Hydrogen Europe Position Paper

Hydrogen emissions – State of play and recommendations

Executive Summary

The International Energy Agency (IEA) estimates in their Net Zero Roadmap that green and low carbon hydrogen demand will increase from 95Mton today to 150Mton by 2030. This amount of clean energy will bring considerable benefits for the climate: the IEA predicts average emissions intensity of hydrogen production drops from the range of 12-13.5 kg CO_2-eq/kg H2 in 2022 to 6-7.5 kg CO_2-eq/kg H2 in 2030[1]. However, integrating more hydrogen in our existing and repurposed infrastructure **will inevitably lead to some hydrogen emissions to the atmosphere.** This can happen either through fugitive (from leaks due to tightness failure and permeation) or operational emissions (from planned operating activities, e.g. from maintenance operations)[2]. Thus, it is essential to understand the impact of these emissions on the climate and the amount of possible emissions throughout the value chain with the objective of reducing, and eventually eliminating, them.

The Decarbonised Gas and Hydrogen Package that entered into force in August 2024 has translated this matter into law. On the one hand, the European Network of Network Operators of Hydrogen (ENNOH) will have to draft a report on best practices on hydrogen leakage, hydrogen operators will have to submit a hydrogen leak detection report and, where necessary, a repair or replacement programme to the competent authorities, making public statistical information on hydrogen leak detection and repair on an annual basis[3]. On the other hand, the European Commission has an obligation to submit a report on the topic to the Parliament and the Council, followed by a legislative proposal should it be found necessary[4].

With this paper, Hydrogen Europe aims to take stock of fundamental knowledge on the topic of hydrogen emissions, based on literature review and the publicly available data, and to situate it within a wider context of the energy transition. The paper proposes policy recommendations to raise awareness among industry and policy makers and several technical best practices that could be adapted to the hydrogen value chain, they are summarised in the table below.

[1] International Energy Agency, “Net Zero Roadmap”, accessible here.
[2] IOGP, IPIECA, GIE, Marcogaz, “Methane Emissions Glossary”, accessible here.
[3] Directive on common rules for the internal markets in renewable and natural gases and in hydrogen (recast), article 50(1)(h), accessible here.
[4] Directive on common rules for the internal markets in renewable and natural gases and in hydrogen (recast), article 8(5)(b), accessible here.

Policy recommendations

1. Empirical data collection should be encouraged and supported. It is important to better understand potential effects of hydrogen deployment on atmospheric composition through a combination of theoretical studies and actual measurements for plant sections where prediction of emission levels is not feasible.
2. European funding (Horizon Europe) should support the development and commercialisation of sensors capable of measuring small leaks, as well as the development of models and methodologies for determining emissions and mitigation methods.
3. Regulators should develop guidance documents to foster the use of prevention measures and systems when building hydrogen infrastructure projects throughout the hydrogen value chain.
4. The European Commission and Member states should support the funding of testing campaigns in existing or future hydrogen projects, as well as encourage unlocking of private funding.
5. The European Commission upcoming report on hydrogen leakage should be elaborated in close collaboration with a broad spectrum of stakeholders and take into account market development and the readiness levels of best available technologies.
6. Any preventive measure should be proportional to its environmental and societal costs.

Technical recommendations that might be adaptable to the hydrogen value chain:

1. Minimise leakage: ensure new infrastructure minimises emissions with measures such as tightening valves and seals or using laminated gaskets.
2. Mitigate fugitive emissions by, for example, quickly reacting to leaks and fixing malfunctioning equipment.
3. Mitigate operational emissions via recovering vented, purged, and residual hydrogen and using it to produce process heat/electricity or implementing the latest technology to maximise the hydrogen recovery rate from purification.

Contents

1. Hydrogen presence and emissions into the atmosphere

Currently, hydrogen's average concentration in the atmosphere (mole fraction) is estimated to be about 530 parts per billion by volume[5]. Hydrogen can be emitted into the atmosphere from several sources, including biomass burning, fossil fuel combustion, biological nitrogen fixation, atmospheric photo-oxidation of methane and volatile organic compounds (VOCs) in the atmosphere, and geological sources[6]. Hydrogen is also naturally removed from the atmosphere by biological uptake in soils and oxidation with hydroxyl radical ($OH^{\cdot}$) in the atmosphere. Soil uptakes rates remain uncertain, but they could reach up to 85%[7]. Overall, the average lifetime of hydrogen in the atmosphere is around two years[8].

