Integrating Hydrogen Emissions Into the EU Policy Framework

Why hydrogen emissions matter, when they will become significant, and how the EU can tackle them

Raffaele Piria

Eike Karola Velten

February 2025

Ecologic Institute

Contact

Rafaele Piria
Senior Fellow
Ecologic Institute
Pfalzburger Straße 43/44
10717 Berlin

E-Mail: raffaele.piria@ecologic.eu

Suggested citation

Piria, Raffaele, and Eike Karola Velten: Integrating hydrogen emissions into the EU policy framework. Ecologic Institute, Berlin, 2025. Available at: https://www.ecologic.eu/19988.

Acknowledgements

This study is part of the project “Opportunities to improve EU policies to reduce methane and hydrogen emissions from the energy sector”, in collaboration with the Environmental Defense Fund Europe.

We thank our colleagues Arne Riedel, Ralph Bodle, Aleksandra Lempp, Anna Mansilla Urban and Gordian Kerner for intellectual contribution, inspiration and support.

Ecologic Institute:
Science and policy for a sustainable world

Ecologic Institute is an independent, academic think tank for environmental research and policy analysis. Since our founding in 1995, Ecologic Institute has been dedicated to improving environmental policy, sustainable development and policy practice. Through findings and ideas Ecologic Institute helps to mainstream environmental issues into other policy areas. Strengthening the European and international dimensions in research, education and environmental policy discourses is a key priority. Ecologic Institute has offices in Berlin, Brussels and Washington DC.

Today more than 100 employees work for Ecologic Institute. Our colleagues come from over 25 countries. Offering diverse expertise and skills, our experts cover the entire spectrum of environmental policy, sustainable development and socio-ecological research in inter- and transdisciplinary projects. Our staff researches, supports and evaluates national, European and international political processes and brings together actors from science, politics and practice. The results are in-depth analyses and practical recommendations. In cooperation with leading American and German universities, the Institute is also active in education.

Ecologic Institute is a private, non-profit institution financed through its project work. Funding partners include the European Commission, the European Parliament, the German Federal Ministry for the Environment, the German Federal Ministry of Education and Research, the German Federal Environment Agency and various foundations.

Ecologic Institute is a member of the Ecological Research Network (Ecornet).

Ecologic Institute is a registered charity. Donations are tax deductible.

Ecologic Institute in Washington DC is an IRC 501 (c) (3) non-profit organization.

Further information: **www.ecologic.eu**

Executive Summary

Hydrogen (H_2) is an indirect greenhouse gas (GHG). While H_2 emissions make up a negligible fraction of today's GHG emissions, they are set to become more significant in the 2030s and, should the EU and the global community progress towards climate neutrality, will likely be substantial in the 2040s, as achieving climate neutrality requires the expansion of hydrogen use alongside the rapid reduction of other GHGs.

As decisions made today will shape hydrogen value chains for decades, it is important to develop and implement strategies to prevent and mitigate H_2 emissions. While this report focuses specifically on strategies to prevent and mitigate H_2 emissions, it is also crucial to recognise the importance and urgency of limiting methane (CH_4) and carbon dioxide (CO_2) emissions associated with hydrogen value chains. Until fossil-based hydrogen production is reduced to well below 10% of overall hydrogen production, - a significant drop from the current level of clearly more than 95% - CO_2 and CH_4 emissions will remain the primary driver of climate impact in H_2 value chains.

This paper explores how the EU can address H_2 emissions using a four-pronged strategy, with various sets of measures discussed in one of the four chapters:

Limit the use of hydrogen and its derivates to beneficial applications: While fossil-based H_2 must be phased out and H_2 demand is set to grow, the availability of renewable H_2 is likely to remain limited. It is thus crucial that public policies prioritise H_2 applications that offer genuine climate mitigation benefits, ensuring that limited green or low carbon H_2 is directed to them. To this end, the EU should clearly define priority H_2 applications. Applications where H_2 use offers no clear benefit or is likely to result in higher GHG emission than available alternatives should generally not be supported by public policies. Accordingly, the EU should adjust its policies and strategies, including the Hydrogen Strategy, infrastructure policies, and certain policies that undervalue the CH_4 emissions embedded in H_2 from fossil fuels.

Establish hydrogen emission reporting systems and target setting: The EU should support research on hydrogen as a precursor gas and actively support the UNFCCC process regarding its recognition as an indirect GHG. At the same time, the EU should not wait for the conclusion of this process, but should begin establishing H_2 emission monitoring and reporting systems as a prudent, no-regret approach. This will generate valuable knowledge to inform future mitigation policies. Once sufficient information is available, the Commission should seize the opportunity provided by Art. 9(6) of the Gas Internal Markets Directive to develop a legislative proposal aimed at minimising H_2 emissions.

Reduce the hydrogen emissions intensity of processes and equipment: H_2 leaks have traditionally been regulated solely by safety standard aimed at preventing fires and explosions. Due to this, H_2 concentrations below hazardous levels are considered acceptable, though they may have a considerable cumulative climate impact. To address this, a regulatory framework is needed to monitor and reduce the H_2 emission intensity across relevant equipment and processes including approaches for upstream, midstream and downstream H_2 emissions.

Research and technological development (RTD): The EU should leverage its RTD programmes to advance knowledge, technologies and research infrastructure that support the strategic goals outlined above. This includes research on natural H_2 sources and sinks, anthropogenic sources, technologies and methods development for quantifying facility-level H_2 emissions and for monitoring H_2 concentrations in the atmosphere, the expansion of research infrastructure for H_2 observation, the inclusion of H_2 in major climate models, and the development of improved technologies to detect hydrogen leakages.

Contents

Abbreviations

BAT	Best available technology
CBAM	Carbon border adjustment mechanism
CCS	Carbon capture and storage
CH_4	Methane
ETS	EU emissions trading system
EU-MER	EU methane emissions regulation
ESPR	EU sustainable products regulation
EVP	Environmental vehicle passport
GHG	Greenhouse gas
GW	Gigawatt
GWP 20/100	Global warming potential over a period of 20/100 years
H2	Hydrogen
IEA	International Energy Agency
IED	EU industrial emission directive
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre of the European Commission
LDAR	Leak detection and repair
MRV	Monitoring, reporting and verification
Mt/y	Million tons per year
MWh	Megawatt-hours
NZIA	EU Net-Zero Industry Act
ppm	Parts per million
RED III	EU renewable energy directive, third version of 2001
RFNBO	Renewable fuels of non-biological origin
RTD	Research and technological development
SLCF	Short-lived climate forcer
SMR	Steam methane reforming
UNFCCC	United Nations Framework Convention on Climate Change

1 Why we must care about hydrogen emissions

In the EU and elsewhere, hydrogen (H_2) emission regulations have traditionally been concerned with the prevention of fire and explosions risks – issues which are not subject of this paper. This conventional focus has resulted in H_2 emissions below hazardous thresholds being deemed negligible and thus acceptable.

However, even below those thresholds H_2 emissions contribute to climate change. While hydrogen is not a direct greenhouse gas (GHG), it reacts with atmospheric components, increasing levels of other GHGs. This is largely because hydrogen prolongs the atmospheric lifetime of methane (CH_4) and enhances ozone levels in the troposphere. CH_4 and ozone are, respectively, the second and third most significant GHGs after CO_2. Additionally, hydrogen increases stratospheric water vapour, which also contributes to global warming.

