simplifying the design of climate policies addressing multiple gases. The GWP of the forcing agent depends on the timespan over which the potential is calculated: gases which are quickly removed from the atmosphere may initially have a large effect, but for longer time periods become less important. To implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (e.g., Kyoto Protocol and COP21), a time horizon of 100 years for the GWP (i.e., GWP$_{100}$) has been adopted as the standard metric.

There are currently only three model estimates for the GWP of hydrogen: the estimate based on the radiative forcing calculated by Paulot et al. (2021), the estimate proposed by Derwent et al. (2020) based on the chemistry-transport model STOCHEM-CRI, and the recently published estimate from Warwick et al. (2022). Models can have either an emission- or concentration-driven approach. Concentration-based models typically prescribe a surface concentration for the different species (e.g., H_2) at each latitude band, based on sparse observations. Since the real world distribution of the gases is unlikely to be perfectly zonally symmetric (i.e., invariant around a band of latitude), concentration-based models likely add sources and sinks in places where there might not be sources/sinks. On the other hand, emission-driven models allow the different species to freely evolve in the atmosphere, implementing sources and sinks of H_2 in places where exchanges are known to happen. The downside of this approach is that concentrations at the different latitudes are inevitably not effectively reproduced.

Derwent et al. (2020) uses an emission-driven approach for all species (i.e., H_2, CH_4, O_3), while Paulot et al. (2021) uses an emission-driven approach for H_2 and O_3, but prescribes CH_4 as a lower boundary condition[5]. In their models, the effect that an extra pulse of hydrogen has on the atmospheric chemistry over a certain period of time is monitored (e.g., the impact on methane and ozone concentrations), allowing an estimate of the variation in the radiative forcing. In Figure 4, the decay rate of the different substances affected by a pulse emission of hydrogen estimated by Stevenson and colleagues is schematically shown. The scheme is

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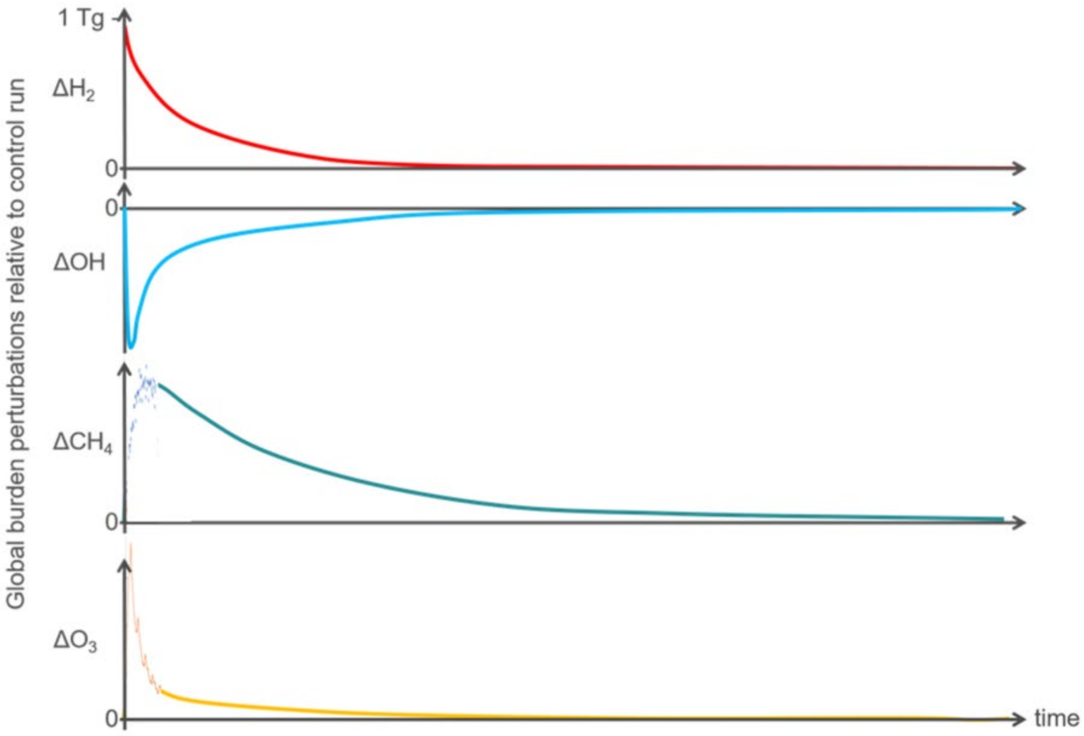
[5] Although Paulot et al. use a concentration-driven approach for methane in their model, its lifetime is affected by the freely evolving OH. This effect can be used to indirectly calculate how CH_4 would respond if it were not prescribed (Paulot et al., 2021).

hand-drawn, but the actual model results for CH_4 and O_3 for 5 years following a pulse of H_2 emissions from Derwent et al. (2020) are superimposed. The decay rate of the substances is affected both by the initial H_2 pulse emission (1 Tg) and the methane perturbation: H_2, CH_4, and O_3 concentrations increase following the hydrogen emission, then decay according to the lifetime of H_2 (~2 years) and CH_4 (~12 years) in the atmosphere. Methane concentration increases over approximately 3 years following the pulse H_2 emission, and then decays with an e-folding time[6] of 12 years (Derwent et al., 2020). Model results superimposed in Figure 4 clearly show the faster response of ozone than methane to the hydrogen emission (i.e., the peak of ozone concentration is reached earlier than methane's peak). Conversely to methane and ozone, the hydroxyl radical concentration initially decreases due to the H_2 emission and the extra CH_4 produced, then returns to the almost original concentration. The negative OH anomaly induced by the H_2 pulse initially decays with the H_2 lifetime, and later with the CH_4 lifetime.

Figure 4. Hand-drawn schematic of the global burden perturbations relative to control run after adding 1 Tg instantaneous pulse of H2. In the case of methane and ozone, the actual model results for 5 years following a pulse of H2 emissions are superimposed on the hand-drawn schematic.



Source: **adapted from presentation by D. Stevenson**

To obtain the GWP_{100}, the variation in the radiative forcing estimated by the models are extrapolated out to 100 years, integrated, and normalised to a pulse of the same mass of CO_2. The resulting GWPs vary from 5±1 kg CO_2e/kg H_2 based on Derwent et al.'s model (2020) to 11±5 kg CO_2e/kg H_2 based on Paulot's et al. (2021) and Warwick et al. (2022) models. The discrepancy in the values arises at least partially from the attribution of the climate effect to different phenomena: while Paulot et al. (2021) and Warwick et al. (2022) attributed approximately one third of the forcing to the increased production of water vapour and ozone in the stratosphere, Derwent et al. did not include these phenomena in their model and attributed half of the climate effect to the methane route and half to the tropospheric ozone (whereas the attribution in Paulot et al. indicated the contribution from methane was more than double that from tropospheric ozone). Different tropospheric lifetimes are obtained for hydrogen and methane in the two models: while Derwent et al.

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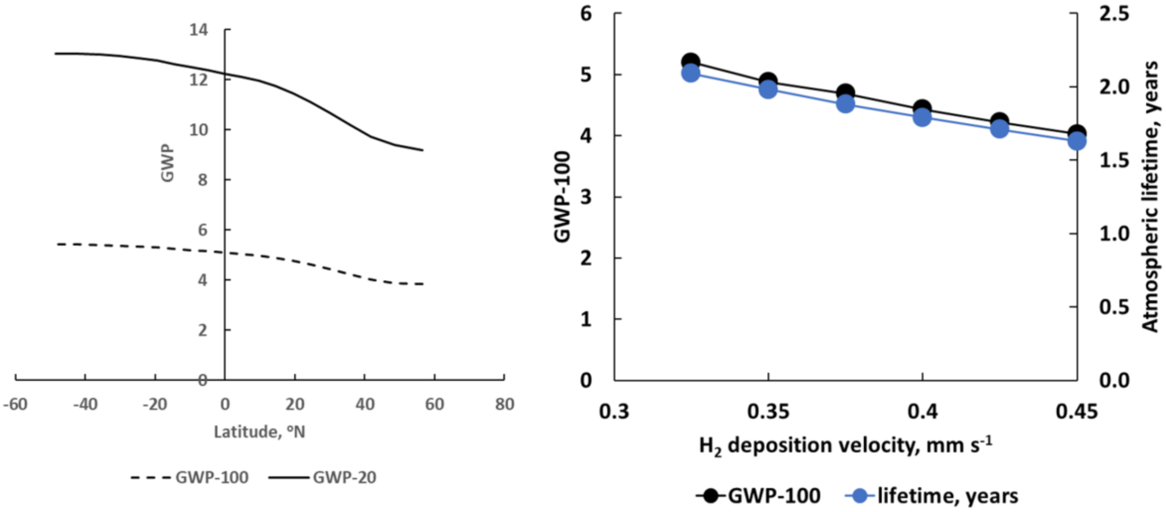
[6] Timescale for a quantity to decrease to 1/e of its previous value

obtained a shorter lifetime (1.5 years for H_2 and 7.2 years[7] for CH_4), Paulot et al. obtained a lifetime of 2.1 and 8.5 years for hydrogen and methane, respectively. Hence different representations of chemistry, as well as soil deposition, influence the derived GWP values.

The GWP figures are affected by a high level of uncertainty. In addition to the aforementioned uncertainties regarding hydrogen sources and sinks (e.g., the hydrogen deposition velocity), a source of uncertainty in the model presented by Stevenson is the limited timescale of the simulation (i.e., 5 years). Assumptions need to be made to extrapolate the curves over 100 years; this is a problem in particular for ozone, given the uncertainty on the exact point in time where its decay kinetic switches from the relatively short lifetime of hydrogen to the longer one of methane. Another source of uncertainty is the dependence of the lifetime on the emission latitude. Concentration-based models likely result in higher H_2 emissions in the southern hemisphere, where H_2 has a longer lifetime, thus generating a larger GWP (Field and Derwent, 2021). Figure 5 highlights the dependence of the GWP estimates by Derwent et al. to the emission latitude (left panel) and to the hydrogen deposition velocity (right panel).

Figure 5. GWP variation depending on emission latitude (left) and deposition velocity (right)



Source: **presentation by D. Stevenson, produced by D. Derwent using the model described in Field and Derwent (2021)**

2.2.2 GWP_{100} vs. GWP_{20}

To assess the climate effect of anthropogenic emissions, different timescales can be considered. In addition to GWP_{100}, a metric widely adopted to present the global warming impact of short-lived gases is the GWP_{20}: i.e., the global warming potential over 20 years. The GWP_{20} for hydrogen based on the model from Derwent et al. can be seen for instance in the left panel of Figure 5, with a value (~12 $kgCO_2e/kg\ H_2$) that is more than double the GWP_{100}. Warwick et al. (2022) obtained a GWP_{20} for hydrogen of 33 $kgCO_2e/kg\ H_2$, with an uncertainty range of 20 to 44. To avoid any misunderstanding, the GWP refers to the amount of hydrogen released to the atmosphere, not to the amount of hydrogen supplied. For instance, if the hydrogen lost to the atmosphere was 1% of the hydrogen supplied, the GWP_{20} for 1 kg of H_2 supplied would be 0.33 kg CO_2e (using the values proposed by Warwick et al. (2022)).

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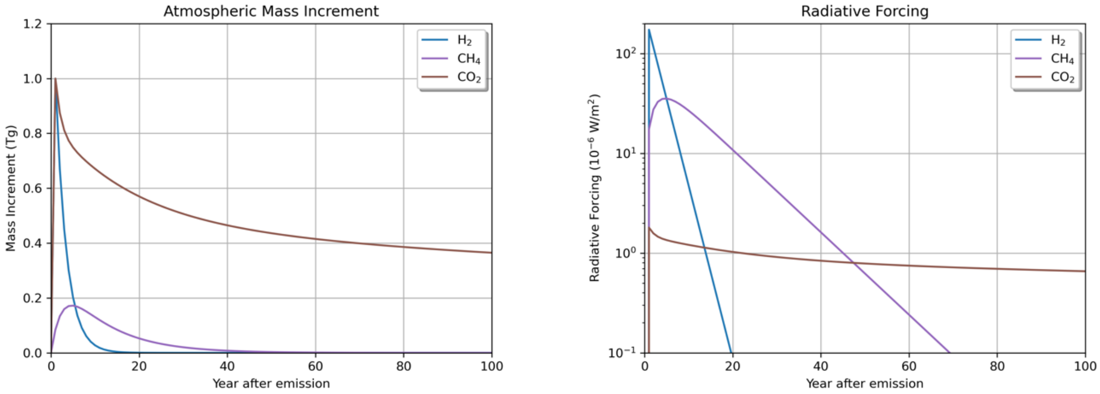
[7] The atmospheric lifetime (or e-folding lifetime) differs from the perturbation lifetime (i.e., 12 years for methane according to the best IPCC estimates) since the atmospheric lifetime do not include the feedback effects. Methane emissions poison their own sink, which significantly lengthens the residence time of a methane pulse added to the atmosphere. This feedback factor varies a little between models (range approximately 1.19-1.45), with a typical value of ~1.3 (Stevenson et al., 2020).

The difference between the GWP_{100} and GWP_{20} values can be explained by the different lifetimes of CO_2 and the species involved with the hydrogen perturbation. Hydrogen and methane have shorter lifetimes in the atmosphere (approximately 2 and 12 years, respectively) than CO_2, for which it takes several hundreds of years to be removed from the atmosphere by natural processes. In Figure 6 the atmospheric mass increment following a pulse emission (1 Tg) of hydrogen and its radiative forcing is compared to the one of 1 Tg of CO_2. In the left panel it can be seen how the hydrogen mass in the atmosphere disappears almost completely after 20 years, while approximately 40% of the CO_2 is still present after 100 years. In the same panel, it can be noticed also the effect on methane's concentration: the hydrogen emission causes the presence of extra mass of methane in the atmosphere, which almost entirely disappears after 70 years. To avoid any confusion, the model takes into account the pulse of H_2, but not the potential displacement of methane emissions. The right panel of highlights how the mass variation in the atmosphere affects the radiative balance: while the radiative effect of hydrogen (and methane) ends long before the 100-year timescale, CO_2 affects the radiative balance throughout the time. Given that the GWP is the ratio of the integral of the radiative forcing caused by the hydrogen emission with the one caused by the CO_2 emission, it is clear how the GWP_{20} results in a larger value for hydrogen than GWP_{100}.