Some emissions also stem directly from the production, transmission, distribution and use of hydrogen itself. Because of its small molecular size, there is a risk some hydrogen will be released into the atmosphere in daily operations along the hydrogen value chain. **Emissions can result from leaks throughout the value chain,** from infrastructure operations or from routine venting and purging operations.

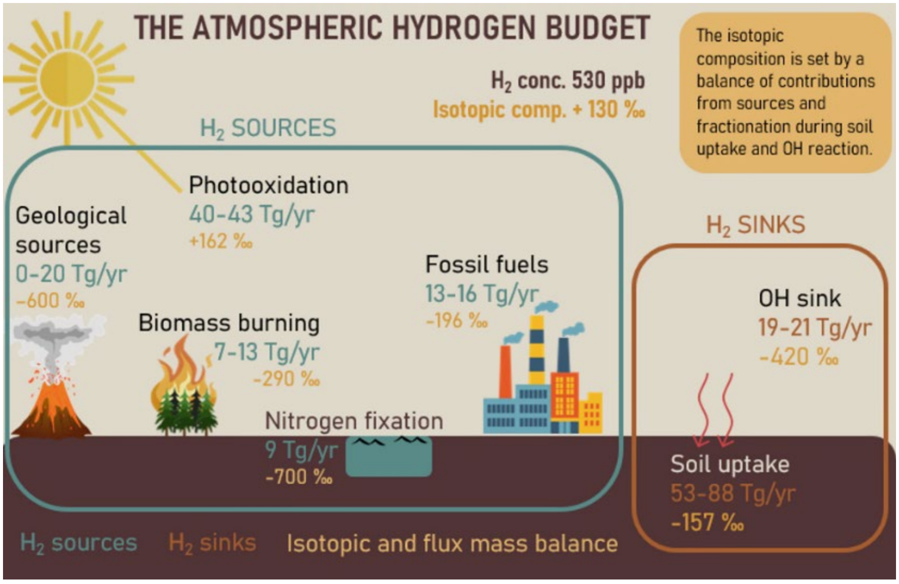

Figure 1: the atmospheric hydrogen budget, Source: CICERO[9](Tg refers to teragram, which is equivalent to a million tonne)

[5] Paulot, F., Pétron, G., Crotwell, A. M., and Bertagni, M. B., "Reanalysis of NOAA H_2 observations: implications for the H_2 budget", accessible here.
[6] Zgonnik V., "The occurrence and geoscience of natural hydrogen: a comprehensive review", accessible here.
[7] Rhee, T. S., Brenninkmeijer, C. A. M. & Röckmann, T., "The overwhelming role of soils in the global atmospheric hydrogen cycle", accessible here.
[8] Ocko I., Hamburg S., "Climate consequences of hydrogen emissions", accessible here.
[9] M. Sand, "Minimizing hydrogen leakages key in future hydrogen economy, accessible here.

2. Quantifying hydrogen emission's effect on the climate

Once hydrogen is emitted into the atmosphere, **hydrogen might react with other molecules already present in the atmosphere**, such as hydroxyl radicals, which in turn reduces the availability of the latter to react with other GHGs. For example, less hydroxyl radical in the atmosphere will prevent it from reacting with methane – a potent GHG - resulting in a higher concentration of methane in the atmosphere, which in turn results in the increasing of radiative forcing (a change in energy balance in Earth's atmosphere)[10].

Estimating the effective impact of hydrogen emissions on the climate is however a complex exercise because of the lack of empirical data we are still facing today. The classic metric to measure the climate impact of gases is the Global Warming Potential (GWP) at the 100-year time horizon. GWP compares the global warming effects of a kilogram of gas to the impact of one kg of CO_2 on the atmosphere for a certain period. For example, a GWP100 of 12 indicates that one kg of a gas has a warming effect 12 times greater than the effects of one kg of CO_2 on a 100-year time horizon. To measure the climate impacts of hydrogen, a measure of the GWP at both the 20- and 100-years horizon is often adopted. Research is still at early stages: the IPCC is yet to agree on a GWP for hydrogen. However, recent scientific consensus seems to converge towards a GWP100 of 12 and a GWP20 of 30-40 for hydrogen[11, 12]. For comparison, methane has a GWP100 of around 28-36 and a GWP20 of 84-87[13].