It has therefore been suggested to regard hydrogen as an **indirect GHG**, or precursor gas.[1]

Global warming potential of hydrogen emissions

A common metric for assessing the climate impact of various GHGs is the **global warming potential (GWP),** which measures the radiative forcing of a unit mass of a given substance over a specified timeframe. By convention, carbon dioxide (CO_2) has a GWP of 1, with all other GHGs being scored relative to CO_2. The standard timeframe used for reporting under the UNFCCC is 100 years (GWP_{100}), which defines the warming potential 100 years after the substance has been emitted to the atmosphere.[2]

Each GHG has unique physical characteristics. In the atmosphere, **hydrogen** is considerably **more short-lived than CO_2**. For this reason, its **global warming potential** is **higher during the first 10-20 years** after emission**.**

Given the escalating damage that climate change is already inflicting on ecosystems and on humans, there is growing interest in strategies that limit global warming over shorter timeframes than the standard 100 years. also other time horizons, such as 20 years (GWP_{20}), are often used to illustrate the specific benefits of reducing short-lived GHGs.[3]

While in previous assessment reports (i.e. AR4 and AR5), the IPCC has included a GWP_{100} value of 5.8 for hydrogen, hydrogen is not (yet) within the scope of the UNFCCC reporting requirements. Based on the latest science, presented in Table 1, hydrogen's GWP is much higher than previously thought. .[4] The wide margins of accuracy shown in Table 1 point to the need of further research about the behaviour of hydrogen in the atmosphere. However, their central values are relatively close to each other, which shows a good level of alignment on the most likely GWP level. Based on their averages, **in the following we use a GWP_{100} of 12** and a **GWP_{20} of 36** to provide simplified estimates of the climate impact of H_2 emissions.

---

[1] See the sources quoted in Table 1. In the UNFCC language, the technical term is "precursor gas". More on this in Chapter 2.2.1 below.

[2] Paris Rulebook, Decision 18/CMA.1, annex, paragraph 37.

[3] IPCC (2023): Climate Change 2021: The Physical Science Basis. Cambridge University Press. https://doi.org/10.1017/9781009157896.

[4] Additionally to the sources indicated in the table, see also: R. G. Derwent (2023): Global warming potential for hydrogen: Sensitivities, uncertainties and meta-analysis, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.219.
I. Ocko and S. Hamburg (2022): Climate consequences of hydrogen emissions, in: Atmospheric Chemistry and Physics, Volume 22, issue 14. https://doi.org/10.5194/acp-22-9349-2022

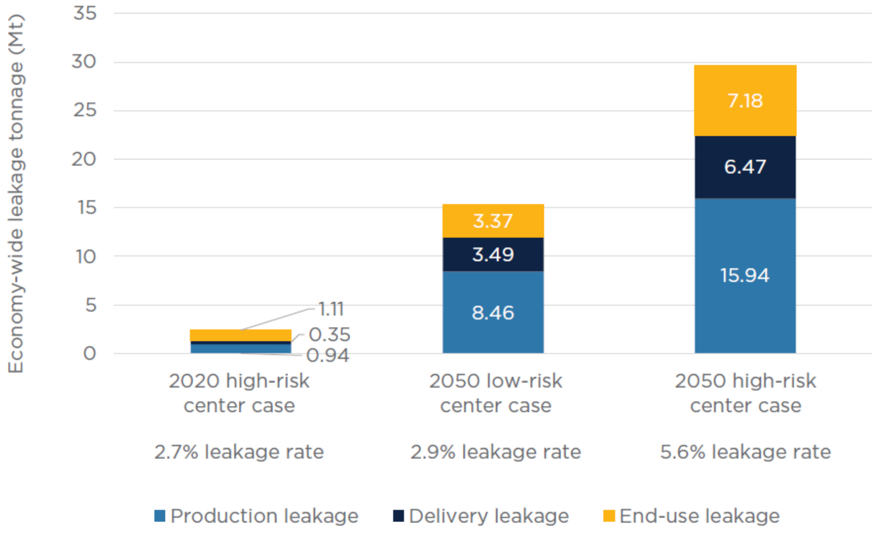
Table 1: Estimations of hydrogen's global warming potential (GWP)

Source	GWP_{100}		GWP_{20}	
Sand et al. (2023) [5]	**11.6**	± 2.8	**37.3**	± 15.1
Warwick et al. (2022)[6]	**12**	± 6	**30**	± 20-44
Hauglustaine et al. (2022)[7]	**12.8**	± 5.2	**40.1**	± 24.1

Estimates for future hydrogen emissions

The increasing recognition that H_2 emissions exacerbate climate change comes at a time when the EU and many governments around the world are intent on **implementing plans to significantly expand hydrogen production**, transportation, and usage, **thereby increasing the potential for H_2 emissions**. Figure 1 presents the volume of H_2 emissions associated with the hydrogen value chain in 2020 and in two scenarios for 2050, according to a 2022 report published by the Center on Global Energy Policy at the Columbia University in New York.

Figure 1: Estimates of global H_2 leakages in 2020 and range for 2050 (in Mt H_2)



Source: Fan et al. (2022).[8]

The **estimate for 2020** relates to 88.5 Mt H_2 produced and consumed globally. Using a GWP_{100} of 12, the estimated 2.4 Mt of H_2 emissions correspond to 28.8 Mt of CO_2, representing **0.06% of the global GHG emissions** for that year.[9] Even when considering the 20-year impact of GHG emissions including hydrogen, H_2 emissions in 2020 remained a very small fraction of global GHG emissions. However, **when considering 2050, H_2 emissions become significantly more relevant**. The values shown in Figure 1 assume a global hydrogen consumption

---

[5] M. Sand et al. (2023): A multi-model assessment of the Global Warming Potential of hydrogen. Communications Earth & Environment 4, 203. https://doi.org/10.1038/s43247-023-00857-8.

[6] N. Warwick et al. (2022): Atmospheric composition and climate impacts of a future hydrogen economy. Atmos. Chem. Phys. Discuss. https://doi.org/10.5194/acp-2023-29

[7] D. Hauglustaine et al. (2022): Climate benefit of a future hydrogen economy Communications Earth & Environment 3, 295. https://doi.org/10.1038/s43247-022-00626-z

[8] Z. Fan et al (2022).: Hydrogen leakage: a potential risk for the hydrogen economy. Center on Global Energy Policy, Columbia-SIPA. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/Hydrogen-LeakageRegulations_CGEP_Commentary_070722_0.pdf

[9] Data on global GHG emissions from World Resource Institute. See: https://www.wri.org/data/world-greenhouse-gas-emissions-2020

of 528 Mt H_2/year by 2050, which is six times higher than in 2020. This figure is based on the IEA's net-zero emissions scenario of 2021. The low and high leakage rates are derived from an extensive literature review and the authors' (Fan et al. 2022) expert assumptions about each segment of the hydrogen value chain. It is important to note that these values are not empirically measured and highly uncertain. Fan et al. as well the authors of the sources cited in the footnotes 5-6-7 emphasise the significant uncertainty in estimates of H_2 emissions rates.[10] However, this represents the best data currently available.

Table 2 presents the values from Figure 1, converted in CO_2 equivalent using both GW_{100} and GWP_{20}.