Figure 6. Comparison of the atmospheric mass increment (left) and radiative forcing with time (right) of pulse emissions of hydrogen and carbon dioxide. The scale of the y-axis in the right panel is logarithmic.

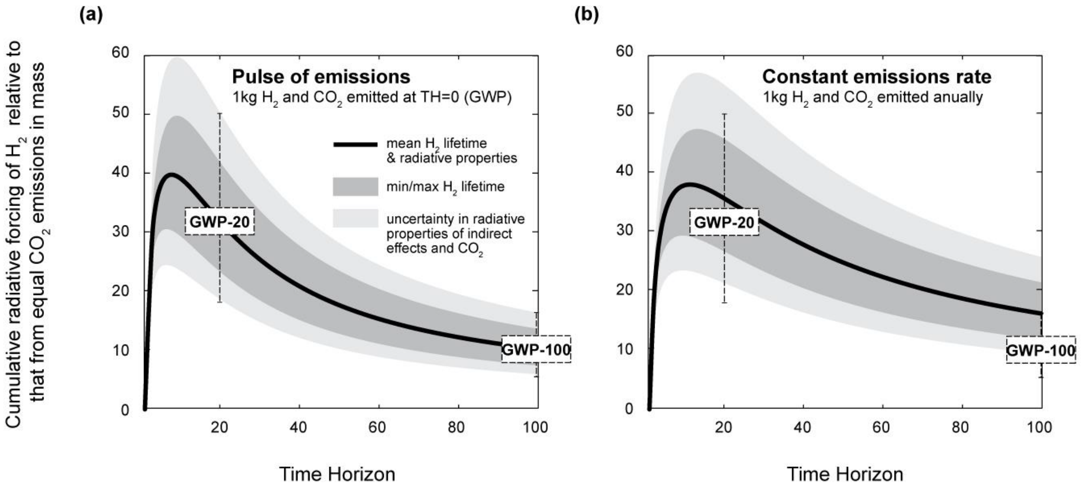


Source: **presentation by D. Hauglustaine**

2.2.3 Pulse vs. continuous emissions

Another method to assess the global warming impact of a gas is to account for the effect of continuous (sustained) emissions rather than pulse emissions. This allows to capture some aspects of short-lived climate forcers overlooked in the GWP: i.e., the temporal dynamics are more realistically reflected in the resulting estimates of net radiative forcing impacts (Alvarez et al., 2012). In Figure 7, the GWP (left panel) is compared to the cumulative radiative forcing of hydrogen relative to that from equal CO_2 emissions (right panel). When sustained emissions are considered, the cumulative radiative forcing of hydrogen over 100 years is significantly higher (approximately double) than the GWP_{100} assessed from a 1 year pulse of emissions. When the Paulot et al. model is considered, the cumulative radiative forcing of hydrogen emissions is approximately 20 times the one of CO_2. Although the short lifetime of hydrogen would eventually lead to a stable higher H_2 concentration in the atmosphere (as opposed to an increasing CO_2 concentration), the higher indirect radiative forcing caused by H_2 oxidation leads to a larger warming effect relative to CO_2 than when a metric based on pulse emissions is used (i.e., GWP).

Figure 7. Cumulative radiative forcing of hydrogen relative to carbon dioxide for equal emissions over time. The unit of the x-axes (time horizon) is years.



Source: **Ocko and Hamburg (2022)**

2.2.4 Which metric to use?

The choice of the metric to adopt when assessing the climate impact of short-lived pollutants (e.g., hydrogen) is often a source of controversy. Every metric has flaws, and the choice must depend on the purpose of the analysis (e.g., which aspect of climate change is most relevant for the application and over which time horizon). For this reason, the latest IPCC reports do not recommend an emission metric, and report emissions and mitigation options for individual gases rather than aggregating them as CO_2e (IPCC, 2021; IPCC, 2022). In line with the IPCC, this JRC report recommends always providing the amount of hydrogen emitted rather than the CO_2e alone.

When the global warming impact of hydrogen needs to be aggregated to other GHGs for policy purposes, the metric that aligns best with the goal of the policy should be used. The latest IPCC report chose the GWP_{100} metric to aggregate emissions in order to align with decisions under the Paris Agreement Rulebook (IPCC, 2022). Nevertheless, the use of other metrics is useful to have a more complete understanding of the climate impact of hydrogen emissions. For instance, the GWP_{20} allows to assess potential unintended consequences (e.g., creating near-term problems while aiming for long-term solutions). It has been suggested that reporting both GWP_{20} and GWP_{100} together is helpful for policy makers to be able to better understand any temporal trade-offs, which are relatively large for hydrogen given its very short residence time in the atmosphere (Ocko et al., 2017). The use of end-point metrics such as the global temperature change potential (GTP) allow to assess the temperature change in a specific year and not the integrated effect. For H_2, the GTP_{100} is estimated to be 7 times smaller than the GWP_{100}, further highlighting the smaller effect that a pulse of hydrogen emission has on long-term climate change compared to shorter timescales. On the other hand, a climate model that considers continuous emissions allows assessing the impact that a sustained or growing hydrogen economy might have on the climate.

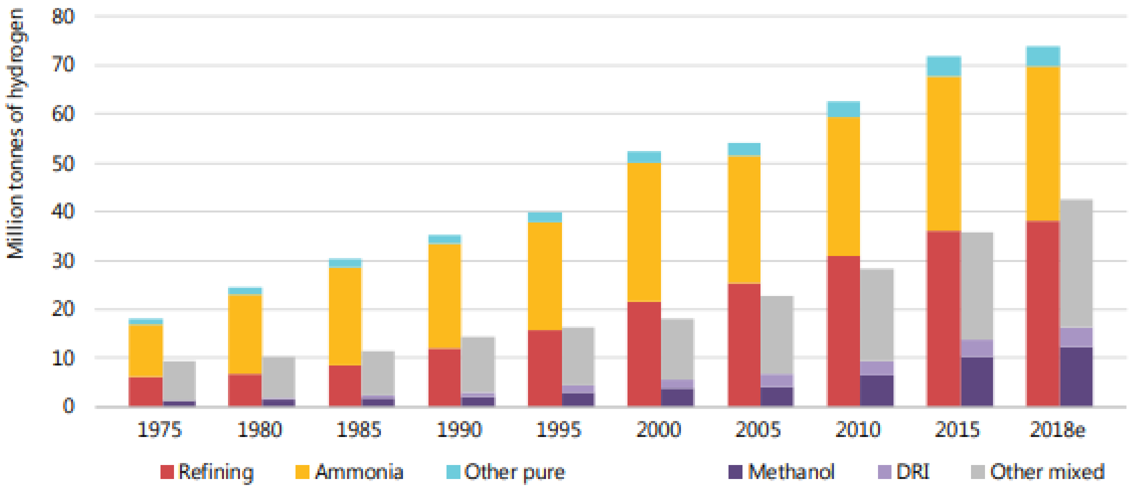
3 Global warming impact of a hydrogen economy

In this section, considerations regarding the potential global warming impact from the deployment at scale of hydrogen are presented. In Section 3.1, a brief introduction to the hydrogen economy and the potential future hydrogen demand are presented. In Section 3.2 the potential hydrogen emissions from the hydrogen economy are discussed and estimated. A hydrogen economy may alter the radiative balance of the atmosphere not only via hydrogen emissions, but also via all the direct and indirect greenhouse gases emitted along the value chain. Considerations and examples of non-hydrogen emissions that also result from the transition towards a hydrogen economy are presented in Section 3.3. In Section 3.4 some potential implications that a hydrogen economy would have on natural gas uses and methane concentration in the atmosphere are discussed. Finally, Section 3.5 states the overall climate consequences from the transition towards a hydrogen economy.

3.1 H_2 demand

Hydrogen is considered as a key energy carrier in many future energy scenarios, especially related to the increased usage of renewable energy sources, due to its versatility. Hydrogen offers ways to decarbonise a range of sectors for which it is proving difficult to significantly reduce emissions using renewable electricity (e.g., long-distance transport, chemicals, steel). The demand for hydrogen, which has grown more than threefold since 1975, continues to rise (see Figure 8). This growth has been driven to a large extent by the US and European mandates to produce cleaner fuels (e.g. hydrogenation / hydro-treatment for the desulphurisation of diesel).

Figure 8. Global annual demand for hydrogen since 1975

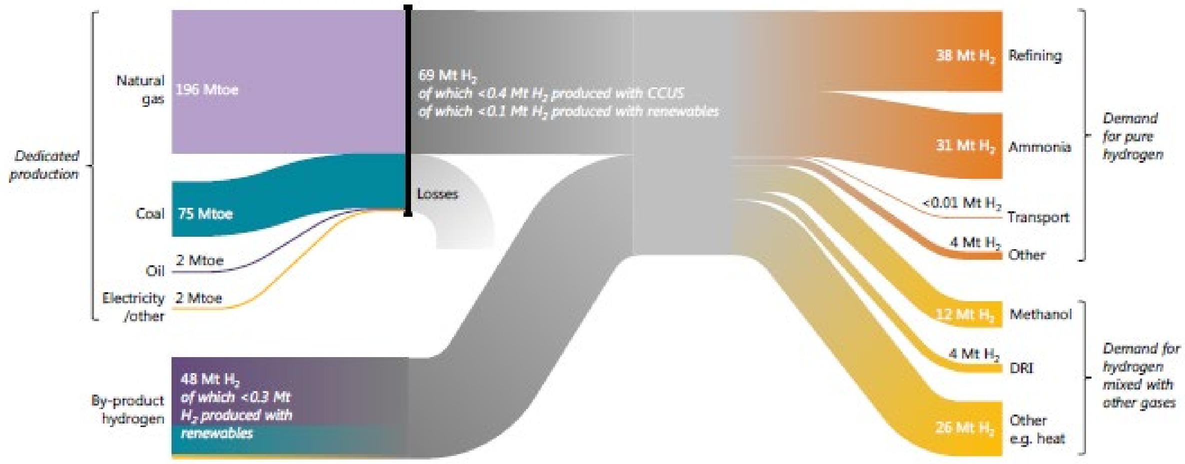


Notes: DRI = direct reduced iron steel production. Refining, ammonia and "other pure" represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

Source: International Energy Agency (2019)

Hydrogen is the third most-abundant element on the Earth's surface, although it is usually combined with other elements forming molecules from which it must be extracted. Owing to its high reactivity, most hydrogen exists combined with oxygen as water or bound to carbon forming liquid or gaseous hydrocarbons. Thus, hydrogen is typically not a primary energy source like coal or natural gas, but an energy carrier that is produced by using energy from a range of primary feedstocks. As can be seen in Figure 8, in 2018 the demand for hydrogen was more than 70 million tonnes per year. This hydrogen is almost entirely supplied from fossil fuels (95 %), most of it is produced from natural gas, some from coal, and a small fraction is produced from water electrolysis. Figure 9 shows the main applications for hydrogen today which are oil refining and ammonia production, mainly for fertilisers. A further 42 million tonnes of demand exists for hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock. The main applications for hydrogen as part of a mixture of gases are methanol production and steel production (International Energy Agency, 2019).

Figure 9. Hydrogen current value chains



Source: International Energy Agency (2019)

Different scenarios are available for future global hydrogen demand. Presenters at the workshop mainly referred to two scenario studies from the Hydrogen Council for their analyses. In 2017, the Hydrogen Council estimated that by 2050 hydrogen could account for approximately 20% of the final energy demand (Hydrogen Council, 2017). This would imply a ten-fold increase of the current hydrogen demand (i.e., from 8 EJ in 2015 to almost 80 EJ in 2050). In terms of mass, the demand would increase from approximately 90 Mt in 2020 (IEA, 2021) to 550 Mt in 2050. This is in line with the International Energy Agency's net zero emissions scenario, where 200 Mt of hydrogen are assumed to be needed in 2030 and more than 500 in 2050 (IEA, 2021). The most recent study from the Hydrogen Council is even more ambitious, estimating a demand of hydrogen in 2050 of 660 Mt, equivalent to 22% of global final energy demand (Hydrogen Council and McKinsey & Company, 2021). To assess the theoretical maximum environmental impact from a hydrogen economy, Hamburg and colleagues investigated also a scenario where all the final energy demand was met by hydrogen (see Section 3.5), corresponding to 400 EJ and 2,750 Mt H_2.

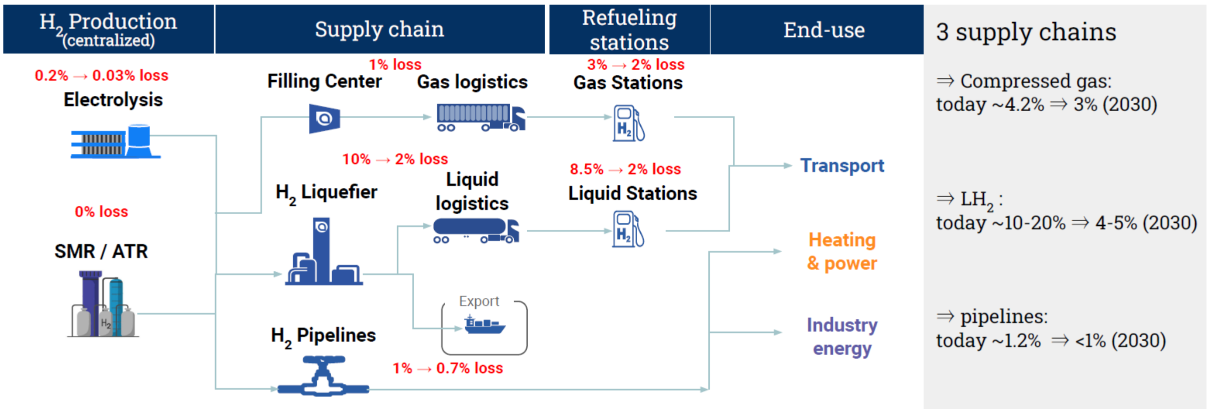
3.2 H_2 losses

3.2.1 Sources of hydrogen losses across the value chain

Hydrogen can be produced from a wide variety of sources and used in a wide variety of applications, with value chains containing different combinations of supply, handling and demand technologies. The different production processes, the transport and distribution options, as well as the variety of end-uses, have associated some hydrogen losses which constitute potential additional hydrogen sources to the atmosphere. Hydrogen emissions can either result from an unintended release (e.g., out of normal events such as an unplanned safety venting, breaches or component failure), from operational releases such as depressurisation events or from design features which typically result in very small releases (e.g., permeation through vessel walls, seals, etc.). Hydrogen releases can happen at any stage of the hydrogen value chain. Guy de Reals from Air Liquide and Pere Margalef and Davide Scrocchi from SNAM provided estimates for credible losses of hydrogen along the chain.