"Estimating the effective impact of hydrogen emissions on the climate is a complex exercise because of today's lack of empirical data."

Another issue is related to the uncertainty regarding hydrogen emission rates. For the moment, measurements of hydrogen emissions have mainly been carried out in the context of hydrogen safety and therefore data is very limited, mostly based on estimations. Indeed, in these (safety) cases the intention is to detect leakages as fast as possible to repair/prevent safety concerns; and this limits long-term measurement opportunities. An example of such emissions estimations coming from different sources is presented in Figure 2. It is important to emphasise that this table only represents an illustrative example, and that **measurements and research are still needed to understand the future impact of hydrogen emissions.**

[10] Warwick et al., "Atmospheric implications of increased hydrogen use", accessible here.
[11] i.e. in 100 years, the warming effect of one kilogram of hydrogen on the atmosphere is equivalent to 12 times the impact of one kilogram of CO_2 and in 20 years the impact will be 30-40 times the one kg of CO_2
[12] M. Sand et al., "A multi-model assessment of the Global Warming Potential of hydrogen", accessible here.
[13] IEA, "Methane and climate change", accessible here.

Leak type	Methane leak rate (m³/h)	Methane leak rate (kW)	Hydrogen leak rate (m³/h)	Hydrogen leak rate (kW)
Hole	0.19 A √(P / 20)	2.0 A √(P / 20)	0.50 A √(P / 20)	1.7 A √(P / 20)
Emergency control valve	0.013 (P / 20)	0.14 (P / 20)	0.016 (P / 20)	0.054 (P / 20)
Meter regulator inlet anaconda	0.0089 √(P / 20)	0.093 √(P / 20)	0.023 √(P / 20)	0.077 √(P / 20)
Meter regulator diaphragm	0.21 √(P / 75)	2.2 √(P / 75)	0.56 √(P / 75)	1.9 √(P / 75)
Loose fitting	0.033 (P / 20)	0.35 (P / 20)	0.050 (P / 20)	0.17 (P / 20)
Meter test point open	0.0089 √(P / 20)	0.093 √(P / 20)	0.023 √(P / 20)	0.077 √(P / 20)
Incorrect appliance operation (hob)	0.19	2.0	0.60	2.0
Incorrect appliance operation (grill or oven)	0.29	3.0	0.89	3.0
Incorrect appliance operation (gas fire)	0.57	6.0	1.8	6.0
Incorrect appliance operation (boiler)	0.021	0.22	0.032	0.11
Pipe damage	0.049	0.51	0.11	0.37
Soldered fitting	0.088 (P / 20)	0.92 (P / 20)	0.12 (P / 20)	0.40 (P / 20)
Compression fitting	0.092	0.97	0.15	0.50
Bayonet fitting	0.0022	0.023	0.0028	0.0094
Valve	0.021	0.22	0.032	0.11
Pipework full bore failure	22	230	56	188
Meter connections not tight	0.13	1.4	0.20	0.67

Figure 2: Methane vs hydrogen emission rates estimations
Source: Hy4inHeat and UK department for Business, Energy & Industrial Strategy[14]

These parameters must also be put into context of early stages of development of hydrogen infrastructure networks and the ensuing lack of data currently available on hydrogen emissions. For pipelines, it is likely that emissions rates will be minimal. As the hydrogen grid will be a new infrastructure, operators have the opportunity of putting forward plans to build hydrogen pipelines with stricter standards compared to the ones applied to current natural gas grid[15]. Estimated emission rates are presented in Figure 3 for different stages of the value chain. Overall, estimations of emission rates remain low for most steps of the value chain, and range between 0.01% for gas turbines and 13.20% for road transport with liquid hydrogen. This figure is also illustrative of the lack of data on estimations. In this example, the value indicated for above ground gas storage is unproportionally high.

[14] Hy4inHeat and UK Department for Business, Energy & Industrial Strategy, "Safety Assessment: Gas Escape Frequency and Magnitude Assessment", accessible here.
[15] For example, change of the valves' standard to ISO 15848-1 (more info here), which recommends much more tight valves, development of centrifugal compressors that will be encapsulated for hydrogen (more info here), or development of 100% leak-proof rotating seals (more info here) will all minimise emissions at pipelines level.