Table 2: Estimated global hydrogen emissions in 2050, converted in Mt $CO_{2\,eq}$

Scenario	GWP_{100}	GWP_{20}
2050 low H_2 emission risk case	184 Mt $CO_{2\,eq}$	551 Mt $CO_{2\,eq}$
2050 high H_2 emission risk case	355 Mt $CO_{2\,eq}$	1056 Mt $CO_{2\,eq}$

Source: Own calculation, based on Fan et al.(2022), see Figure 1: H_2 $GWP_{100\,/\,20}$ assumed at 12 / 36.

The projected emission volumes are substantial and may not be ignored in the long-term. Already by the 2040s, when hydrogen usage is expected to have significantly increased, global temperatures will be notably higher than today, intensifying the urgency of reducing short-lived GHGs. By 2050, the world is envisaged to achieve **climate neutrality** under the Paris agreement. By then, any remaining GHG emissions will need to be offset by limited natural and technical removals, which will also be essential for balancing unavoidable emissions from sectors such as agriculture and the manufacture of certain products, such as cement.

CO_2 and CH_4 emissions are the most urgent and in the short to medium term the larger concern in hydrogen value chains

The facts described above underscore the importance of addressing H_2 emissions before they become a substantial climate problem. However, before discussing how H_2 emissions can be addressed in the remainder of this paper, it is essential to recognise that – as long as significant quantities of hydrogen continue to be produced from fossil energy sources – the CO_2 and CH_4 emissions associated with these production processes will far exceed the H_2 emissions from the entire hydrogen value chain. Consequently, at present and over the coming years, the greatest potential for GHG emission reduction in hydrogen value chains lies in decreasing the production of hydrogen derived from fossil fuels. Simultaneously, policy makers must establish the foundations to ensure that H_2 emissions do not become a significant climate issue in the long term.

Table 3 below compares the impact of different GHGs resulting from hydrogen production and usage in terms of CO_2 equivalent. It shows that, as long as significant quantities of hydrogen are produced from fossil fuels, **the combined effect of CO_2 and CH_4 emissions** resulting from hydrogen production is at least **an order of magnitude greater than that of H_2 emissions**.

Based on the data presented above, the H_2 leakages across the entire hydrogen value chain in 2020 amounted to 0.29 $kgCO_{2\,eq}/kgH_2$. In the low- and high- leakage risk cases for 2050, this value is expected to increase to between 0.35 and 0.67 $kgCO_{2\,eq}/kgH_2$. Table 3 also shows the H_2 emissions from the production process, allowing specific comparison with CO_2 and CH_4 emission values, which refer only to hydrogen production, since hydrogen usage itself does not

---

[10] See also: Esquivel-Elizondo et al. (2023): Wide range in estimates of hydrogen emissions from infrastructure. Sec. Sustainable Energy Systems Volume 11 – 2023. https://doi.org/10.3389/fenrg.2023.1207208

produce CO_2 or CH_4 emissions. However, the values relative to the entire value chain are more relevant, as midstream and downstream H_2 emissions will occur regardless of the hydrogen production method.

Globally, the vast majority of hydrogen is currently produced through unabated **steam methane reforming (SMR)**. Depending primarily on the upstream CH_4 emission intensity of the natural gas used in SMR, the GHG intensity (GWP_{100}) of hydrogen produced through SMR varies between 10 and 17 $kgCO_{2\,eq}/kgH_2$, when considering only CO_2 and CH_4 emissions. This is 15 to 50 times greater than the CO_2 equivalent value of the H_2 emissions relative to the entire hydrogen value chain in 2050. For **coal gasification**, the IEA estimates an even higher intensity, ranging from 22 to 26 $kgCO_{2\,eq}/kgH_2$.

Table 3 also shows the lower GHG values that could theoretically be achieved if carbon capture and storage (CCS) with a 93% CO_2 abatement rate were applied to hydrogen production. However, this may be an optimistic assumption by the IEA, as no existing CCS project has consistently achieved even an 80% abatement rate, with many achieving less than 50%.[11] Even with a 93% CO_2 abatement, CO_2 and CH_4 emissions from fossil-fuel-based hydrogen production would still be 5 to 35 times higher than the corresponding CO_2 equivalent value of the H_2 emissions relative to the entire hydrogen value chain.

Table 3: Impact of different GHGs caused by hydrogen production and usage (GWP_{100})

GHG	Value chain segment	$kgCO_{2\,eq}$ / kgH_2
H_2 emissions 2020	Entire value chain	0.29
H_2 emissions 2050	Entire value chain	0.35 – 0.67
H_2 emissions 2020	Production only	0.11
H_2 emissions 2050	Production only	0.19 – 0.36
CO_2+CH_4 emissions	Production only (unabated SMR)	10 – 17
CO_2+CH_4 emissions	Production only (unabated coal gasification	22-26
CO_2+CH_4 emissions	Production only (SMR + CCS 93%)	3 – 12
CO_2+CH_4 emissions	Production only (coal gasification + CCS 93%)	3 – 7

Source: Own calculation, based on Fan et al.(2022) for H_2 emissions, Bauer et al. (2022)[12] for steam methane reforming (SMR), and IEA (2023)[13] for coal gasification, with a GWP_{100} of H_2 assumed at 12. We did not use the IEA data for SMR because Bauer et al. uses more sophisticated assumptions concerning CH_4 emissions. Note that IEA (2023) and Bauer et al. (2022) likely applied different assumptions, particularly concerning CH_4 emissions. Therefore, this table should not be used to compare SMR and coal directly; however, the order of magnitude in the difference between H_2 emissions and CO_2+CH_4 emissions is reliable.

Using the central values from Table 3 as a reference, even if only 7% of the hydrogen directly or indirectly consumed in the EU (e.g., via imports of ammonia or other hydrogen carriers) were derived from unabated SMR, with the remainder sourced from renewable energy, the CO_2 and CH_4 emissions resulting from the fossil-based production of that 7% would still be greater, in terms of $CO_{2\,eq}$, than the H_2 emissions associated with the entire value chain. H_2 emissions

---

[11] Institute for Energy Economics and Financial Analysis (2023): Carbon Capture and Storage: An unproven technology that cannot meet planetary CO_2 mitigation needs. https://ieefa.org/ccs

[12] Bauer et al. (2022): On the climate impacts of blue hydrogen production, in: Sustainable Energy Fuels, 2022,6, 66-75. https://doi.org/10.1039/D1SE01508G The lower value of the range 10-17 assumes a very optimistic methane emission intensity of the natural gas used in SMR of 0.2%, the higher value a pessimistic intensity of 8%.

[13] See: https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021

become the main source of GHG emissions from the hydrogen value chain only once the unabated fossil share goes below 7%.

All values discussed in this section are based on various assumptions resulting in relatively broad ranges of likely values. However, their order of magnitude clearly shows that the total GHG footprint of the hydrogen value chain is largely dependent on the share of fossil fuel-based hydrogen, with H_2 emissions playing a secondary role.