For hydrogen production, losses are currently estimated around 0.2% when produced via electrolysis. In addition to accidental leakage, hydrogen losses are mainly linked to hydrogen and oxygen crossover through the membrane, and to processes such as dryers' regeneration. By 2030, hydrogen losses during electrolytic production are expected to drop to 0.03% thanks to the maturing of the technology (e.g., reduced crossover through the membrane). On the other hand, hydrogen losses are very limited (0.0001%) when produced via steam methane reforming (SMR). Losses from SMR are currently typically flared, not causing an increase of hydrogen concentration in the atmosphere. Hydrogen losses in the delivery step varies with the form of hydrogen. In Figure 10 a summary of the current and future hydrogen losses along the hydrogen supply chain estimated by Air Liquide is presented. Figures are based on operation feedback and know-how.

Figure 10. Hydrogen release fractions to the atmosphere along the hydrogen supply chain and design goals for 2030



***Source:* presentation by G. de Reals (Air Liquide)**

Filling and transportation of compressed hydrogen via tube trailers is a mature technology with low losses, estimated as less than 1% of the delivered hydrogen. These losses are mainly linked to the purging of the trailer hose, and to leakages from fittings and valves. On the other hand, the delivery chain for liquefied hydrogen is still under development and currently more prone to leakages. Air Liquide estimates an average loss of 10% of the delivered hydrogen, related mainly to the liquefaction process and the boil-off during transfer operations. Due to the high economic value of hydrogen and the low maturity level of liquid hydrogen delivery for widespread fuelling applications, these supply chain losses will likely reduce in the coming years. 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 vapour will be emitted to the atmosphere. Air Liquide estimate for 2030 is a 2% loss of the delivered liquefied hydrogen at the hydrogen refuelling stations and an additional 2% loss due to dispensing. Finally, international transportation via pipelines in Europe has a current estimated leakage of approximately 1% of the delivered hydrogen, which is expected to reduce to less than 0.7% by 2030.

Additional losses happen at the end-use site: refuelling stations for instance lose from 3% to 8.5% of the delivered hydrogen, depending on the form of hydrogen (i.e., gaseous vs. liquid). Losses at the refuelling station are mainly due to purging and, in the case of liquefied hydrogen, boil-off. Since refuelling technologies are still under development, the margin for improvement in reducing losses is high. Air Liquide target for 2030 is 2% losses of the delivered hydrogen.

In total, the current compressed hydrogen supply chain is estimated by Air Liquide to lose to the atmosphere approximately 4.2% of the hydrogen delivered to the gas stations, while the current losses for liquefied hydrogen can reach up to 20% of the hydrogen delivered to liquid stations. Losses are expected to reduce significantly in 2030, with average losses to the atmosphere of 3% and 4-5% for gaseous and liquefied hydrogen, respectively. The delivery pathway with lower losses is via pipeline, with expected losses in 2030 of less than 1% of the delivered hydrogen.

Hydrogen losses via pipelines were also estimated by SNAM, the main Italian operator for the transport and dispatching of natural gas in Italy. Based on their experience with methane losses, they calculated how much hydrogen could leak if their pipelines were converted for hydrogen transport. According to ASME B31.12 (ASME, 2020), all of their existing pipelines are ready to transport 100% hydrogen, most of which (70%) with no or limited reductions on the maximum operating pressure. Four types of losses currently occur in SNAM’s natural gas pipelines: fugitive emissions due to tightness failure (50%), intentional and unintentional vented emissions (26%), pneumatic emissions resulting from gas operated devices such as controllers, positioners, and actuators (23%), and unburned methane in the exhaust gases from natural gas combustion devices (1%). Overall, these losses represent 0.038% of the total volume of natural gas injected in the SNAM's grid. When repurposed to hydrogen pipelines, pneumatic emissions will cease to exist thanks to the replacement of pneumatic actuators by electrical actuators. On the other hand, fugitive hydrogen emissions are expected to be 1.25 to 3 times the methane ones (depending on the dynamics of the flow in the pipeline, whether laminar or turbulent) due to the different gas characteristics (Kiwa Technology, 2019). Finally, vented emissions are not expected to change due to the same volume displacements, and incomplete combustion emissions are considered to be negligible.

3.2.2 Overall hydrogen losses

Air Liquide estimated the potential overall hydrogen losses to the atmosphere by combining the hydrogen losses data with the expected hydrogen demand. Results are presented in Table 3. For hydrogen demand, 140 Mt are assumed to be needed in 2030, and 660 Mt in 2050 (Hydrogen Council and McKinsey & Company, 2021). The figures in Table 3 are calculated assuming that all the end uses except for mobility are supplied by pipelines, while transportation is covered for 70% by liquefied hydrogen and 30% by compressed hydrogen. The share of hydrogen lost out of the total hydrogen produced and its contribution to the overall hydrogen sources to the atmosphere are also reported in Table 3. For the hydrogen sources, a value for 2020 including both natural and anthropogenic sources was considered (i.e., ~90 Mt). Results show that by 2050, hydrogen lost to the atmosphere would represent approximately 2% (i.e., 13 Mt) of all the hydrogen produced. This means an increase of approximately 10% of the overall hydrogen sources to the atmosphere. The increase from 2030 to 2050 of the hydrogen losses is due to the expected larger use of liquefied hydrogen after 2030. The average losses estimated by AirLiquide for 2050 are significantly lower than the ones estimated in a recent report by Center on Global Energy Policy of the Columbia University (Fan et al., 2022), where a range from 2.9% (low-risk case) and 5.6% (high-risk case) loss rate is estimated for the hydrogen economy in 2050. Most of the losses (54%) are assumed to happen in the production phase, while delivery and end-use losses are assumed to account for 22% and 24%, respectively. Assuming a total hydrogen demand of 660 Mt, total losses would reach a value of 37 Mt in the high-risk case.

Table 3. Potential hydrogen losses from the deployment of hydrogen at scale.

End-use	Unit	2020	2030	2050
Power generation buffering	Mt	0	0.18	0.47
Transportation	Mt	0.02	0.20	10.6
Building heat and power	Mt	0	0.07	0.80
Industry feedstock	Mt	1.08	0.73	1.46
Total losses	Mt	1.10	1.18	13.3
Share losses of hydrogen produced	%	1.2	0.8	2
Share industry losses of hydrogen sources	%	1	1	10

***Source:* adapted from presentation by G. de Reals (Air Liquide)**

3.3 A life cycle view on H_2 economy emissions

The deployment of hydrogen at scale affects the planet's temperature not only because of hydrogen losses, but also because it implies the increase or reduction of other direct and indirect greenhouse gas emissions (e.g., CO_2, CH_4, NO_x). To investigate the overall climate implications of a hydrogen economy, life cycle assessments (LCAs), taking into account all the changes in emissions due to hydrogen production and use, should be performed (European Commission, 2003). Replacing fossil fuels with hydrogen is expected to lead to significant GHG emission reductions because it does not emit CO_2 when used. However, the life cycle of hydrogen is not free of emissions: from the energy to produce hydrogen, through the losses along the supply chain, to the emissions when used. Even when the hydrogen is produced by renewable sources, emissions are generated to build the renewable energy infrastructure or when the hydrogen is transported and used. For instance, hydrogen produced via electrolysis powered by solar power is expected to generate approximately 1.0 kg CO_2e/kg H_2 in 2030, and 0.6 kg CO_2e/kg H_2 in 2050 due to production of the materials used in the infrastructure (Hydrogen Council, 2021). Depending on the leakage rate, these emissions could generate a larger impact on climate than the hydrogen lost along the supply chain. Hydrogen end-use can generate indirect greenhouse gases too: when hydrogen is combusted in high-temperature engines, it produces NO_x which warm the planet by increasing the amount of ozone in the troposphere (Lammel and Graßl, 1995). Although an LCA of the overall climate impact of a hydrogen economy is outside the scope of the present report, a couple of examples provided during the workshop on how the use of renewable hydrogen could affect global warming via non-H_2 emissions are summarised in this section: hydrogen delivered via ammonia (3.3.1), and hydrogen used as fuel for aviation (3.3.2).

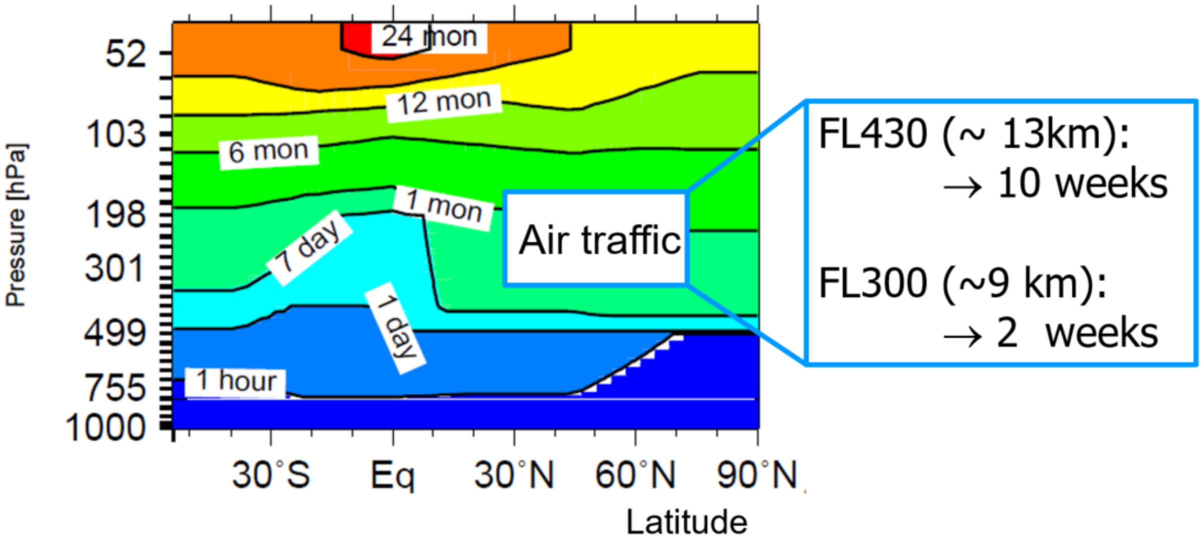
3.3.1 Hydrogen delivery: ammonia

Hydrogen delivery is expected to play an important role in the global decarbonisation efforts. The European Hydrogen Strategy for instance recognises the important role that the transport of hydrogen will play in enabling the market penetration of renewable hydrogen in Europe (European Commission, 2020). One attractive option to transport and deliver hydrogen is to convert it into ammonia and use the existing infrastructure to deliver it where needed (Ortiz Cebolla, Dolci, and Weidner, 2021). Despite the clear advantage of transporting hydrogen via a carrier with a higher volumetric energy density using a consolidated infrastructure, the transformation and shipping processes could generate unintended consequences in terms of environmental impact. Ammonia is not a direct GHG, but when emitted to the atmosphere it leads to particulate matter formation, acidification, and eutrophication, affecting air quality and biodiversity (Van Damme et al., 2018). Moreover, ammonia and ammonium deposited on soils can be converted by bacteria into nitrous oxide, indirectly contributing to global warming (Wrage-Mönnig et al., 2018). Although these impacts could be avoided if ammonia was not lost throughout the supply chain, ammonia users for fertiliser production and other industrial uses, were identified by infrared satellite images as hotspots for ammonia emissions(Van Damme et al., 2018). Moreover, direct (e.g., CO_2) and indirect (e.g., NO_x) greenhouse gases could be emitted in the conversion process of hydrogen to ammonia and during ammonia combustion (if used directly as fuel), respectively. If ammonia was reconverted to hydrogen at the delivery site, a recent JRC study showed that the life cycle GHG emissions of the H_2 delivery would be higher in the case of ammonia compared to deliver it as compressed or liquefied H_2 (Arrigoni et al., 2022).

3.3.2 Hydrogen use: fuel for aviation

A particularly relevant case for the global warming consequences of a hydrogen economy is aviation. Liquefied hydrogen is considered a potential solution to decarbonise the aviation sector, but research is still underway on the effects that hydrogen-powered aircraft would have on climate. In addition to the CO_2 emitted when producing and using the fuel, non-CO_2 emissions during flights (i.e., water vapour, nitrogen oxides, soot particles, and oxidised sulphur species) currently alter the chemical composition of the atmosphere and the cloudiness, perturbing the radiative balance. It is estimated that these non-CO_2 impacts could currently account for two thirds of the overall aviation net positive radiative forcing, though with quite an uncertain range (EASA, 2020). It is therefore fundamental to understand how fuel replacement would affect the overall aviation impact. Grewe presented the results of the AHEAD EU-project (Advanced Hybrid Engines for Aircraft Development) during the workshop, on the potential global warming consequences of replacing aviation's traditional fuel (kerosene) with liquefied hydrogen (Gangoli Rao, Yin, and P. van Buijtenen, 2014; Grewe et al., 2017). Results show that renewable hydrogen could significantly reduce the global warming impact of aviation from a life cycle perspective. Moreover, NO_x emissions could be reduced as well by optimising the combustion chamber. On the other hand, using hydrogen would produce roughly 3 times the water vapour produced with traditional fuels. The increase of atmospheric water vapour increases global warming (currently around 3% of the aviation's global warming impact is due to water vapour emissions (Lee et al., 2021)), though largely depending on the altitude and location where the water vapour is released. In Figure 11 the variation of the water vapour lifetime with the latitude and the pressure altitude (expressed in hecto-Pascal) is presented. Most air traffic takes place in the northern hemisphere between 9 and 13 km from the Earth's surface. At the lower boundary of the interval, water vapour emissions will remain in the atmosphere on average for 2 weeks. The situation however becomes critical at higher altitudes, where water vapour molecules can linger in the atmosphere for months (for approximately 10 weeks at 13 km).