Sector	Specific Area		Predicted Emission Confidence level	
			50 %	99 %
Production	Electrolytic	With venting and purging	3.32 %	9.20 %
		With full recombination of hydrogen from purging and crossover venting	0.24 %	0.52 %
	CCUS-enabled		0.25 %	0.50 %
Transport and Storage	National Transmission System		0.04 %	0.48 %
	Distribution Network		0.26 %	0.53 %
	Underground Storage		0.02 %	0.06 %
	Above Ground Storage (gas)		2.77 %	6.52 %
	Road Trailering (gas)		0.30 %	0.66 %
	Road Trailering (liquid)		3.76 %	13.20 %
End-uses	Residential		0.30 %	0.69 %
	Gas Turbines		0.01 %	0.01 %
	Refuelling Stations		0.25 %	0.89 %
	Fuel Cells	With venting and purging	1.36 %	2.64 %
		With full recombination of hydrogen from purging and crossover venting	0.56 %	1.02 %
	Combustion Engines		0.30 %	0.66 %
	Process Industry		0.25 %	0.50 %

Figure 3: Hydrogen leakage estimates
Source: Fugitive Hydrogen Emissions in a Future Hydrogen Economy, Frazer Nash Consultancy[16]

These estimations seem to point out that the highest emission rates are related to liquefied hydrogen handling and above ground gas storage, which will represent only a small fraction of overall hydrogen transport and storage activities. Overall, most parts of the value chain, including production, transport, distribution and final uses present leakage rates well below 1%.

To grasp the full effects of hydrogen emissions on the atmosphere it is paramount to put potential adverse effects in perspective with regards to the positive effects of switching to hydrogen. Some studies have tried to balance positive effects of switching to hydrogen alternatives and negative effects linked to hydrogen emissions[17, 18, 19] and indicate that benefits will significantly outweigh the negative effects of hydrogen emissions.

[16] Frazer-Nash consultancy, "Fugitive Hydrogen Emissions in a Future Hydrogen Economy", accessible here.
[17] D. Hauglustaine et al. "Climate benefit of a future hydrogen economy", accessible here.
[18] JRC, "Hydrogen emissions from a hydrogen economy and their potential global warming impact", accessible here.
[19] Hamburg and Ocko, "Climate consequences of hydrogen emissions", accessible here.