Furthermore, **CCS applied to hydrogen production is not a practical best use of limited CCS resources**, limiting its feasibility on a large scale. Researchers analysing limitations on global geological CO_2 storage potential and suggesting a judicious prioritisation of uses conclude that other applications with no viable alternatives should be prioritised and very little **CCS resources** can be allocated to fossil-based hydrogen production.[14]

Conclusion:

- Currently, H_2 emissions make up only a very small fraction of global GHG emissions. However, they are likely to become increasingly relevant in the medium and long term. Therefore, strategies to avoid and mitigate H_2 emissions need to be developed and implemented.
- As long as substantial quantities of hydrogen are produced from fossil fuels, CO_2 and CH_4 emissions will continue to be by far the most significant source of climate impact in hydrogen value chains. The priority should thus remain on phasing out fossil-fuel-based hydrogen production and, in the interim, reducing the CH_4 intensity of the fossil fuels used for hydrogen production (as well as for any other purpose) as much as possible. Utilising CCS in fossil-based hydrogen production is not a practical best use of limited CCS resources, limiting its feasibility at scale. In a climate neutral world, hydrogen must be produced from renewable energy sources.

---

[14] Grant et al. (2022): Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO_2 storage capacity. International Journal of Greenhouse Gas Control, Volume 120. https://doi.org/10.1016/j.ijggc.2022.103766 On the limits to the global CCS potential, see also: Zhang et al. (2024): The feasibility of reaching gigatonne scale CO_2 storage by mid-century. Nat Commun 15, 6913. https://doi.org/10.1038/s41467-024-51226-8

2 How can the EU address hydrogen emissions

2.1 Limit hydrogen use to beneficial applications

As noted in Chapter 1, phasing out fossil-fuel-based hydrogen production is a key priority for reducing the GHG impact of hydrogen. At the same time, as further discussed below, the availability of renewable hydrogen is likely to remain limited in the foreseeable future. Consequently, it is essential that public policies focus on promoting hydrogen applications that deliver genuine climate mitigation benefits, directing the available green or low carbon hydrogen to them.

Summary of recommendations:

The key recommendations from this chapter are:

- **Define priority hydrogen applications:** The EU hydrogen policies should actively promote the uptake up of hydrogen in applications with clear climate benefits, such as steel making, ammonia production, other chemical processes, power system backup as well as the production of low carbon synthetic fuels for aviation and long-distance shipping.
- **Identify uncertain and non-beneficial applications:** The EU should explicitly identify applications where hydrogen use offers no clear benefit or is likely to cause more GHG emissions than available alternatives. Such applications should generally not be supported by public policies. At a minimum, non-beneficial applications include low-temperature heat (space heating, low temperature processes) and light duty vehicles.
- **Adjust strategies and individual policies accordingly:** The EU Hydrogen Strategy and various energy infrastructure policies should be revised to align with these priorities. Moreover, some policies that undervalue the methane emissions embedded in hydrogen from fossil fuels should be amended to reflect hydrogen's GHG balance accurately. Specifically, the outdated and overly low CH_4/CO_2 equivalency rate in Annex V of the Renewable Energy Directive should be updated to align with current science and with the UNFCCC climate reporting standards. Hydrogen production from fossil fuels should be no longer included in the NZIA list of net-zero technologies. All policies aimed at reducing the demand for energy services and materials that are, or could potentially be, based on hydrogen should be strengthened. The same applies to policies aimed at increasing the availability of renewable energy, which can either be used to produce green hydrogen or to meet the electricity and heat demand for applications that might otherwise rely on hydrogen or hydrogen-based technologies.

2.1.1 Priority hydrogen applications

Achieving a climate-neutral Europe requires phasing out hydrogen production from fossil fuels which is the main source of GHG emissions. At the same time, however, hydrogen consumption needs to rise significantly, as hydrogen and hydrogen-based materials are the most viable or even the only possible paths to decarbonise essential economic activities, such as steel making, ammonia production, other chemical processes as well as the production of low carbon synthetic fuels for aviation and long-distance shipping. For Europe and other regions, hydrogen can also provide essential long-term energy storage and serve as a critical power system backup during periods when high demand coincides with low wind and solar power generation.

All these activities will need to be powered by renewable hydrogen. Apart from a small potential for hydrogen production from biomass, the bulk will need to be produced via electrolysis, a process with approximately 35% energy loss[15]: in other words, producing 1 MWh of hydrogen requires at least 1.43 MWh of electricity as well as significant amounts of highly purified water, which in many locations requires additional energy input for production. Despite rapid growth, renewable energy generation will remain limited in the foreseeable future, as it must also replace direct fossil fuels use. Therefore, **hydrogen and its derivates should be directed to applications where they are the only or the most viable solution**, such as those mentioned above.

2.1.2 Non-beneficial hydrogen applications

There is strong evidence that **direct electrification is more efficient** than hydrogen-based solutions **for decarbonising light duty vehicles** and **low-temperature heat production**. The overall energy efficiency of battery-electric passenger cars is more than 2.5 times higher than that of fuel cell passenger cars and five times higher than that of cars with combustion engines running on hydrogen-based synthetic fuels. For heating systems in individual buildings, electric heat pumps are over five times more energy efficient than fuel cell heating and gas condensing boilers that burn hydrogen-based synthetic fuels.[16] These figures do not include the energy required to manufacture components like batteries, internal combustion engines, heat pumps and conventional space heaters. However, even when these are taken into account, the argument remains largely unchanged: direct electrification is significantly more efficient. This means that the same demand can be met with significantly fewer wind turbines, solar panels, and hydro power stations, thereby conserving space, scarce materials, and energy, while also accelerating the decarbonisation of other sectors.

Recent evidence suggests that the benefits of direct electrification apply to a wider range of applications than previously thought. In **heavy-duty road transport**, direct electrification is not only more energy-efficient and climate-friendly, it is also gaining acceptance among both vehicle manufacturers and buyers.[17] Battery-electric trucks are likely to remain more cost-effective than hydrogen-based vehicles over the next two decades, both for vehicle owners and operators, and from a systemic perspective.[18] In Europe, hydrogen-based solutions for road transport are therefore increasingly expected to be relevant only for niche applications, if at all. As for the industrial sector, a recent study shows that currently available direct **electrification** technologies could deliver more than 60% of the **industrial process heat**, while technologies expected to be available by 2035 could meet up to 90% of that demand.[19] In a climate neutral world, hydrogen-based solutions will remain essential for a relatively small portion of industrial process heat.

Road transport and space heating are highly **decentralised applications**. If supplied by hydrogen, both would require extensive hydrogen distribution grids. Alternatively, hydrogen for

---

[15] In a 2020 IRENA report, 65% efficiency was assumed as current efficiency of new, best efficiency electrolysers. International Renewable Energy Agency: Green Hydrogen Cost Reduction: Scaling up Electrolysers to meet the 1.5°C Climate Goal: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf Recently, new electolyer designs have reported efficiencies over 80%. See: https://www.iea.org/energy-system/low-emission-fuels/electrolysers

[16] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels. See: https://www.agora-energiewende.org/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf#page=12 .

[17] ITTC (2024): Race to Zero: European Heavy Duty Vehicle Market Development Quarterly (January – June 2024) https://theicct.org/publication/r2z-eu-hdv-market-development-quarterly-jan-june-2024-sept24/

[18] Ainalis, David, Christ Torne, David Cebon (2022): An electric road system and hydrogen for decarbonizing the UK's long-haul freight.' Research in Transportation Business & Management. https://doi.org/10.1016/j.rtbm.2022.100914. ITTC (2023): A total cost of ownership comparison of truck decarbonization pathways in Europe https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/

[19] Fraunhofer ISI (2024): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry. https://publica.fraunhofer.de/bitstreams/a3e17b7f-1c91-444e-86a6-7b4880c0bf57/download

road vehicles could be supplied by midstream hydrogen supply chains using truck-transport, which is considered to have particularly high leakage rates of up to 10% (see Chapter 2.3.2 below). Space heating demand could be met by blending in hydrogen into existing natural gas networks. However, this approach is associated with higher costs for the energy system overall as well as for consumers when compared to heat pumps or district heating, and it faces numerous other technical, safety and environmental challenges.[20] Moreover, using scarce hydrogen for low temperature heating may limit its availability for priority applications.