Figure 11. Water vapour lifetime



Source: **presentation by V. Grewe, adapted from Grewe and Stenke (2008).**

The probability to form contrails will increase using hydrogen, but their lifetime is expected to decrease. Contrails have an average lifetime of a few hours (2-5 hours), but they can occasionally reach a maximum of roughly a day. The use of hydrogen is expected to reduce the number of ice particles in the contrail since no soot is emitted, leading to lower lifetimes of the contrails and lower temperature changes. Nevertheless, this topic needs to be investigated further.

Based on these assumptions, the investigated AHEAD aircraft propelled with liquefied hydrogen and sustainable alternative fuels are expected to reduce the global warming potential by 8 to 12% compared to reference aircraft using conventional fuels (including future enhancements of the overall propulsion efficiency). The results are very much dependent on the investigated aircraft type that is operated at the upper end of current cruise altitudes. However, the use of hydrogen as an aviation fuel very likely will still contribute to a net warming of the planet through water vapour, contrails, and NOx effects.

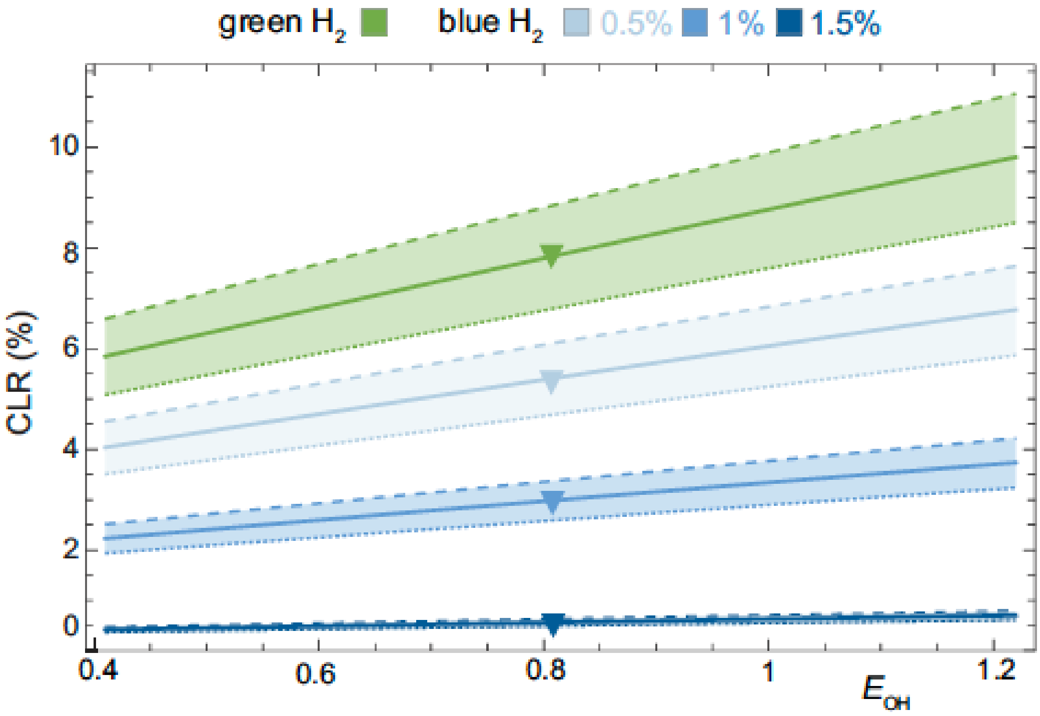
3.4 Methane

As presented in Section 2, the global warming potential of hydrogen emissions is partly linked to methane concentration in the atmosphere. Current atmospheric models, however, do not take into account that the use of hydrogen could reduce the demand for fossil fuels and therefore methane emissions. A reduction in methane emissions in the atmosphere will certainly reduce global warming, both from the reduction of its concentration and the reduction in the stratospheric water vapour. In this section, the effect that replacing natural gas with hydrogen might have on the climate is explored. In Section 3.4.1 the consequences on methane concentration in the atmosphere when natural gas is substituted with renewable hydrogen or fossil hydrogen with carbon capture are presented, while in Section 3.4.2 the climate consequences of replacing natural gas with hydrogen in the existing gas pipelines are discussed.

3.4.1 Hydrogen production: implications for methane sources to the atmosphere

In a recent work (not yet peer-reviewed) presented by Paulot, Bertagni et al. estimated the maximum hydrogen loss rate that would avoid an increase in methane concentration in the atmosphere via a simple box model. Results are shown in Figure 12, where CLR (%) on the y-axis indicates the critical loss rate and E_{OH} on the x-axis indicates the amount of OH reacting with compounds other than H_2, CO, and CH_4 normalised by the amount reacting with H_2, CO, and CH_4. Assuming a hydrogen demand by 2050 of 550 Tg yr^{-1} (17% lower than the assumption by Air Liquide), if all the hydrogen was produced via renewable sources (i.e., "green H_2" in Figure 12) and no loss occurred, methane sources to the atmosphere would reduce by approximately 18 Tg yr^{-1}. This reduction is directly linked with the reduction in natural gas use, assuming that anthropogenic methane emissions are reduced in proportion to the reduction in fossil-fuel energy (~16% of 110 Tg yr^{-1}). However, savings would reduce if hydrogen losses occurred or if hydrogen was produced via steam methane reforming with carbon capture (i.e., "blue H_2"). If all the hydrogen produced was renewable, the maximum hydrogen loss rate that would avoid an increase in methane concentration in the atmosphere would be in the range of 5 to 11%, accounting for uncertainty in OH and the rate of hydrogen uptake from the soil. Under the most realistic scenario (represented by the triangles in Figure 12), the critical loss rate would be 7%. If the hydrogen produced was "blue" and no hydrogen losses occurred, a methane loss rate of 0.5% would lead to a net reduction of methane sources to the atmosphere of 12 Tg yr^{-1}. Net reductions would drop to 6 Tg yr^{-1} if methane losses were 1%, and there would be no net reduction if methane losses were 1.5%. Even in the best case scenario for "blue" hydrogen considered by Bertagni et al. (i.e., 0.5% methane loss rate), hydrogen loss rate should be limited to 5% to avoid an increase of methane sources to the atmosphere. The critical hydrogen loss rate would drop to 3% and 0% in the cases of methane loss rates of 1% and 1.5%, respectively. The error range in the curves indicate the effect that a variation of 20% in the biological removal would have on the results, highlighting the importance of better understanding the processes governing hydrogen concentration in the atmosphere. It is worth highlighting that this study investigates only the effect on methane concentration, and not the overall climate effect of replacing natural gas with hydrogen. In addition to the potential savings of methane sources, replacing natural gas with hydrogen would lead to a net change in the carbon dioxide emissions too.

Figure 12. Loss rate for hydrogen causing an increase rate in atmospheric methane. CLR: critical loss rate; E_{OH}: amount of OH reacting with compounds other than H_2, CO, and CH_4 normalised by the amount reacting with H_2, CO, and CH_4.



***Source:* presentation by F. Paulot from Bertagni et al. (in review).**

3.4.2 Hydrogen delivery: repurposing of natural gas pipelines

Pere Margalef and Davide Scrocchi presented the potential global warming impact from losses when natural gas is replaced with hydrogen in SNAM pipelines. The analysis considers the emissions taking place during gas transmission, storage, and regasification; emission variations in natural gas production and distribution are not included. Both the global warming potential over 20 and 100 years were considered in the assessment. The GWP_{20} and GWP_{100} values considered are 84 and 28 for methane, and 70.5 and 21 for hydrogen. Global warming potential values for hydrogen were mistakenly derived from the preprint of Ocko and Hamburg (2022), and are significantly higher than those reported in section 2.2. Nevertheless, results show that a switch from natural gas to hydrogen in the SNAM pipelines would lead to a reduction of the global warming impact from losses of 81% in a 20 year timeframe, and 83% in a 100 year timeframe (Figure 13). In fact, notwithstanding the higher fugitive rate of hydrogen (see section 3.2), the lower volumetric density of hydrogen compared to natural gas leads to lower CO_2e emissions when the gases are transported at the same pressure (70-75 bar). Given the lower volumetric energy density of hydrogen, the flow rate of hydrogen needs to be increased 3 times to deliver the same amount of energy delivered with natural gas. This, however, is achieved thanks to the different fluid-dynamics characteristics of natural gas and hydrogen (i.e., density, kinematic viscosity, and compressibility). At the same design conditions (i.e., pipeline length, diameter, and pressure difference between starting and end points), hydrogen travels in fact three times faster than natural gas.

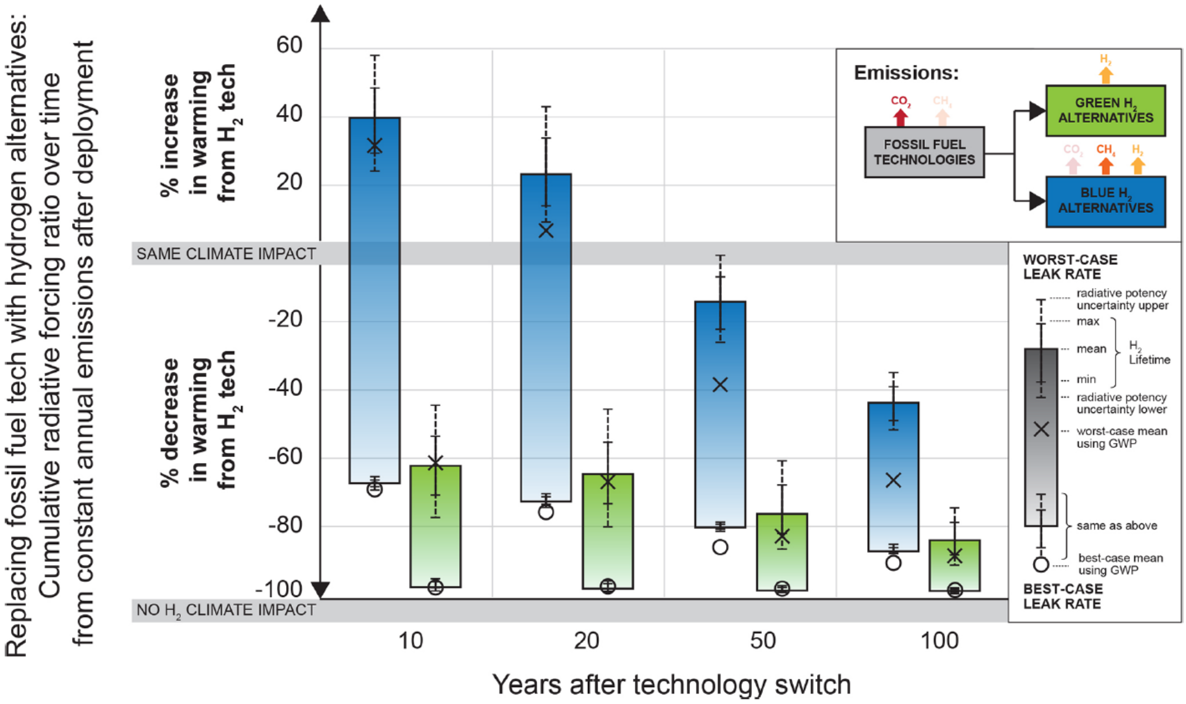
Figure 13. Global warming implications of substituting natural gas with hydrogen in SNAM pipelines.

Source: **presentation by P. Margalef and D. Scrocchi (SNAM).**

3.5 Overall climate consequences

In this section, the first attempts to estimate the overall climate consequences of replacing fossil fuel systems with hydrogen are presented. This is a developing area of research, and initial models may conflict due to different underlying assumptions and extrapolations. This report presents statements given directly by the presenters at the workshop and is not intended to support or refute the opinions of the presenters. In Figure 14, the climate impact results from the technology switch presented by Hamburg is shown. In their analysis, a metric considering sustained emissions was used and an average avoided emission value (11 kg CO_2/kg H_2) for the replacement of fossil fuel with hydrogen technologies was assumed. Two hydrogen production pathways (i.e., renewable ("green" in Figure 14) and fossil with carbon capture ("blue")), and a range of loss rates from 1% to 10% per unit H_2 deployed was considered. In the case of "blue" hydrogen, methane loss rates from 1% to 3% per unit methane consumed[8] were also considered. For all scenarios considered, the climate benefits of replacing fossil fuel with hydrogen are clear in the long term. However, the study shows the potentially deleterious consequences for the global temperatures in the short term when switching to “blue” hydrogen. The authors estimated that a switch from fossil fuel to “blue” hydrogen could lead to up to a 40% increase in warming over the first 10 years, considering the worst case scenario for losses (i.e., 10% for hydrogen and 3% for methane). On the other hand, a switch to renewable hydrogen would guarantee climate benefits from the very beginning, with a reduction from 60% to more than 95% of the fossil fuel climate impact over the first 10 years. Over 100 years, switching to renewable hydrogen would guarantee a climate impact reduction larger than 80% even in the worst case scenario for hydrogen losses (10%). Nevertheless, a 100% reduction (i.e., “no H_2 climate impact” in Figure 14) would not be possible unless all the hydrogen was renewable and there were no losses.

Figure 14. Relative climate impact over time from replacing fossil fuel systems with renewable (“green”) or fossil with carbon capture (“blue”) hydrogen alternatives for a generic case. Error bars represent a 20% uncertainty in hydrogen’s radiative efficiency. Corresponding GWP100-derived climate impacts are shown using the “X” and “O” markers, for worst-case and best-case loss rates, respectively. [The figure was updated by the author with respect to the one presented at the workshop].