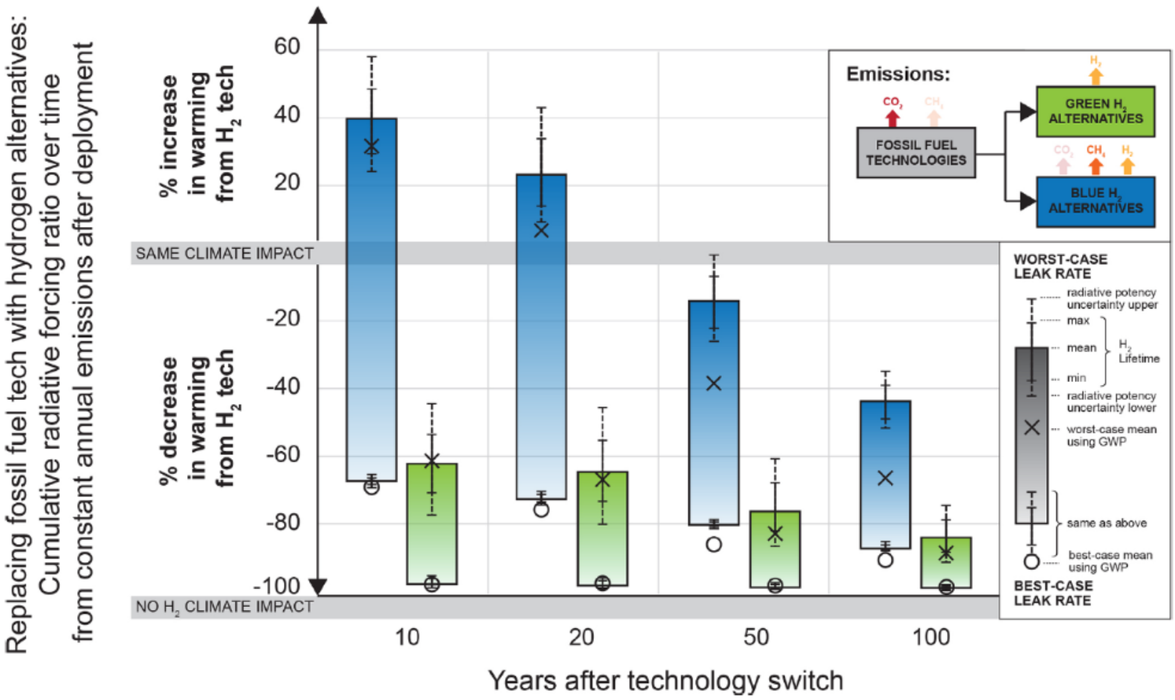

Figure 4: Relative warming impact over time from replacing fossil fuel technologies with green or blue hydrogen alternatives for a generic case, Source: Hamburg and Ocko. Underlying assumptions are detailed in Annex[20]

For example, Ocko and Hamburg (see Figure 4) estimate that even with a GWP of 11-12, 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 (GWP100 based) by replacing fossil fuels. This indicates that the climate impact would be reduced by 96-99.8% if fossil fuels were replaced by renewable hydrogen.

These conclusions are, however, heavily dependent on many underlying assumptions such as type of hydrogen production and associated emissions (both upstream and downstream), leakage rates and total amount of hydrogen handled. More research will be necessary to ensure the veracity of the information presented in this section.

Other effects to consider are emission reductions in molecules currently emitted by the production and consumption of fossil fuels (and replaced by cleaner forms of hydrogen), including methane, CO,

[20] Hamburg and Ocko, "Climate consequences of hydrogen emissions", accessible here. A cumulative radiative forcing ratio for annually deploying 1 kg of H2 vs. annually avoided fossil fuel emissions is used as a proxy for relative warming impacts. Emissions from hydrogen alternatives are hydrogen for green hydrogen and hydrogen and methane for blue hydrogen. Emissions from fossil fuel technologies are carbon dioxide, estimated at 11 kg CO2 avoided per 1 kg H2 deployed, based on estimates from Hydrogen Council (2017). Emissions of hydrogen and methane include a range of plausible leak rates from 1 % (best case) to 10 % (worst case) per unit H2 deployed for hydrogen and from 1 % (best case) to 3 % (worst case) for methane. The height of each bar corresponds to the range of leakage. Error bars represent uncertainties in both hydrogen's soil sink and lifetime (solid lines) as well as uncertainties in the radiative effects of hydrogen and carbon dioxide (20 %; dashed lines). The corresponding GWP results (only difference is pulse emissions rather than constant emission rate) are shown using the "x" and "o" markers. Details on emissions inputs and equation used in the calculation and input parameters are in Annex.

NOx (i.e. NO + NO2) and volatile organic compounds (VOCs), which will also induce positive feedback on atmospheric composition and air quality. These reductions may additionally reduce the effect of hydrogen emissions on the atmosphere. Also, the climate effects of hydrogen will depend strongly on the specific use cases, production method, actual hydrogen and methane emission rates, transport, distribution and storage of the molecule and the time scale looked at.

"The net impact of replacing fossil fuels with clean hydrogen is largely positive, but specific results are heavily dependent on many underlying assumptions and require more research and commonly agreed assumptions by regulators."

With that in mind, it is important to recognise that some solutions (developed below) already exist and can be deployed at larger scale to minimise the impact of potential emissions on the climate. This requires looking both at technological aspects (i.e. which solutions adopted to reduce methane emissions can be transposed to hydrogen) as well as the regulatory measures that could be adopted and adapted in the coming years.

3. Recommendations for an accurate accounting of hydrogen emissions

3.1. Policies need to evolve

Overall, the impact of hydrogen emissions on the climate should be better understood (e.g. the IPCC has not yet decided on a GWP for hydrogen), and stakeholders should be encouraged to measure hydrogen emission rates linked to their installations. Some suggestions that could accelerate this process include:.