2.1.3 Focus the EU Hydrogen Strategy on priority applications

The **2020 EU Hydrogen Strategy**[21] focuses mainly on the priority hydrogen applications outlined above. However, it remains open to a range of non-beneficial applications in the industry and mobility sectors. In the transport sector, the strategy views hydrogen as "a promising option where electrification is more difficult", **including for light-duty road vehicles**. In industry, the Commission's 2020 strategy focused on hydrogen use in steel making, refineries, and ammonia and methanol production, but it does not exclude any industrial application**, including those with low-temperature requirements**.

On the **supply side**, the 2020 EU Hydrogen Strategy sets ambitious goals: at least 6 GW of domestically installed electrolysers producing up to 1 Mt of hydrogen per year by 2024, and 40 GW by 2030, all powered by renewable electricity. In its REPowerEU plan, launched in May 2022, the Commission raised these non-binding targets, aiming to increase consumption to 20 Mt per year by 2030, with half produced domestically and half imported as hydrogen, ammonia or other hydrogen carriers and derivatives. Compared to the earlier "Fit for 55" modelling, projected hydrogen usage in transport by 2030 increased from 0.9 to 2.3 Mt/y, with additional 1.3 Mt/y intended to be blended into the gas grid.[22]

Currently, **progress on both the supply and the demand side is well below target**. As of May 2024, the combined operational electrolysis capacity in the EU, including capacity with just a final investment decision, amounted to merely 0.2 Mt/y. Only a portion of this capacity is likely to be operational by the end of 2024, compared to the target of 1Mt/y. BloombergNEF forecasts that no more than 23 GW of electrolysis capacity will be deployed in the EU by 2030, well below the 125 GW required to meet the REPowerEU target. On the demand side, as of May 2024, binding offtake agreements accounted for less than 5% of the supply needed to meet the REPowerEU targets. Similarly, there are rising doubts about whether the import targets for 2030 can realistically be achieved. [23] The sluggish progress and anticipated further delays in hydrogen production strengthen the case for limiting policies that promote hydrogen demand to priority hydrogen applications.

Therefore the EU and its Member States should **reconsider their hydrogen strategies**. By deciding early on not to promote the use of hydrogen for highly decentralised applications such

---

[20] Rosenow, Jan (2024): A meta-review of 54 studies on hydrogen heating, Cell Reports Sustainability, Volume 1, Issue 1, 2024. ISSN 2949-7906, https://doi.org/10.1016/j.crsus.2023.100010 . See also: Martin, Paul et al. (2024): A review of challenges with using the natural gas system for hydrogen. Energy Science & Engineering, Volume 12, Issue 10, October 2024. https://doi.org/10.1002/ese3.1861

[21] European Commission: A hydrogen strategy for a climate-neutral Europe, COM/2020/301. See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301

[22] Commission Staff Working Document "Implementing the REPower EU Action Plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets, accompanying the "REPowerEU Plan". See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2022%3A230%3AFIN&qid=1653033922121

[23] BloombergNEF (2024): Hydrogen Supply Outlook 2024: A Reality Check: https://about.bnef.com/blog/hydrogen-supply-outlook-2024-a-reality-check/ European Court of Auditors (2024): The EU's industrial policy on renewable hydrogen - Legal framework has been mostly adopted – time for a reality check. https://www.eca.europa.eu/en/publications/sr-2024-11. Ricardo (2024): Weighing the EU's options: Importing vs Domestic Production of Hydrogen/E-fuels. https://www.ricardo.com/media/htvldj10/ricardo-report-weighing-the-eu-options-importing-versus-domestic-production-of-hydrogen-efuels.pdf

as road transport, space heating and other low temperature heat demand, the EU could **reduce hydrogen infrastructure costs** by confining pipelines to the more centralised essential applications mentioned above, and reduce the need for storage. Additionally, **decentralised applications** create many **more potential hydrogen leakage points**, both in the distribution chain and in the end-use devices. Providing clearer guidance on the respective roles of hydrogen and of electrification in the EU's decarbonisation strategy would also enhance investment security, thereby reducing the costs of implementing electrification in road transport and building.

2.1.4 Adjusting individual policies

Adapting the Hydrogen Strategy to focus on high-priority applications and excluding those with limited or no benefit would be a significant step. However, the practical impact will largely depend on a wide array of specific policies. This section provides a brief, non-exhaustive overview of selected policies that could be adjusted in line with this approach.

2.1.4.1 Accurately accounting for the climate impact of hydrogen

It is essential that the EU policy framework relies on realistic data regarding the climate impact of hydrogen and its applications, since underestimations could lead to an unjustified prioritisation of hydrogen applications. This requires, on one hand, establishing a robust framework for monitoring and reporting H_2 emissions, as discussed in detail in Chapter 2.2. Even more urgently, it is essential not to underestimate the CO_2 and CH_4 emissions associated with fossil-based hydrogen production, which, as seen in Chapter 1, have a higher impact than the H_2 emissions caused throughout the entire value chain.

Three relevant EU legal acts apply, or may soon apply, an **outdated and too low CH_4/CO_2 equivalency factor**, which significantly **undervalues methane emissions embedded in hydrogen** and hydrogen derivatives. This issue affects the EU's methodology to assess the GHG intensity of renewable fuels of non-biological origin (RFNBO) and recycled carbon fuels adopted in February 2023,[24] as well as the draft methodology for assessing GHG emissions savings from low-carbon fuels published by the European Commission in September 2024 and currently in the process of being adopted[25]. Both these delegated regulations refer to Part C, Point 4 of Annex V to the Renewable Energy Directive 2018/2001 (RED III) for establishing CO_2 equivalent values of GHGs in their emissions calculations. However, **RED III defines a CH_4/CO_2 equivalency factor of 25** (1g CH_4 = 25g $CO_{2\ eq}$), with no mechanisms in place to adapt this factor to recent findings in climate science and to international agreements.

The CH_4/CO_2 equivalency factor of 25 was already outdated when RED III was adopted. Successive IPCC Assessment Reports have upgraded the GWP of methane. For GWP_{100}, the 2014 IPCC 5th Assessment Report raised the equivalency factor to 28 (1g CH_4 = 28g $CO_{2\ eq}$), forming the basis for reporting under the Paris Agreement.[26] In the latest **IPCC 6th Assessment Report** published in 2021, the **equivalency was further updated to 29.8** for methane of fossil origin.[27]

---

[24] Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. See: http://data.europa.eu/eli/reg_del/2023/1185/oj

[25] Draft Annex to the draft Commission Delegated Regulation supplementing Directive (EU) 2024/1788 of the European Parliament and of the Council by specifying a methodology for assessing greenhouse gas emissions savings from low-carbon fuels. See: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14303-Methodology-to-determine-the-greenhouse-gas-GHG-emission-savings-of-low-carbon-fuels_en

[26] European Environmental Agency (2023): Methane emissions in the EU: the key to immediate action on climate change. https://www.eea.europa.eu/publications/methane-emissions-in-the-eu

[27] IPCC Sixth Assessment Report. Working Group 1: The Physical Science Basis (2021): https://www.ipcc.ch/report/ar6/wg1/

Notably, recital 2 of the **EU Methane Emissions Regulation** (EU-MER) explicitly **references the updated 29.8 GWP for methane**. The EU-MER was published in the Official Journal on 13 June 2024, the same day as the EU Internal Gas Markets Directive 2024/1788, which serves as the legal basis for the aforementioned Commission Delegated Regulation with the draft methodology for assessing GHG emissions savings from low-carbon fuels. Regrettably, the Internal Gas Markets Directive does not explicitly mention the GWP of methane. It is paradoxical that a draft delegated act for this Directive still uses the outdated GWP of 25.