***Source*: Ocko and Hamburg (2022)**

Hamburg presented also the potential global-mean surface air temperature responses to different hydrogen emission scenarios depending on loss rate and extent of deployment. Results show that a hydrogen-intensive economy (20% final energy demand, corresponding to a H_2 demand of 600 Tg) with high losses (10%) could contribute 0.05 °C additional warming in mid-century. It is important to remark that this warming would cease to exist if hydrogen losses were prevented, given the short lifetime of the species affected by hydrogen emissions in the atmosphere. Moreover, the analysis did not take into account the potential cooling effect generated by a reduction in methane concentration in the atmosphere thanks to fossil fuel replacement with hydrogen.

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[8] Range for methane losses in the assessment are from Alvarez et al (2018), which assumes an average value of 2.3% along the supply chain.

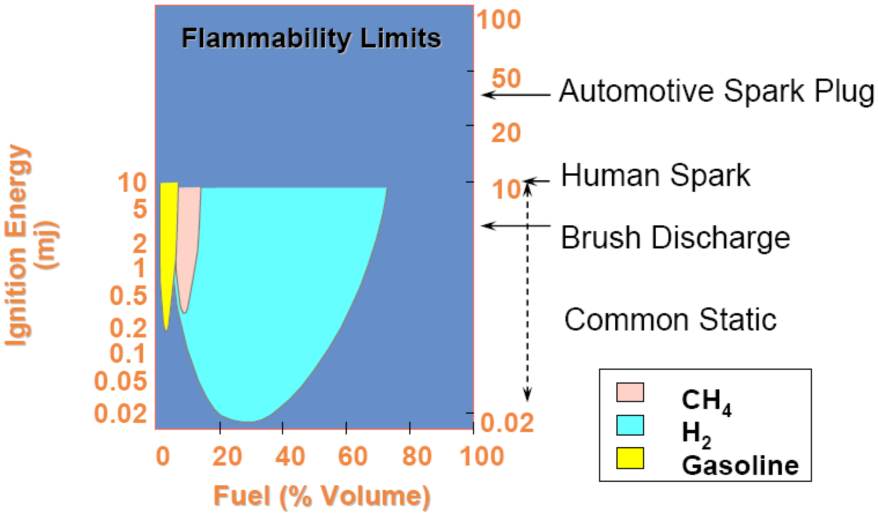
Hauglustaine further stressed during the workshop the clear climate benefits arising from a transition to a renewable hydrogen economy. Based on the estimations from Hauglustaine and colleagues (not yet peer-reviewed), assuming a hydrogen demand by 2050 of 549 Mt/year and a loss rate for hydrogen of 1-3%, the CO_2 equivalent emissions from using renewable hydrogen would represent only 1-4% of the CO_2 emission avoided (GWP_{100} based) by replacing fossil fuels. The percentage would drop to 0.2-0.7% if the GTP_{100} metric was used instead. In other words, this means that the climate impact would be reduced by 96 to 99.8% if fossil fuels were replaced with renewable hydrogen. This is in line with what presented by Hamburg (Figure 14) for the renewable hydrogen scenario with low leakage rate. If "blue" hydrogen is included in the equation (assuming a 30% share of the total H_2 supply being "blue" H_2), the climate impact reduction would be limited to 70-80% (i.e., the CO_2 equivalent emissions would represent 20-30% of the CO_2 emission avoided (GWP_{100} based)).

Although further research is needed to improve the accuracy of the estimates presented in this section, results clearly shows the importance of preventing and minimising hydrogen losses along the hydrogen value chain to minimize the climate impact of a hydrogen economy. Better monitoring and quantification of hydrogen concentration in the atmosphere would allow a better assessment of the environmental impact of the hydrogen economy, and the prevention of future emissions. In the next chapter (Section 4), the state of the art and the main challenges on hydrogen leakage prevention, detection and quantification are presented.

4 Prevention and monitoring of hydrogen losses

Chapter 2 and 3 clearly show the importance of preventing hydrogen losses to reduce the global warming impact from a full-fledged hydrogen economy. In addition to the potential environmental concerns, there are safety concerns when dealing with hydrogen releases. Hydrogen has a wide flammability range (4% to 75% by volume), about seven times wider than methane, and the amount of energy required for ignition is small, see Figure 15. Special handling is required to prevent fires or explosions that could result from mixing hydrogen with air. At atmospheric pressures and temperatures, hydrogen is a highly diffusive, buoyant, colourless, odourless, tasteless, non-irritating, and nontoxic gas. Additionally, it does not present the same optical/thermal signatures as hydrocarbon leaks, which means different methods may be needed for detection, as it will be further discussed in Section 4.2. For all these reasons, the prevention and monitoring of hydrogen emissions is paramount in systems in use today and is reflected in the industry standards (Fuel Cells and Hydrogen Observatory), (Kotchourko and Jordan, 2022), European Industrial Gases Association (EIGA) and US Compressed Gases Association (CGA). Many of these standards have been adopted or referenced by CEN, ISO and ADR and by regulators. Section 4.1 details prevention measures to minimise hydrogen releases in hydrogen production facilities and across the supply chain. Section 4.2 expands on the detection and monitoring tools available at different length scales and the remaining technological challenges.

Figure 15. The flammability range of hydrogen compared to methane and gasoline



Source: EIGA presentation

4.1 Leakage prevention: design considerations

Hydrogen production is a highly regulated process. Permits under the industrial emission directive (Directive 2010/75/EU Industrial Emissions, 2010) are required in Europe, irrespective of the plant size. This corresponds to Title V permits in the US (EPA), the highest level of permitting. In addition, ATEX legislation on hazardous atmospheres/areas applies to these facilities (Directive 2014/34/EU (ATEX), 2014). Further, as hydrogen production is cross sectoral the EIGA has a best available techniques (BAT) guidance document available for hydrogen facilities (EIGA Document 155).

Hydrogen point sources are typically minimised by reusing the fuel gas in the process. For a typical hydrogen plant the gas is purified, the pure gas is the product and the impure gas stream which contains some hydrogen is returned to the process to be used as fuel. This is part of the permit requirements and represents BAT. In emergency cases, hydrogen is usually flared, however, direct releases go through relief valve systems at times, especially further down the supply chain where it is not possible to install a flare. The direct hydrogen releases often result in a 'light off' where the hydrogen is consumed due to low ignition energy. For safety reasons vents are elevated due to possible thermal radiation.

The hydrogen supply chain is also regulated, e.g. via the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) for road transport which is the basis for EU rules (Directive 2008/68/EC, 2008) and for many countries globally that have adopted it via the UN, and via the Department of Transportation (DoT) in the US and around the world. These have specifications and rules for container design, operation, maintenance and methods to minimise leakage in transit.

In terms of fugitive emissions control, the plants and pipelines are designed to minimise these emissions by reducing the number of pipe connections (potential leak points), by using welded connections rather than flanges, and by ensuring that the valves are leak tight (e.g. the valves in hydrogen service are typically designed in accordance with API 602, API 600, API 594 highest specifications). Welded pipes are continuous, minimising leak points, whereas flanged connections can leak at the flanged connection. Leak tight valves have additional packing in the valve to minimise the leaks for the valve stem. Further, the hydrogen facilities use plant-wide automatic flammable gas detection systems (see more details on sensors in Section 4.2).

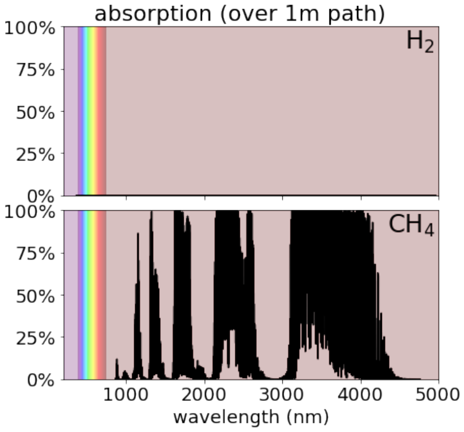
In addition to the design considerations, there are operational measures to control fugitive emissions that are put in place. Some of these operational measures are: 1) proactive leak detection and repairs (leak patrols), 2) stringent control during maintenance and line breaking activities using ‘permits to work’ and making sure lines are not containing products, 3) periodic maintenance and good operational practices in place so not to set off relief valves, and 4) pipeline monitoring systems (e.g. sectioning of the pipeline so sections can be sealed off without having to empty the whole pipeline, pipeline patrols), see EIGA document 235/21 on pipeline integrity management.

4.2 Leakage monitoring: detection and quantification methods

The main drivers for the detection of hydrogen releases have been traditionally associated with safety concerns and to a lesser extent the maximisation of product throughput in specific applications. Accordingly, sensor development for hydrogen releases has been primarily oriented to detect hydrogen on the order of 1,000 - 10,000 ppm (0.1 to 10 vol %), mainly due to the flammable and explosive behaviour of hydrogen gas. Detection is currently intended to identify hydrogen leakages and avoid accumulation beyond the lower flammability limit of 4 vol. % in confined spaces. Alternatively, within the context of the potential environmental concerns stated in Chapter 2, the main driver is the need to monitor and quantify hydrogen losses across the whole value chain, resulting from the transition towards a hydrogen economy. This would require detecting hydrogen a distance away from the source/leak, as is the case for the methane value chain. Environmental impacts of hydrogen may arise from cumulative effect of sub-ppm levels of released hydrogen across the value chain. Consequently, the desired monitoring range of interest for hydrogen release quantification needs to be extended at the lower end by several orders of magnitude, to about 0.01 to 1 ppm (0.001 – 0.1 vol. %). The lower the sensor detection limits, the lower the concentration of hydrogen that can be monitored and quantified, thus allowing wide area monitoring at concentration levels relevant for atmospheric and environmental modelling. The ultimate goal is to be able to quantify more accurately the hydrogen concentrations in the atmosphere and therefore reliably detect and quantify hydrogen losses along the value chain arising from the hydrogen economy.

Hydrogen gas is colourless and odourless, similarly to methane gas. However, it presents signature differences with respect to methane, making hydrogen leaks more difficult to detect. This means that the techniques applied to detect methane and other hydrocarbon leaks are not directly transferable to hydrogen in many cases. For example, the optical detection of hydrogen is really challenging. There are many commercial products for imaging methane leaks at a wide range of length scales, including increasing precise measurements from space, e.g. aerial imaging to detect medium to large leaks and high precision fast response gas analysers capable of detecting and quantifying small leaks. These devices provide quantitative concentration data using the infrared absorption features of methane, which in turn can be converted to flux rates. However, these absorption features are not present for hydrogen, and therefore these devices are not applicable (see the comparison of the absorption bands for hydrogen and methane in Figure 16.

Figure 16. Comparison of absorption spectra of hydrogen and methane



Source: Sandia National Laboratories

Gas sensors/detectors are the most common strategy for the direct detection and empirical characterisation of hydrogen releases. There are numerous different platforms for the direct detection of hydrogen. These include thermal conductivity (TC), combustible gas sensors (CGS), metal oxide sensors (MOX), platinum thin films and electrochemical sensors. However, not all these sensors are able to specifically detect hydrogen. For example, a particular property of hydrogen that can be measured is its low density but that is also a feature of helium gas. Similar cross-sensitivity occurs with hydrogen combustion properties. Selective hydrogen detection is quite challenging due to cross-sensitivity issues, but is achievable with palladium thin film sensors. Cross-sensitivity is a phenomenon that occurs when a gas other than the gas being monitored causes the gas sensor to show a reading, even when the target gas is not present.

An overview of the sensor technologies for hydrogen detection is given in Section 4.2.1. Optical detection techniques are being explored for the detection of hydrogen despite the many challenges associated with hydrogen signatures. An overview of these techniques is given in Section 4.2.2. Other strategies exist to support quantification of hydrogen losses from a facility, e.g., leak rates through system components, etc. These strategies and other industry compatible techniques are discussed in Section 4.2.3. Atmospheric hydrogen monitoring approaches are detailed in Section 4.2.4. It is also important to remark that hydrogen-methane blends could serve as a bridge towards the hydrogen economy, especially in specific industrial sectors so not only hydrogen leaks have to be assessed, also the behaviour of hydrogen-methane blends needs to be evaluated. Sections 4.2.1.1 and 4.2.2.1 are dedicated to the detection and quantification of hydrogen-methane blend leaks by point sensors and optical techniques, respectively.

4.2.1 Overview of sensor technologies for hydrogen detection

Sensors represent one strategy for detecting and quantifying hydrogen releases. Hydrogen gas sensing technology uses various methods where a specific property, usually electrical in nature, of a sensing element changes in presence of hydrogen gas. This specific property can be thermal based, resistance based, optically assisted, acoustically assisted, mechanical or electrochemical change based. Instrumental techniques such as gas chromatography (GS) and mass spectrometry (MS) can also be employed for direct hydrogen detection. These instruments have shown good response over a wide concentration range of detection, however they suffer from several disadvantages such as the large size and weight, portability issues, slow response times, high cost, time consuming process, requirement of trained personnel to operate them and dedicated maintenance. These limitations restrict the continuous operation of such instruments and thus the ability to quantify emissions in the open.

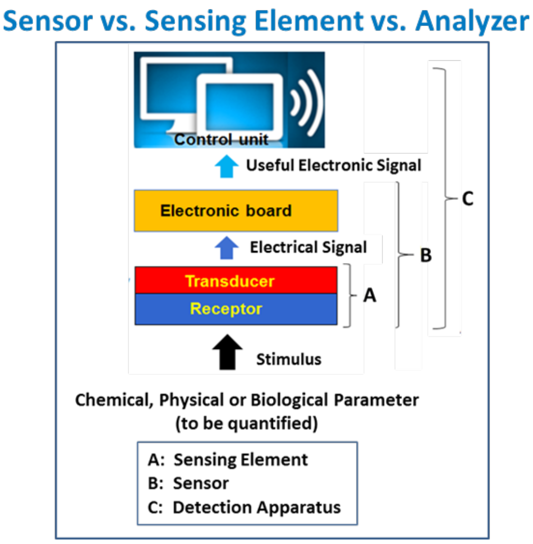
Ranging from fundamental elements to whole instrument systems, the term “sensor” can have different meanings among stakeholders within the hydrogen community. We can use the following terminology based on terminology used in ISO 26142 for different aspects of what constitutes a “sensor” (ISO 26142, 2010), see Figure 17:

Sensing element: device dealing with the interaction between stimuli and transduction into electrical signal. As above mentioned, different platforms represent different types of sensing element, for example: combustible gas sensor (CGS), thermal conductivity (TC), electrical conductivity (EC), metal oxide sensor (MOX), etc.