- Scientific studies should be supported: to better understand the behaviour of hydrogen in the atmosphere. Closure of knowledge gaps, particularly the role soils play in removing hydrogen from the atmosphere, is needed.
- Develop support through European funding (ex: Horizon Europe) for the development and commercialisation of sensors capable of measuring leaks.
- Regulators should develop guidance documents to foster the use of prevention measures and systems when building hydrogen infrastructure projects throughout the hydrogen value chain. The Hydrogen & Gas Package (article 9 par. 5 Gas Directive) mandates the Commission with developing a report on the topic of hydrogen leakage, and if needed, to accompany it by a legislative proposal. This exercise should be carried out in a way that ensures adequate participation from stakeholders and the scientific community to help better understanding the environmental aspects related to hydrogen emissions and inform regulatory process accordingly.
  The Package also mandates regular hydrogen leak detection and repair surveys at the level of operators (article 50(1)(h) of Gas Directive). It also indicates that data collected through this process should be considered in the methodology for assessing GHG emission savings from low-carbon fuels. Similar considerations are to be included at a later stage in the methodology

for defining Renewable Fuels of Non-Biological Origin (RFNBOs)[21]. Before these considerations are added to the different delegated acts, the data should be widely peer-reviewed, and stakeholders should be consulted before the methodologies are officially published.

- Finally, it is also important to note that the recently finalised Methane Emission Regulation[22] will provide many innovations and best practices applicable to methane emissions. Some of these could also be applicable to future hydrogen system. However, any set of rules applied to minimising hydrogen emissions should take into account the nascent stage of the market to ensure the rules do not stifle its development. The rules should be **proportionate: the societal impact of the emission reduction achieved should be significantly balanced with the societal costs of the measure itself**. Any mitigation rules should be based on a cost-benefit analysis methodology or similar.

3.2. Lessons from the Natural gas sector that could be transposed to hydrogen

To mitigate methane emissions[23], some solutions have already been developed and applied to natural gas infrastructure[24]. Some might be replicable to the hydrogen value chain[25, 26], but they would need to be tested and adapted to the particularities of the sector, for example:

- To minimise leakage:
  - Ensure new hydrogen infrastructure is built as leak free as possible,
  - Tighten valves and seals,
  - Use laminated gaskets and welded joints,
  - Avoid flanged and threaded joints,
  - More insulation of pipes and storage tanks, specifically for liquified hydrogen,
  - Minimise number of pipeline seams,
  - Minimise points or pressurisation and depressurisation.
- To mitigate operational emissions:
  - Recover vented, purged, and residual hydrogen and use it to produce process heat/electricity,

[21] Article 9 par. 5 of the Gas Directive states that the methodology to define low carbon fuels "shall include the treatment of emissions due to the leakage of hydrogen, and take into account methane upstream emissions and actual carbon capture rates", and that this methodology shall be consistent with the methodology for assessing GHG emission savings from RFNBOs.
"RFNBOs" refers to liquid or gaseous fuels other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass – this includes renewable hydrogen. The methodology to define RFNBOs is defined in two delegated acts published under the RED. This methodology will need, according to the Gas Directive, to be adapted to reflect hydrogen leakage once the impact of leakage has been assessed by the Commission in the report mandated by the Gas Directive.

[22] Directive 2024/1787 on the reduction of methane emissions in the energy sector

[23] Methane Guiding Principles, "Enabling Action to Reduce Methane Emissions Globally", accessible here.

[24] Marcogaz, "Best Available Techniques to reduce methane emissions from venting and flaring activities in the mid-downstream gas sector", accessible here.

[25] Environmental Defense Fund, "Preventing and mitigating hydrogen emissions from infrastructure, accessible here.

[26] NHyRA project, "pre-Normative Research on Hydrogen Releases Assessment", accessible herev.

- Implement the latest technology to maximise the hydrogen recovery rate from purification,
- Maximise combustion efficiency if flaring is necessary,
- Install control devices to minimise emissions from storage tanks,
- Install vapor recovery unites to capture gas and boil off and compress it into the gas line,
- Recover and recompress emission in the process gas,
- Reduce pressure before venting,

- To mitigate fugitive emissions:
  - Immediately repair leaks and fix/replace malfunctioning equipment,
  - Minimise the volume that must be depressurised in a pipeline or vessel (use temporary line stops to isolate the section where repairs are needed),
  - Verify repairs are successful through follow-up leak monitoring,
  - Replace or eliminate components that leak,
  - Replace or retrofit high-leakage devices,
  - Reduce the number of blowdowns by coordinating repairs and maintenance events into a single downtime,
  - Flaring or recompression instead of venting,
  - Careful maintenance plans.