As a result, relevant EU legal acts **undervalue methane-related GHG emissions embedded in hydrogen by 16%**. This distortion makes applications using fossil-based hydrogen appear more beneficial for climate mitigation than they are in reality, potentially leading to excessive support for, and ultimately overuse of, hydrogen. The simplest remedy would be to amend the methane GWP in Part C, Point 4 of Annex V to RED III. Based on current IPCC science, and in alignment with the EU-MER, it should refer to a GWP of methane of 29.8, with an indication that the value will be updated in case of new IPCC findings.

Notably, under the current legislative framework, **neither of the two Delegated Regulations** referenced in this section **accounts for the climate impact of H_2 emissions** associated with hydrogen production and transportation to end users. The reason for this is that both Delegated Regulations are designed to establish methodologies to quantify GHG savings from renewable hydrogen and from low carbon fuels, respectively. However, since hydrogen is not included in the official list of GHGs, these methodologies do not consider H_2 emissions. Whether it is legally feasible to include such emissions before hydrogen is officially classified as an (indirect) GHG is a critical question that requires careful consideration of both the internal consistency of the EU's GHG monitoring and reporting systems, and external factors, particularly given that the methodologies may affect international trade and have thus implications under WTO rules. These issues, however, are beyond the scope of this paper.

2.1.4.2 Infrastructure policies

Limiting hydrogen use to the aforementioned priority applications affects policies regulating the planning, permitting, financing and operation of energy infrastructure in many ways.

Such a limitation will most likely result in a higher degree of electrification that will increase demand for power grid infrastructure, while significantly reducing – and, in some regions, probably eliminating – the need for hydrogen distribution networks. The necessity for widespread hydrogen refuelling stations for road vehicles will also diminish or may be avoided altogether. Hydrogen transmission and storage will be affected as well: on one hand, lower hydrogen consumption volumes may reduce the need for certain hydrogen transmission pipelines. On the other hand, a power system with very high shares of variable renewables will require robust backup capacities to meet demand during periods when high electricity consumption coincides with low solar and wind power generation. Hydrogen may be particularly well suited for providing this type of back-up capacity, most likely creating a need for large-scale hydrogen storage. If the EU limits hydrogen use to the aforementioned priority applications, it is neither necessary nor meaningful to upgrade natural gas infrastructure for hydrogen blending. Instead, in some areas, the need to plan the orderly and timely decommissioning of gas distribution grids will arise earlier than thought, as there is no longer a prospect of repurposing from natural gas to hydrogen distribution.

In addition to the Hydrogen Strategy and the REPower EU Action Plan, these considerations suggest a need to reconsider certain aspects of several EU policies and strategies .The following list may not be exhaustive:

- The EU Action Plan for Grids (COM/2023/757 final) and the EU strategy for energy system integration (COM/2020/299 final).
- The provisions regarding the ten-year development plans for the electricity, natural gas and hydrogen networks contained in the Directive on internal markets for renewable gas, natural gas and hydrogen (EU/2024/1788) and in the Directive on the internal market for electricity (EU/2019/944, amended by Directive 2024/1711).
- The Regulation 2022/689 on trans-European energy infrastructure (TEN-E Regulation), amended by the Commission Delegated Regulation 2024/1041 on the projects of common interest and of mutual interests.
- The commitment to ensure a minimum number of hydrogen refuelling stations according to Article 6 of the Alternative Fuel Infrastructure Regulation (Regulation 2023/1084).

2.1.4.3 Other policies

The **Net-Zero Industry Act (NZIA)** includes a list of 19 net-zero technologies. These technologies will benefit from a range of public policies designed to ensure the security and sustainability of their supply. One of the technologies is defined as “*hydrogen technologies, including electrolysers and fuel cells*”. By specifically referring to electrolysers, while omitting any mention of technologies for hydrogen production from fossil fuels, the text clearly signals a focus on renewable hydrogen. However, the Act does not explicitly exclude fossil-fuel-based hydrogen technologies. Although it seems unlikely that such technologies would be eligible for NZIA support, their explicit exclusion would be a prudent measure.

The EU **state aid regime** should be adapted as well. The General Block Exemption Regulation should ensure that state aid for investments aimed at reducing H_2 emissions is treated in the same way as state aid for investments that reduce emissions of gases that are already recognised as greenhouse gases.

In addition to the policies mentioned thus far, there exists a **broad range of measures** aimed at **reducing the demand for energy services and materials** that are, or could potentially be, based on hydrogen. These include, among others, policies designed to reduce overall energy and material consumption across the economy (e.g., the EU Energy Efficiency Directive), in buildings (e.g., the Energy Performance of Buildings Directive), in transport (e.g., any policy supporting public transport, cycling, and urban planning that reduces car use), in agriculture (policies supporting a lower use of fertilisers based on ammonia), and in the economy as a whole (e.g. the Waste Framework Directive and other policies that support a circular economy). There are also policies aimed at **increasing renewable energy capacities**, which can either be used to produce green hydrogen or to meet the electricity demand for applications that might otherwise rely on hydrogen or hydrogen-based technologies. **Strengthening these policies** can help limit hydrogen use to truly beneficial applications. Given that their impact on hydrogen emissions is indirect, however, they are not discussed in further detail here.

2.2 Establish hydrogen emissions reporting systems and target setting

As noted in Chapter 1, H_2 emissions currently represent only a negligible fraction of global GHG emissions: approximately 0.06% in 2020. Clearly, the bulk of the EU’s and global climate mitigation efforts must focus on the remaining 99.9%. However, if the EU progresses towards climate neutrality in line with its targets, H_2 emissions are set to become significant in the 2030s and substantial in the 2040s, as hydrogen production and usage increase while emissions of other major GHGs – especially CO_2 and CH_4 – are anticipated to decline rapidly. As the EU and the world prepare to significantly expand hydrogen production, consumption, storage, and usage, there is a risk of locking in high H_2 emission processes and technologies.

Therefore, it is necessary to establish monitoring and reporting systems for H_2 emissions early on, as such emissions are not currently monitored systematically within the EU or globally. This issue has two key dimensions, discussed in the following two subchapters: the process towards classifying hydrogen as a precursor gas in the UNFCCC framework, and establishing H_2 emission monitoring and reporting systems in the EU.