Sensor: device that provides quantitative information. It is composed of a sensing element(s) and support electronics that converts the electrical response from a sensing element into a useful signal.

Detection apparatus / analyser: equipment providing quantification, alarm, and control functions capabilities.

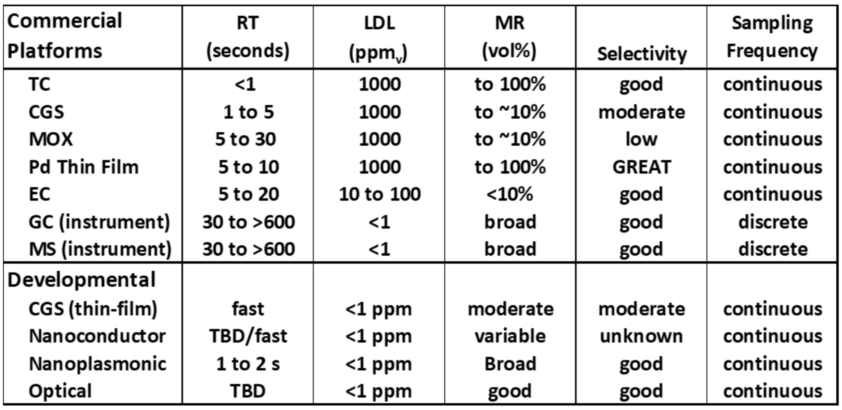
Figure 17. Schematic of sensing element, sensor and analyser



Source: (Hübert, Boon-Brett, and Buttner, 2016)

Taken into account the above mentioned terminology, a practical definition for a hydrogen sensor would be the one describing it as a device that provides quantitative information on the presence and amounts of hydrogen. An overview of the various hydrogen sensors, commercially available or in development state, and its performance (response metrics) is presented in Table 4:

Table 4. Overview of hydrogen sensors / detectors and metrological performance (nominal metrics): response time (RT), lower detection limits (LDL), measurement range (MR), selectivity, and sampling frequency.



Commercial Platforms	RT (seconds)	LDL (ppm$_v$)	MR (vol%)	Selectivity	Sampling Frequency
TC	<1	1000	to 100%	good	continuous
CGS	1 to 5	1000	to ~10%	moderate	continuous
MOX	5 to 30	1000	to ~10%	low	continuous
Pd Thin Film	5 to 10	1000	to 100%	GREAT	continuous
EC	5 to 20	10 to 100	<10%	good	continuous
GC (instrument)	30 to >600	<1	broad	good	discrete
MS (instrument)	30 to >600	<1	broad	good	discrete
Developmental					
CGS (thin-film)	fast	<1 ppm	moderate	moderate	continuous
Nanoconductor	TBD/fast	<1 ppm	variable	unknown	continuous
Nanoplasmonic	1 to 2 s	<1 ppm	Broad	good	continuous
Optical	TBD	<1 ppm	good	good	continuous

Source: NREL

Many of the sensors metrics presented in Table 4 represent nominal response time (RT), lower detection limits (LDL), measurement rage (MR), selectivity rating and sampling frequency values for the indicated sensor platform type. Most met the concentration range for safety applications (measurement range 0.1 to 10 vol. % H_2). However, most of the sensors do not have an appropriate detection limit for applications requiring hydrogen detection below 100 ppm let alone less than 1 ppm. Only few types of sensors are available for these applications, such as miniaturised combustible gas sensors whose operation has been optimised with specialised electronic circuitry coupled with controlled sampling and operation methodology. With proper configurations, some CSG sensor elements are able to measure low ppm levels of methane and would be expected to respond similarly to hydrogen or to hydrogen-methane mixtures, albeit without the possibility to differentiate between hydrogen and methane constituents.

Improved detection limits of hydrogen detectors are feasible with further technology development. An emerging technology which has significantly improved lower detection limits is plasmonic hydrogen detection, based on palladium nanoparticles. Plasmonic sensors rely on optical resonances in metal nanoparticles. Hydrogen is typically absorbed inside optically-lossy palladium nanoparticles achieving detection limits that are at the low ppm range (Nugroho et al., 2019; Nugroho et al., 2022). This technology is advancing quickly with commercial developers producing nanoplasmonic sensor prototypes with detection limits below 1 ppm and exceptional selectivity in pre-production models. (Insplorion)

Another emerging approach to achieve a rapid and sensitive detection of molecular hydrogen relies into transforming hydrogen from an infrared transparent molecule through a gas phase reaction to produce a product with an infrared signature proportional to the hydrogen concentration. Aerodyne Hydrogen analysers work by chemically converting ambient hydrogen to an infrared active molecule that is quantified using an Aerodyne Tuneable Infrared Laser Differential Absorption Spectrometer (TILDAS), providing high sensitivity, selectivity, and speed. Ongoing instrument development effort is supported by the US Department of Energy SBIR program, through which Aerodyne plans to commercialise three versions of the analyser ranging from highly portable to highly sensitive (<0.5 ppb at 1 Hz, 10 Hz operation), (US DOE SBIR). The advancement of this technology allow the development of remote monitoring methods similar to those developed for ammonia monitoring, looking at infra-red absorption profiling from satellites (Van Damme et al., 2018).

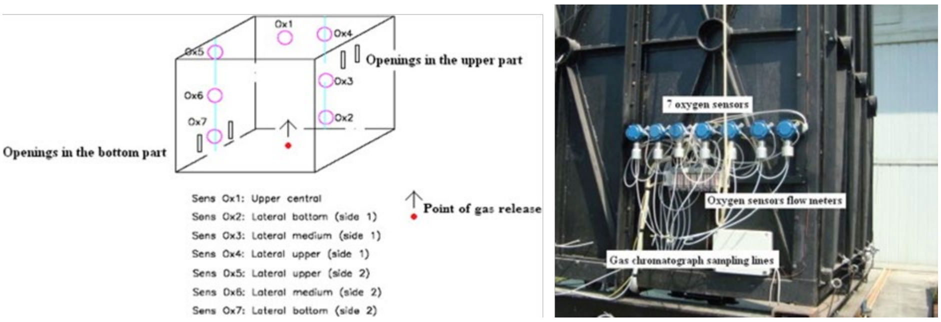
Other emerging developments rely in the improvement of advanced materials and manufacturing approaches to produce hydrogen sensing element prototypes with exceptional analytical performance metrics. Most of the research advances are focused on semiconductor thin-films (Zhou et al., 2021), nanotubes (Xiao et al., 2018) and nanostructures (Liang et al., 2022). However, there is still uncertainty on the chemical interference for possible cross-sensitivity and more data is required on the impact of environmental parameters such as temperature, pressure and humidity in the sensitivity of these novel sensors.

Most of the sensors discussed above are point sensors in that hydrogen must physically interact with the sensing element. However, point sensors can be arranged in a distributed array to perform wide area monitoring, allowing spatial and temporal detection of hydrogen releases. NREL Hydrogen Wide Area Monitor (HyWAM) research program is following this approach, developing a distributed network of hydrogen point sensors supplemented by additional parameter measurements, including wind speed, wind direction and other environmental conditions to guide monitoring strategies. This technique is helping to elucidate the hydrogen dispersion behaviour serving as a validation tool of modelling approaches (e.g., computational fluid dynamics simulations). Correlating sensor measurements profiles to source hydrogen releases requires modelling. Therefore, research activities should also be focused at advancing the development of inverse models to use concentration measurements from the sensors to quantify source releases. NREL is also investigating the development of advanced methodologies for wide area monitoring including fiber optic sensors specifically designed for hydrogen leak detection signatures, ultrasonic leak detection methods, Schlieren imaging, Raman methods and wireless systems. A commercial wrap has been developed to fit around pneumatic components, such as valves and fitting. A hydrogen leak occurs if the fitting fails, and the wrap changes colour. At present the wrap is visually interrogated to identify leak sources. The wrap is now being configured with RFID (Radio Frequency Identification) tags to allow for remote interrogation of the exposed wrap. Research advances on Schlieren imaging, Raman methods and other optical techniques are further developed in Section 4.2.2.

4.2.1.1 Hydrogen-methane blends

It is known that hydrogen disperses differently from methane due to the fact that hydrogen is more diffusive and buoyant than methane. Point sensors have been applied to study the dispersion behaviour of hydrogen-methane blends in recent years. By using extractive measurements at different points within enclosures and then running those extractive measurements across oxygen sensors it is possible to detect the displacement of oxygen in the enclosed test cell and elucidate what the concentrations are over time, see (Lowesmith et al., 2009; Marangon and Carcassi, 2014). However, it is worth mentioning that the use of oxygen sensors to quantify hydrogen releases in enclosures can induce significant errors (Buttner et al., 2014). Handheld combustible gas sensors were also used to inspect test sections for leaks prior to testing.

Figure 18. Experimental setup using oxygen sensors to evaluate hydrogen-methane mixtures.



Source: (Marangon and Carcassi, 2014)

4.2.2 Overview of optical techniques for hydrogen detection

There is a wide range of optical detection techniques available to visualise gas flows, however not all of them work for hydrogen gas. A summary of the most common optical techniques and its suitability to monitor hydrogen is shown in Table 5.

Table 5. Overview of optical detection techniques and its suitability for hydrogen detection

Technique	Principle	Works with H_2	Gas specific	Quantitative
Shadowgraphy	Refractive index gradients bend light rays as they pass through density variations	✓		
Schlieren	Same as shadowgraphy except knife edge enables focused image to form	✓		✓
Fluorescence	Photons are absorbed by molecules at a resonant transition and light is reemitted at a shifted wavelength		✓	✓
Absorption	Gases have absorption features for certain wavelengths of light		✓	✓
Rayleigh scattering	Elastic scattering off of different molecules is proportional to their cross-section and number density	✓		✓
Raman scattering	Inelastic scattering off of different molecules gives each component a spectral fingerprint	✓	✓	✓

Source: Sandia National Laboratories

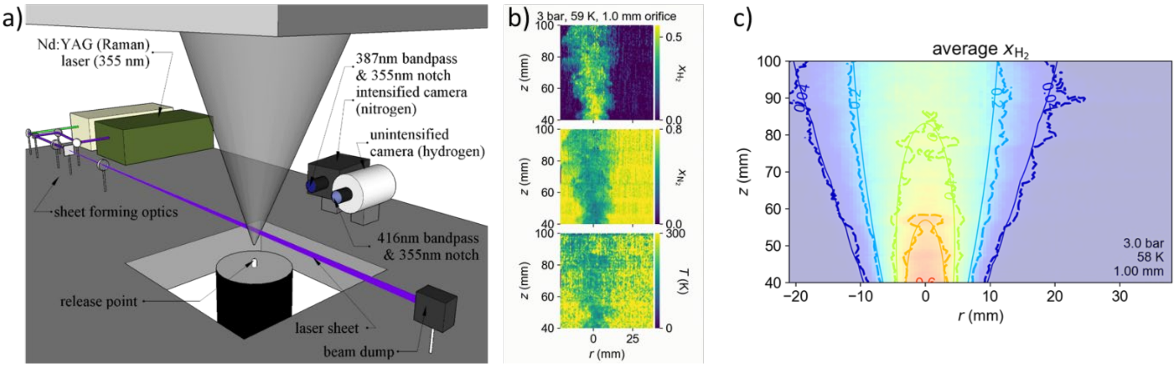
Shadowgraphy and Schlieren techniques, which rely in the principle of light rays bending as they pass through density variations, work with hydrogen but they are not hydrogen specific. This means that if there was a hydrogen leak these techniques will be able to detect a change in density. However, they are not able to differentiate that the detection signal comes from hydrogen itself. These techniques are based on evaluating index of refraction differences and these differences can also be caused by temperature gradients as well as by the specific molecule (hydrogen, or other density gases) itself. Additionally, they present further complications if quantification is attempted. Shadowgraphy does not allow hydrogen quantification but it is possible for specific Schlieren techniques. However, a patterned background and imaging processing (tomography) are required to perform hydrogen quantification, assuming that hydrogen is the only gas present (except air).

Fluorescence detection works by molecules absorbing light at a resonant transition and then re-emitting at a shifted wavelength. This technique is gas specific and quantitative, but it does not detect pure hydrogen. Using fluorescence would require mixing the hydrogen with another molecule. Infrared absorption does not work with hydrogen either because of the lack of absorption features, as previously discussed. Transforming hydrogen from an infrared transparent molecule to a chemically reacted molecule producing an infrared signature proportional to the hydrogen concentration is a way around to apply this technique that is currently under investigation.(US DOE SBIR)

Rayleigh scattering is a technique based on elastic scattering of light that has been used to measure hydrogen leaks in the lab. However, its performance presents many challenges when attempting to measure cryogenic hydrogen leaks. The moisture from the entrained air condenses in the flow, presenting an overwhelming Mie scattering signal at the same wavelength as the Rayleigh signal. Furthermore, quantitative Rayleigh scattering relies on knowledge of the temperature of the gas flow, which can be managed for room temperature releases, but not for cryogenic releases. Rayleigh scattering is also not specific to hydrogen; the technique is suitable for laboratory experiments, but not for a diagnostic measurement in environments where other gases might be present.