Additionally, developing and making sensors and methods capable of measuring small leaks commercially available, as well as gathering more data on the actual emission rates will help:

- Better understand actual emission rates, then use them to determine potential effects of hydrogen deployment on climate,
- Carry out field measurements of emission rates along the various pieces of the supply chain that would improve life cycle assessment by accurately accounting for the net GHG impact of the switch to hydrogen compared to alternative systems,
- Establish detailed measurements which would help identify major emission sources and mitigation opportunities to inform best practices and to implement correction measures/actions.

4. Annex

		Best-case leaks, H_2 and CH_4: 1 %	Worst-case leaks, H_2: 10 %; CH_4: 3 %
Hydrogen (green and blue)	Produced	1.01	1.11
	Consumed	1	1
	Emitted	0.01	0.11
Methane (blue only)	Produced	3.06	3.44
	Consumed	3.03	3.33
	Emitted	0.031	0.103

Table 1: Hydrogen and methane emissions (in kg) for deploying 1 kg of either green or blue hydrogen based on best- and worst-case leak rates. It is assumed that 3 times the mass of hydrogen is needed in the form of methane for using methane as a feedstock for hydrogen production. Data is used as emission inputs for hydrogen and methane in Figure 4, Source: Hamburg and Ocko[27].

Variable		Definition	Unit	Value	Source
H		Time horizon	Years	1–100	n/a
$AGWP_{CO_2}$					
A_{CO_2}		Radiative forcing scaling factor	$W\,m^{-2}\,ppb^{-1}$	1.33×10^{-5}	Forster et al. (2021)
a_{0-3}		Coefficient for fraction of CO_2 remaining in atmosphere	Unitless	$\alpha_0 = 0.2173; \alpha_1 = 0.224; \alpha_2 = 0.2824; \alpha_3 = 0.2763$	Myhre et al. (2013)
τ_{1-3}		Timescale for fraction of CO_2 remaining in atmosphere	Years	$\tau_1 = 394.4; \tau_2 = 36.54; \tau_3 = 4.304$	Myhre et al. (2013)
$AGWP_{CH_4}$					
A_{CH_4}		Radiative forcing scaling factor	$W\,m^{-2}\,ppb^{-1}$	3.88×10^{-4}	Forster et al. (2021)
τ		Perturbation lifetime	Years	11.8	Forster et al. (2021)
f_1		Tropospheric ozone indirect effect scaling	Unitless	0.37	Forster et al. (2021)
f_2		Stratospheric water vapor indirect effect scaling	Unitless	0.106	Forster et al. (2021)
$AGWP_{H_2}$					
τ_{H_2}		H_2 lifetime (combined chemical and deposition lifetime)	Years	1.9 [1.4, 2.5]	Warwick et al. (2022); Paulot et al. (2021)
C		Conversion factor for converting H_2 mixing ratio (ppb) into H_2 mass (kg)	$ppb\,kg^{-1}$	3.5×10^{-9}	Warwick et al. (2022)
tp		Length of step emission	Years	1	n/a
A_i	CH_4	Radiative forcing scaling factor	$W\,m^{-2}\,ppb^{-1}$	3.88×10^{-4}	Forster et al. (2021)
	O_3		$W\,m^{-2}\,DU^{-1}$	0.042	Warwick et al. (2022)
	H_2O		$W\,m^{-2}\,ppb^{-1}$	1×10^{-4}	Warwick et al. (2022)
a_i	CH_4	Production rate of species resulting in the	$ppb(CH_4)\,ppb(H_2)^{-1}\,yr^{-1}$	1.46×10^{-2}	Warwick et al. (2022)
	O_3	indirect forcing (mixing ratio per year) per ppb H_2	$DU\,ppb(H_2)^{-1}\,yr^{-1}$	0.0056	Warwick et al. (2022)
	H_2O	change at steady state	$ppb(H_2O)\,ppb(H_2)^{-1}\,yr^{-1}$	0.042	Warwick et al. (2022)
τ_i	CH_4	Perturbation lifetime		11.8	Forster et al. (2021)
	O_3	of species causing the	Years	0.07	Warwick et al. (2022)
	H_2O	radiative forcing		8	Warwick et al. (2022)

Table 2: Input parameters and sources used for the absolute global warming potential (AGWP) calculations shown in Figure 4. Source: Hamburg and Ocko[28].

[27] Hamburg and Ocko, "Climate consequences of hydrogen emissions", accessible here.
[28] Hamburg and Ocko, "Climate consequences of hydrogen emissions", accessible here.