Summary of recommendations:

The key recommendations from this chapter are:

- **Support research on hydrogen as a precursor gas:** Although hydrogen's indirect warming potential has been acknowledged in previous IPCC reports, recent studies indicate its GWP100 value could be much higher than previously thought. Through its funding programmes (see also Chapter 2.4), the EU should support research on hydrogen as a precursor gas. This includes, for example, reducing uncertainty about its GWP, improving understanding of its soil sink dynamics, and quantifying H_2 emissions through empirical measurements.

- **Actively support the UNFCCC process:** Once the IPCC incorporates the latest research on hydrogen's role as an indirect GHG and updates the GWP values in its reports, the EU and its Member States should advocate for its swift inclusion in the UNFCCC reporting framework.

- **Implement and strengthen the Gas Directive's H_2 monitoring and reporting provisions**: The recent update of the EU Gas Internal Markets Directive introduced obligations for monitoring and reporting H_2 emissions from hydrogen networks, terminals and storage. These obligations should be fully implemented and made more specific.

- **Establish H_2 reporting and monitoring requirements for other sectors:** The Gas Directive does not cover upstream, downstream emissions or midstream emissions associated with truck-transported hydrogen, including those from trucks, compressors and liquefiers. The EU should develop effective monitoring systems for these sectors.

- **Include H_2 emissions in the EU's climate targets and reporting when feasible:** Once the necessary preconditions are fulfilled, which is expected to take several years, the EU should include H_2 emissions in its climate targets and reporting instruments.

2.2.1 Classifying hydrogen as a precursor gas in the UNFCCC reporting framework

The UNFCCC inventory reporting obligations[28] require all participating countries to submit inventories of the six GHGs[29], and to report on four precursor gases: carbon monoxide (CO), nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOCs), and sulphur oxides (SO_X). **Including hydrogen in this list of precursor gases would provide a strong incentive for improving monitoring and mitigation of hydrogen leakages**. It would also

---

[28] UNFCCC (2014): Decision 24/CP.19, Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention. It is based on IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1, Chapter 7. See: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

[29] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3).

establish a more robust legal foundation for future EU policies, both domestic and external, aimed at mitigating H_2 emissions.

The most likely pathway for hydrogen, or any other gas, to be included in the UNFCCC list of precursor gases is for its role as a short-lived climate forcer (SLCF) to be recognised by the Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the science related to climate change. Already in 2001, the 3rd IPCC Assessment Report (AR3) acknowledged that H_2 indirectly increases the volume of GHGs and that "*future emissions may need to be considered as a potential climate perturbation*".[30] Hydrogen was mentioned in AR4 with a GWP_{100} value of 5.8, based on a study produced in 2001 that neglected the effects due to stratospheric water vapor. The same GWP value was mentioned in the Supplemental Material of AR5.[31] As discussed extensively above in Chapter 1 of this paper, the 5.8 GWP value from AR4 is much lower than suggested by more recent science. However, the latest (2021) 6th IPCC Assessment Report still does not include hydrogen in the SLCF list.[32]

This has hindered the consideration of hydrogen as a precursor gas in the UNFCCC framework and restricts the possibility of including hydrogen in the SLCFs to be covered in the "2027 IPCC Methodology Report on Inventories for Short-lived Climate Forcers"[33]. However, based on the recent advancement in the understanding of hydrogen's role in global warming and of its GWP, the terms of reference for this report, adopted by the IPCC in its July-August 2024 session in Bulgaria, established that hydrogen will be considered in the Appendix *«Basis for future methodological development"* subject to the IPCC's Principles and Procedures on review and adoption»".[34]

It is beyond the scope of this paper to assess whether the results from recent peer-reviewed literature, as referenced in Chapter 1, provide sufficient evidence to classify hydrogen as an SLCF, and if so, by when such a classification might be adopted.

In any case, further research is clearly needed to advance scientific understanding and address remaining uncertainties regarding hydrogen emission sources, its atmospheric behaviour, and its climate impact. **The EU and its Member States should support this research through their funding programmes** (see Chapter 2.4 below). If sufficient evidence becomes available, the EU and its Member States should actively support efforts to swiftly include hydrogen in the UNFCCC reporting framework.

2.2.2 Hydrogen emission monitoring and reporting systems in the EU

Given the clear long-term significance of H_2 emissions for climate mitigation, the EU does not need to wait for the formal recognition at the UNFCCC level. Establishing H_2 emission monitoring and reporting systems is a prudent, no-regret approach that will build valuable knowledge to inform future mitigation policies.

---

[30] J.T. Houghton t al.(2001): Climate Change 2001: The Scientific Basis. https://archive.ipcc.ch/ipccreports/tar/wg1/index.php?idp=1

[31] Kathleen Mar, Rainer Quitzow et al. (2024): Controlling Emissions in Germany's Future Hydrogen Economy: Entry-Points for Policy Action. RIFS Study, October 2024. https://publications.rifs-potsdam.de/pubman/item/item_6003744

[32] S. Szopa, V. Naik, et al. (2021): Short-Lived Climate Forcers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 817–922. https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-6/

[33] See: https://www.ipcc.ch/report/methodology-report-on-short-lived-climate-forcers/

[34] IPCC: Decision IPCC-LXI, 2024. See: IPCC-61_decisions-adopted-by-the-Panel.pdf

The **EU Directive on Gas Internal Markets,** adopted in June 2024,[35] represents an important step forward. Art. 50(1) requires operators of **hydrogen networks, terminals, and storage facilities** to take "*all reasonable measures available to prevent and minimise hydrogen emissions in their operations*" and to carry out, "*at regular intervals, a hydrogen leak detection and repair survey of all relevant components under the operator responsibility*." Moreover, the operators must 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*." These **monitoring and reporting requirements** as well as leak detection and repair (LDAR) requirements apply to all the specified operators without exception – including those of existing hydrogen networks (Art. 51) and geographically confined hydrogen networks (Art. 52).

These provisions must now be implemented promptly and thoroughly across all Member States. This process will yield valuable information on hydrogen leakages from the systems governed by the Directive. The competent authorities should be encouraged to publish as much information as possible to support research and policy development aimed at mitigating H_2 emissions in EU Member States and beyond. While the monitoring and reporting requirements established by the Gas Internal Markets Directive are a step forward, they remain vague and unspecific ("*all reasonable measures*", "*regular intervals*"). These requirements should be clarified and reinforced at the earliest opportunity.

Moreover, the hydrogen monitoring and reporting provisions of the Gas Internal Markets Directive do not apply to upstream or downstream H_2 emissions, nor do they cover midstream emissions associated with hydrogen transports other than by pipelines or at terminal (e.g., by truck).

Establishing monitoring, reporting, and verification (MRV) systems for the upstream sector and the bulk of industrial hydrogen consumption should be relatively straightforward, given the limited number of production and consumption facilities.

Monitoring the H_2 emissions from small-scale consumption devices will be more challenging. While CO_2 emissions from vehicle engines or space heaters can be calculated based on the carbon content of the fuel burned, downstream H_2 emissions are more complex. Like downstream methane emissions, these emissions consist of unburned hydrogen and leakages, which can only be estimated. The leakage intensity may increase as vehicles or heating devices age. The difficulty of managing emissions from widespread end-user devices provides an additional argument against the widespread adoption of hydrogen-based road vehicles and space heating systems, reinforcing the points made in Chapter 2.1.

However, if such hydrogen applications are introduced on a large scale in the EU market – particularly if they benefit from public policies for climate mitigation – reliable methods for estimating H_2 emissions will be essential. These methods are necessary both for statistical monitoring and for designing effective mitigation measures.