Raman scattering, which is inelastic light scattering, is the only common optical technique suitable for hydrogen, as it is specific to hydrogen and quantitative. The visualisation of room temperature and cryogenic hydrogen releases has been demonstrated applying Raman. Figure 19 describes how this technique is performed at Sandia National Laboratories (Hecht and Panda, 2019). Hydrogen is projected through a high powered laser sheet and the Raman scattering from the hydrogen molecules is detected by a camera with filters to only detect light at a specific wavelength (the Raman shifted light). This setup also requires a second camera detecting the light that scatters off the nitrogen molecules. A small portion of the hydrogen plume is imaged at a time and from the combination of images planes a full image of the hydrogen mole fraction is obtained, capturing the turbulent fluctuations. This has allowed the validation of hydrogen dispersion models.

Figure 19. Raman imaging of room temperature and cryogenic hydrogen releases: a) Schematic of the experimental setup, b) Instantaneous full images of the hydrogen and nitrogen mole fractions from a combination of multiple image planes, c) Comparison of average hydrogen dispersion 2D image measured (thick, dashed lines and shading) and model-predicted (thick, solid lines).

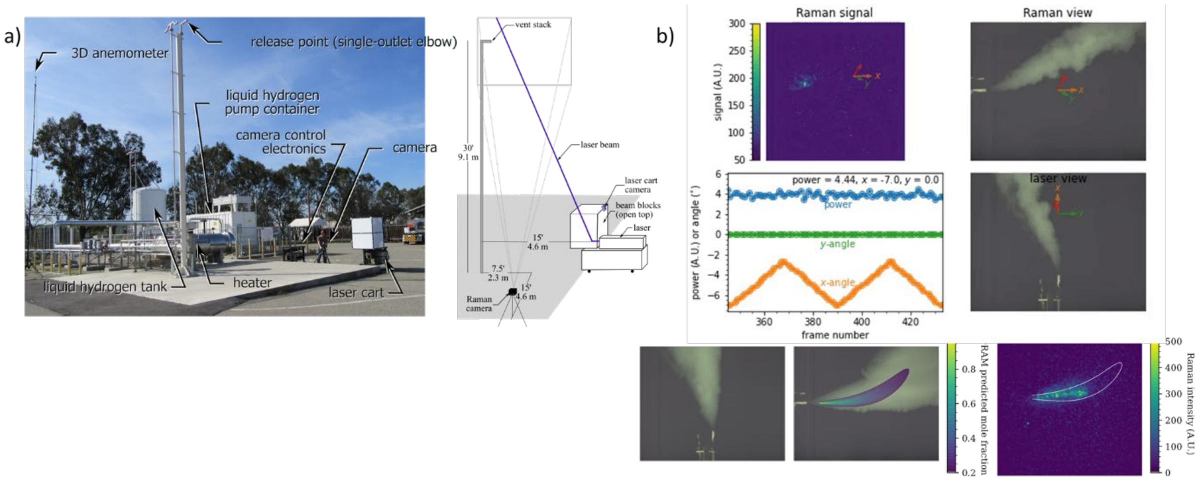


Source: Sandia National Laboratories

Despite the challenges associated with Raman technique (high power illumination and sensitive detectors required due to the low signal strength) several research groups are working on miniaturising Raman based detection systems. (Ninomiya, 2007; Liméry et al., 2017; Shiina, 2018; Choi et al., 2019).

Raman scattering technique has also been demonstrated at a larger scale by Sandia researchers, detecting hydrogen from 10 meters away (Hecht and Killingsworth, 2021). Figure 20 shows how the technique is performed to evaluate the hydrogen dispersion from venting. Similar to lab-scale experiments, the technique requires high-powered laser illumination and presents some challenges when attempting quantification with small signals.

Figure 20. Demonstration of Raman scattering applied at large scale to monitor hydrogen from venting: a) Experimental setup, b) Raman signals and validation of dispersion model

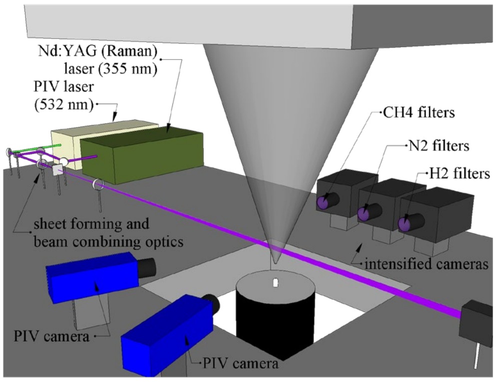


Source: Sandia National Laboratories

4.2.2.1 *Hydrogen-methane blends*

Raman scattering is currently applied to measure the dispersion behaviour of hydrogen-methane blends at lab scale by Sandia researchers. The experimental setup includes an additional camera looking for the Raman scatter off methane, as can be seen in Figure 21. These experiments will elucidate the dispersion evolution of blends, whether the hydrogen and methane molecules stay well-mixed as they disperse or whether they tend to separate.

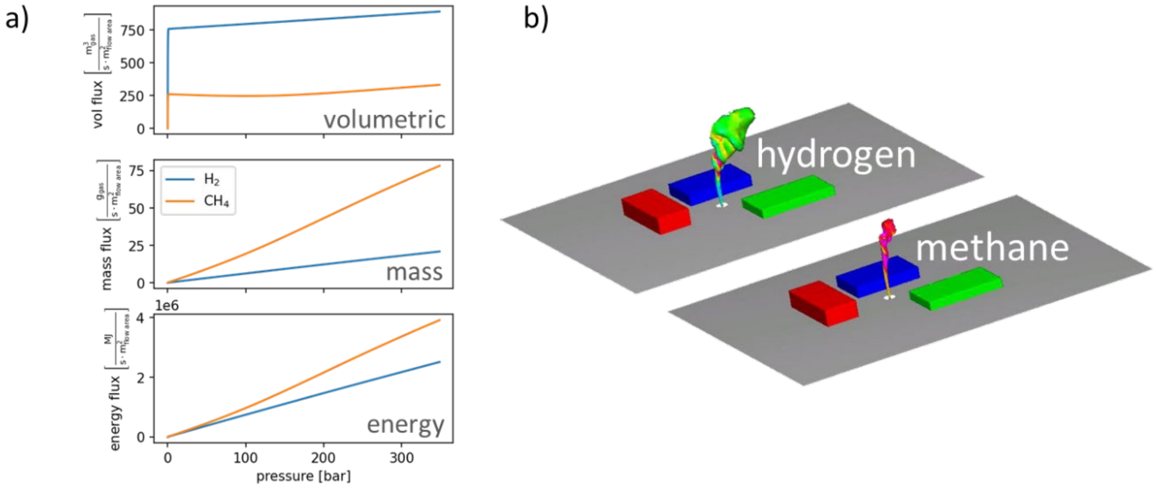
Figure 21. Schematic of the experimental setup of Raman imaging for hydrogen-methane blends



Source: Sandia National Laboratories

To understand better the behaviour of hydrogen-methane blends, experimental approaches must be combined with modelling activities. The relationships between pressure, flow rate, rate of pressure drop, and the Reynolds number have been evaluated to analyse fixed simulated leaks (equivalent leak of hydrogen and of methane) by Sandia researchers. The volumetric flowrate of hydrogen is higher than for methane at fixed pressure. In contrast, mass and energy flow rate of methane are higher than hydrogen at fixed pressure. Figure 22 a) shows that volumetric flow rate of hydrogen, depicted in blue, is about three times that of the methane for an equivalent leak. However, the mass flow of hydrogen is significantly lower. This means that the leak rate is substantially lower on a mass basis for hydrogen due to the lower density of hydrogen vs methane.

Figure 22. a) Comparison of volumetric flow rate, mass flow rate and energy flow rate for an equivalent leak size of hydrogen and methane, b) Comparison of the CFD simulations of the flammable plume of hydrogen and methane from an equivalent leak.



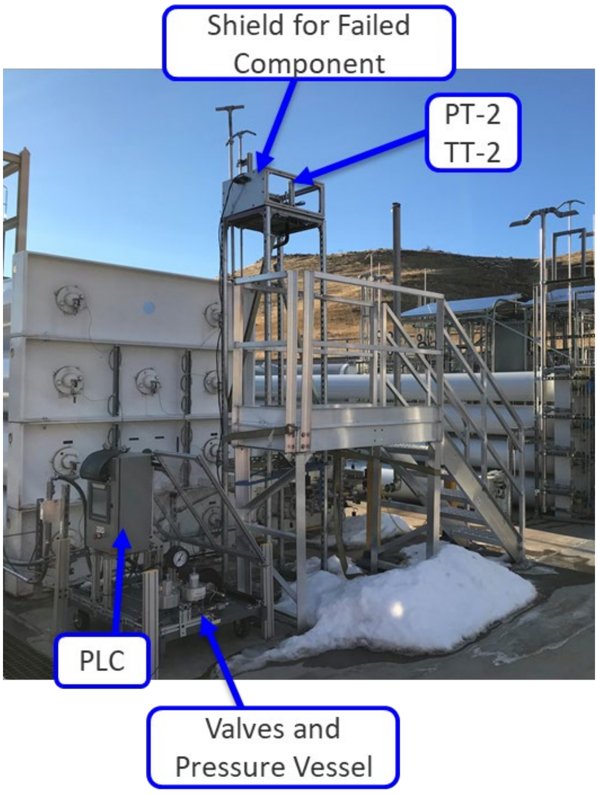
Source: a) Sandia National Laboratories, b) Joint Research Centre

Taking these observations into account, it is assumed that as the hydrogen content increases in blends with methane, the behaviour of the blend will change. Additionally, hydrogen is more diffusive and buoyant than methane, as previously mentioned. Figure 22 b) shows the results from computational fluids dynamics simulations on equivalent leaks of hydrogen and methane (Wilkening and Baraldi, 2007). It can be observed that for a given pressure and leak size, the flammable plume of hydrogen will likely be larger than the flammable plume of methane. This means that as the percentage of hydrogen increases in a methane blend the dispersion behaviour changes, the diffusion and buoyancy of the resulting blend would increase and consequently the flammable plume. Conversely, for a given pressure and leak size, the energy and mass released will be less for hydrogen than for methane. Therefore, as the percentage of hydrogen increases in a methane blend the energy and mass released will be lower.

4.2.3 Other leak quantification methods: industry compatible techniques

Gas sensing techniques constitute the most common approach to detect and quantify leaks in industrial settings. However, there are other strategies to support the quantification of hydrogen releases from a facility in addition to sensors. One such strategy consists of leak rate quantification through system components. Leak rate quantification research has been performed at NREL with the purpose of getting a better understanding of leak behaviour and leak sizes for different components and failure modes. This research is intended to help industry to understand leaks better and quantify these leaks in the field. To do this NREL has developed a test apparatus to measure the mass flow rate of leaks from failed hydrogen components, see Figure 23.

Figure 23. Leak rate quantification apparatus setup at NREL



Source: NREL

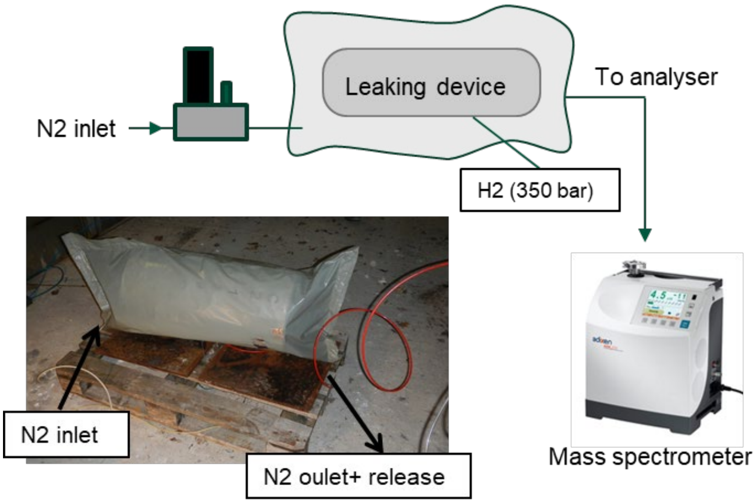
This Leak Rate Quantification Apparatus (LRQA) can nowadays test a variety of components up to 85 MPa. The test pressure is determined by the pressure rating and the expected leak rate of the installed failed component. The LRQA methodology consists of four steps. First, the failed component is pressurised using the storage vessel of known volume of gas from the LQRA. Then the pressure and temperature are measured to calculate the mass at each time step. The mass flow rate (dm/dt) is then determined from those measurements. Finally, an equivalent orifice diameter is calculated from the obtained mass flow rate using standard equations (ISO 9300). In this way, similar failed components can be compared.

Testing using the LRQA has been performed on a variety of components, including orifices, air operated valves, manual valves, check valves, and a thermocouple using N_2, H_2, and He gas. Component failure modes can include internal or external leakage. The testing will be expanded to a greater number and other types of components at varying pressures using different types of gases (including hydrogen-methane blends) to quantify leak rates. Component failure is one potential source of hydrogen emissions. The data and results from the LRQA testing would help understand the different types of component failures and the associated hazard. Additionally, the data obtained will feed into hydrogen leak and plume modelling.

Similar approaches are adopted to characterise the leakages that could possibly appear through the lifetime of hydrogen dispensers in the WP2 of MultHyfuel project.(FCH JU2 MultHyFuel) Project partner INERIS investigates the quantification of large leakages from storages and reservoirs by establishing tests and validated methods to evaluate mass flow rates. For example, they experimentally determined the mass flow rate of a leak in a reservoir from the slope of the mass loss vs time trendline, measuring the mass loss using load cells. This method may be used to provide an instantaneous flowrate value, with an update rate and an accuracy, depending significantly on the sampling rate. Another test method validated by INERIS to evaluate leak flow rate in large reservoirs is similar to the NREL approach, measuring pressure and temperature and using equations of state. INERIS performed this method to evaluate the flow rate of a leak in a 50L cylinder at 700 bar and observed that the accuracy strongly depends on the temperature measurement conditions. From the testing performed by INERIS it can be concluded that large leaks from dynamic processes can be detected through mass, pressure and temperature measurements.

INERIS is also evaluating different methods for detection and quantification of small leaks in system components (e.g., fittings, valves, manifolds, etc.). One way of doing this is calculating the leak mass flow rate of a component from the pressure increase measured in a closed tight volume. The accuracy of this method is a function of the pressure, temperature, time and acquisition rate. It is possible to measure very small pressure increments accurately, in the order of magnitude of 1 Pa. However, the difficulty resides in the temperature management. Keeping the leak upstream and downstream temperatures the same ($\Delta T_{max} < 0.1$ °C) is the key to obtain a good accuracy as temperature variations have a huge impact in the pressure slope. Another experimental method performed by INERIS to detect and quantify small leakages from components relies on mass spectrometry, see Figure 24. The failed component is enclosed in a tight volume and the gas concentration inside that volume is monitored by a mass spectrometer, measuring the hydrogen concentration in a calibrated stream of a carrier gas. A gas vector (e.g., nitrogen on air) is needed to continuously flush the volume. This experimental technique is very sensitive since the accuracy only depends on the sensitivity of the mass spectrometer and the gas vector flow (perfect mixture with the leakage). The gas spectrometer could be replaced by any other gas analyser or sensor (electrochemical cells, catalytic sensors, katharometric sensors, etc.).

Figure 24. Experimental setup based on mass spectrometry.



Source: INERIS

These experimental methods for hydrogen leak detection and quantification in components have been demonstrated in the lab but they are not easily transferable to industrial/larger scales, especially for small leaks involving small ΔP measurements. Gas sensing techniques could be better suited for detecting these types of leaks and even provide a mean to estimate the flow rate, but they need to be placed where the hydrogen is leaking and the leak should be trapped in an enclosed volume. Since the hydrogen flows up, collecting the gas in the upper part of a casing or canopy could be a good strategy but the dynamic of the accumulation must be known (transfer function). Additionally, these sensors must be maintained periodically and present other limiting issues (calibration, sensitivity, response time, sampling rate, etc.).

To further support industry with validated methods and compatible detection techniques, the WP4 of EMPIR Metrology for Decarbonising the Gas Grid (DECARB) project led by NPL is focusing on the development and application of leak detection equipment for use with hydrogen and hydrogen-enriched natural gas (EURAMET Decarb, 2022). The objectives of the task 4.1 which started in June 2021 and will expand until May 2024 are: 1) Perform an assessment of the available techniques, 2) Perform an assessment of the required metrology infrastructure to support the calibration and traceability of hydrogen detectors, 3) Develop suitable traceable reference hydrogen leaks providing industry with the metrology infrastructure to calibrate leak detection equipment, 4) Assess the spectroscopic issues of measurement of hydrogen-enriched natural gas, and 5) Assess down-selected sensors in the laboratory, and then test them at Enagas's hydrogen leak facility.

4.2.4 Monitoring tools for hydrogen detection in the atmosphere

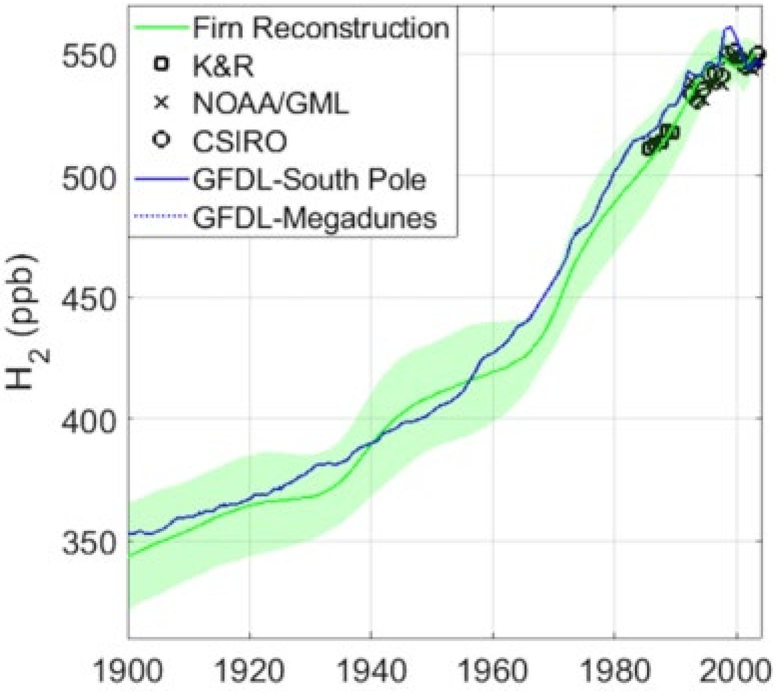
As previously mentioned, the hydrogen molecule lacks a dipole moment which makes it infrared transparent and renders infrared absorption monitoring techniques employed for the detection of other gases in the atmosphere not applicable. Hydrogen is also present at a low amount fraction of around 500 nmol mol^{-1} in the atmospheric background. Instruments based on gas chromatography separation with a gas reduction detector have been deployed at atmospheric monitoring stations for many decades. The time series recorded at Mace Head on the West Coast of Ireland extends to 1990 and is representative of the Northern Hemisphere background. Measurements are made on mainland UK at Weybourne Atmospheric Observatory.

Such atmospheric measurements are already used to verify emissions inventory for other greenhouse gases, such as methane, nitrous oxide, and sulphur hexafluoride. The University of Bristol and NPL maintain a network of tall-tower sites in mainland UK, and at Mace Head, measuring these gases at hourly time resolution. An atmospheric transport model is used to interpret the data and provide estimates of the regionally-resolved annual emissions (Manning et al., 2011; Lunt et al., 2021). Hydrogen is not currently measured at these sites, and interpretation in terms of regional emissions is difficult due to the poorly constrained local emissions and sinks. However, extending the capability of this UK tall tower network in the near term will help in the baseline estimation of natural hydrogen emissions before increased anthropogenic emissions associated with deployment of hydrogen as an energy gas.

Research measurements are performed aiming to improve the understanding of emission scenarios to improve the impact of models. Other observatory networks such as the ones from CSIRO (Australia), AGAGE (US) operate H_2 monitoring throughout the world. Currently there are only 11 observing stations for hydrogen worldwide, eight of which are in the southern hemisphere (World Data Centre for Greenhouse Gases, 2022). Ongoing work as NOAA (US) is expected to greatly expand the number of H_2 monitoring stations.

Moreover, Patterson et al. recently managed to reconstruct hydrogen concentration in Antarctica from ice cores (Patterson et al., 2020; Patterson et al., 2021). The historical hydrogen concentration estimated by Patterson et al. is presented in Figure 25 (firn reconstruction), showing a good agreement with the model results provided by Paulot et al. (GFDL in the figure).

Figure 25. Historical hydrogen concentration in Antarctica.



Source: presentation by F. Paulot, courtesy of James Patterson (UCI)

5 Conclusions

The Clean Hydrogen JU organised a two-day workshop aimed at uncovering the current knowledge on the potential hydrogen emissions from a hydrogen economy and their indirect global warming impact. The main conclusions from the workshop are summarised in the following points:

- **Hydrogen emissions to the atmosphere impact the lifetime of other greenhouse gases, namely methane, ozone, and water vapour, indirectly increasing the Earth's surface temperature.** Current best estimates for the Global Warming Potential of hydrogen emissions are 5±1 and 12±5 kg CO_2e/kg H_2 over a 100-year time horizon (GWP_{100}), and 12-33 kg CO_2e/kg H_2 over 20 years (GWP_{20}). The average lifetimes of hydrogen (~2 years) and the species affected by hydrogen emissions responsible for global warming are much shorter than the one of CO_2, reducing the global warming effect of hydrogen emissions (compared to an equivalent mass of CO_2) over longer time frames.

- **Hydrogen emissions to the atmosphere from the hydrogen value chain are expected from gas providers to be in the range of 1-5% of the hydrogen delivered, with an average value of 2% by 2050**. Assuming a hydrogen demand of 660 Mt/year by 2050 and a GWP_{100} value of 12.8, the CO_2 equivalent emissions arising from hydrogen leaks would be approximately 170 Mt CO_2e/year (i.e., 0.3% of current global CO_2e emissions).

- Although it will not be climate neutral, **a low-carbon and, in particular, a renewable hydrogen economy would significantly reduce the global warming impact compared to a fossil fuel economy.** Estimates as to the scale of that reductions depends on several uncertain parameters, such as the evolution of energy demand, the fraction of it that will be covered by hydrogen (and what technology hydrogen will substitute), the hydrogen production pathway, and loss rates. Nevertheless, switching technologies would guarantee a lower climate impact in the long term even under high hydrogen loss rate scenarios. However, high loss rates could significantly reduce the climate benefits in the near-term.

- **To reach climate neutrality, the additional warming caused by the hydrogen economy needs to be minimised and residual emissions compensated for** (e.g., increase hydrogen sinks, reduce methane emissions, or carbon capture). Hydrogen supply (renewable versus fossil with carbon capture) and losses appear as the key parameters to minimise the climate impact of an H_2 economy transition. Reducing hydrogen leakage would also increase the safety of using hydrogen.

- **Estimates of industrial hydrogen emissions and their global warming impact are subject to a high level of uncertainty.** Uncertainties are mainly due to lack of monitoring data, lack of industry data, and knowledge gaps.

- **The physical characteristics of hydrogen** (highly buoyant, colourless, odourless, tasteless, non-irritating and IR inactive) **make it difficult to detect**. Sensors are the most common strategy for the direct detection and empirical characterisation of hydrogen releases with conventional point sensors the most used.

- **The optical detection of hydrogen is challenging** as it does not present common optical signatures for its monitoring such as infrared absorption bands. Only Raman scattering can be specific to hydrogen and quantitative but requires high power illumination and sensitive detectors.

- Other **wide area monitoring techniques** for hydrogen detection and quantification that work well at lab scale exist but further development is needed to demonstrate effectiveness ***in situ* industrial/larger scales**.

To improve the accuracy of the estimates of the global warming impact of a future hydrogen economy, and to prevent unintended consequences we advocate for the following:

- **More data**: more monitoring stations of hydrogen in the atmosphere and more transparent, accurate, and precise data from the industry regarding emission rates are necessary to improve value chain emission estimates as well as global hydrogen budget models, and therefore global warming impact estimates.

- **More research**: there is still a limited understanding of some natural and anthropogenic phenomena affecting the global warming impact of a hydrogen economy. Topics emerged during the workshop that need to be further investigated are:

    - **Natural hydrogen sources and sinks**. In particular, more research is needed to understand the behaviour of hydrogen consuming organisms in soil. How they are distributed and how they will behave with an increase in hydrogen emissions in a changing climate (i.e., different temperatures, land uses, and hydrology). Moreover, more research is needed regarding natural hydrogen sources (e.g., geological sources).

    - **Anthropogenic hydrogen sources and impacts**. More research (and transparency) is needed to precisely quantify the hydrogen uses (e.g., how much hydrogen will be burned compared to how much will be used in fuel cells) and emissions from the industry. Moreover, more research is needed to understand the climate effect of specific hydrogen applications: e.g., the effect on contrails from hydrogen use for aviation.

    - **Life cycle assessments.** More research is needed regarding the life cycle impacts of hydrogen systems: from the production of the infrastructure, to other potential environmental impacts caused by hydrogen use (e.g., ammonia emissions when ammonia used as hydrogen carrier).

    - **Quantification of hydrogen losses**. Sensor development has traditionally focused on the 1,000 - 10,000 ppm measurement range for safety purposes. However, to evaluate the environmental impacts arising from the cumulative effect of sub-ppm levels of released hydrogen across the value chain there is a need to expand towards lower detection limits and quantification capabilities. Deployment of fast response instruments with five orders of magnitude greater sensibility using emerging technologies such as nanoplasmonic detection, miniaturising Raman scattering and infrared adaptation among others, is needed to accurately measure (detect and quantify) emissions in situ.

    - **Dispersion mechanisms.** Owing to its high diffusivity and buoyancy, hydrogen does not behave like methane when emitted to the atmosphere, it disperses differently and this should be taken into account when assessing hydrogen and hydrogen-methane blend releases. Experimental and modelling approaches should be combined to elucidate the dispersion of hydrogen and hydrogen-methane blends. Novel sensor applications should be investigated to help in the dispersion model validation.

    - **Scale-up of novel detection and quantification techniques**. Further research into how to scale-up experimental detection and quantification techniques which work well at the lab scale is needed to further support an emerging hydrogen industry with validated methods and effective detection and quantification techniques.

- **Always reporting the amount and location of hydrogen emissions throughout the life cycle when assessing the environmental impact of an activity, not only the CO_2 equivalents**. The climate impact depends on the latitude and altitude of the emission. If the global warming impact of hydrogen needs to be aggregated to other greenhouse gases for policy purposes, the metric that aligns best with the goal of the policy should be used (e.g., GWP_{100} in the framework of UNFCCC agreements). We also advocate for standardised experimental methodologies to increase the consistency and comparability of the GWP estimations from different models.

- **Inclusion of hydrogen emissions in the IPCC models**. Hydrogen emissions from a hydrogen economy could represent approximately 10% of the overall hydrogen sources to the atmosphere; it is therefore important to include them in the hydrogen budget and models to estimate the GWP.

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List of abbreviations and definitions

ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road
BAT	Best available techniques
CEN	European Committee for Standardisation
CGA	Compressed gas association
CGS	Combustible gas sensor
CO_2e	CO_2 equivalents
EC	Electrical conductivity
EIGA	European Industrial Gases Association
EPA	US Environmental Protection Agency
ERF	Effective radiative forcing
GC	Gas chromatography
GHG	Greenhouse gas
GTP	Global temperature change potential
GWP	Global warming potential
GWP_{20}	Global warming potential over 20 years
GWP_{100}	Global warming potential over 100 years
ISO	International Committee for Standardisation
JU	Joint undertaking
LDL	Lower detection limit
LRQA	Leak rate quantification apparatus
MOX	Metal oxide sensors
MR	Measurement range
MS	Mass Spectrometry
NDIR	Non-Dispersive Infrared
NMHC	Non-methane hydrocarbons
NOAA	National oceanic and atmospheric administration
Ppbv	Parts per billion by volume
Ppmv	Parts per million by volume
RFID	Radio Frequency Identification Detection
RT	Response time
SMR	Steam methane reforming
TC	Thermal conductivity

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