An opportunity to make further progress on these issues is provided by Art. 9(6) of the Gas Internal Market Directive, which requires the European Commission to "*submit a report to the European Parliament and to the Council that evaluates hydrogen leakage, including environmental and climate risks, technical specificities and adequate maximum hydrogen leakage rates".* Based on that report, *"the Commission shall, if appropriate, submit a legislative proposal*

---

[35] Directive (EU) 2024/1788 of the European Parliament and of the Council of 13 June 2024 on common rules for the internal markets for renewable gas, natural gas and hydrogen, amending Directive (EU) 2023/1791 and repealing Directive 2009/73/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401788

to introduce measures that minimise possible risks of hydrogen leakage, set maximum hydrogen leakage rates and establish compliance mechanisms."

This potential legislative proposal could offer an opportunity to address the gap in the methodologies for calculating GHG savings from renewable and from low-carbon fuels, discussed in the last paragraph of section 2.1.4.1 above.

In the long term, it may be desirable to **include H_2 emissions in the EU's climate mitigation targets**. The feasibility and timing of this inclusion depend on **three conditions**:

- **IPCC consensus on hydrogen as a precursor gas:** If the IPCC recognises hydrogen as a precursor gas with a certain GWP, its inclusion in UNFCCC inventory reporting obligations will likely follow. The EU could preemptively consider H_2 emissions when further developing its climate mitigation targets.
- **Growing significance of H_2 emissions:** As noted in Chapter 1, value-chain H_2 emissions currently represent a negligible portion of global GHG emissions. This could change by the 2030s if hydrogen production and use increase substantially and if CO_2 and CH_4 emissions are reduced substantially in line with EU and Paris Agreement targets.
- **Establishment of effective MRV systems for H_2 emissions**, as discussed in Chapter 2.2.2: Effective monitoring, reporting and verification is a necessary precondition for meaningful target setting and monitoring.

It will likely take several years before these conditions are fulfilled. Once they are, **the EU Climate Law** and the **EU Governance Regulation**[36] would be the appropriate legislative frameworks for integrating H_2 emissions into the EU's GHG reporting and target setting regime.

2.3 Reduce the hydrogen emissions intensity of processes and equipment

Hydrogen leakages and emissions have traditionally been regulated solely by safety standard aimed at preventing fires and explosions. As such, H_2 emissions are not included in the EU Emission Trading System Directive[37]. Similarly, hydrogen is not listed as a pollutant under the EU Industrial Emissions Directive (IED)[38], which regulates the integrated prevention and control of pollution arising from industrial activities. Within this regulatory context, H_2 concentrations below hazardous levels are considered acceptable, though they may have a considerable cumulative climate impact.

---

[36] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality, https://eur-lex.europa.eu/eli/reg/2021/1119/oj . Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, http://data.europa.eu/eli/reg/2018/1999/2023-11-20 (consolidated version).

[37] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading. http://data.europa.eu/eli/dir/2003/87/2024-03-01 (consolidated version)

[38] The name of the Directive commonly referred to as IED has been changed in 2024 to "*Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial and livestock rearing emissions (integrated pollution prevention and control)*". This is established in Article 1 of the Directive (EU) 2024/1785 of the European Parliament and of the Council of 24 April 2024 amending Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC on the landfill of waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AL_202401785

To address this regulatory gap, a comprehensive framework is needed to monitor and reduce the H_2 emission intensity across relevant equipment and processes. This chapter outlines potential approaches for upstream, midstream and downstream H_2 emissions.

Summary of recommendations:

The key recommendations from this chapter are:

Upstream Emissions

- **Introduce mandatory H_2 emissions monitoring:** Mandatory H_2 leakage monitoring for SMR plants and electrolysers should be set at or near BAT (best available technology) levels.
- **Introduce mandatory measures to limit H_2 emissions:** Mandatory measures to limit H_2 emissions from SMR and electrolysers should be developed, either by expanding the scope of the IED or by adopting a regulation dedicated to H_2 emissions, as contemplated under Article 9(6) of the recently adopted EU Directive on Gas Internal Markets. Policy makers must be mindful to avoid unintended consequences.
- **Adapt the EU State Aid Regime**: The EU state aid regime should be revised to allow Member States to easily provide aid for reducing upstream H_2 emissions. This may involve updating Article 36 of the General Block Exemption Regulation and point 16, section 2.2., of the Climate, Energy and Environmental Aid Guidelines. Currently, these provisions facilitate state aid to address GHGs and support “environmental protection” or “pollution” control. However, hydrogen might fall outside this scope, as it is not yet officially recognised as a GHG and may not be seen as a pollutant.

Midstream Emissions

- **Implement the EU Gas Directive’s hydrogen monitoring, reporting and LDAR provision**: All Member States should promptly and thoroughly implement the monitoring, reporting and LDAR provisions for H_2 emissions from hydrogen networks, terminals and storage systems, which have been introduced through the recent update of the EU Gas Internal Markets Directive and will be further developed and promoted by the future European Network of Network Operators for Hydrogen (ENNOH), according to Art 59 of the recently adopted EU Gas Internal Markets Regulation[39].
- **Mitigate emissions from hydrogen networks, storage and terminals:** The European Commission should promptly initiate the process of collecting the technical information required to leverage the opportunity provided by Art. 9(6) of the Gas Internal Markets Directive to submit a legislative proposal aimed at minimising H_2 emissions. Given the long lead times required for the development and construction of hydrogen pipelines and underground storage systems, any delay in adopting such regulations might undermine investment security and escalate compliance costs. Retrofitting infrastructure is typically more expensive than ensuring compliance during the planning and design stages.
- **Mitigate emissions from truck-transported hydrogen:** The EU should introduce mandatory H_2 leakage monitoring for trucks and should consider setting emission limits at or near BAT levels, at least for new vehicles. The limits should focus on minimising leakages due to hydrogen’s climate impact, rather than solely on health and safety concerns.

---

[39] Regulation (EU) 2024/1789 of the European Parliament and of the Council of 13 June 2024 on the internal markets for renewable gas, natural gas and hydrogen. http://data.europa.eu/eli/reg/2024/1789/oj

- **Mitigate emissions from hydrogen fuelling stations and other facilities:** The EU should consider implementing specific regulations to limit H_2 emissions from hydrogen fuelling stations and other associated facilities, such as hydrogen compressors, liquefiers and regassification facilities, at or near BAT levels. These provisions could be part of a climate-oriented legal instrument, such as the potential legislative proposal mentioned in Article 9(6) of the Internal Gas Markets Directive.

Downstream Emissions

- **Mitigate emissions from large scale applications:** for hydrogen consumption at steelmaking, ammonia production, refineries, industrial processes, power plants and other large-scale applications, similar recommendations to those presented in the section on upstream emissions should be implemented.
- **Mitigate emissions from small-scale applications:** for small scale, but potentially widespread such as vehicles and heating systems, the primary recommendation is to discourage their adoption wherever electrification solutions are feasible. If hydrogen-based small-scale applications are adopted in EU markets, H_2 emissions should be regulated using the same regulatory instruments currently in force for CO_2 emissions.

2.3.1 Upstream hydrogen emissions

Upstream emissions occur during hydrogen production. Based on the data presented in Figure 1, **hydrogen production** accounts for more than half of the total H_2 emissions across the value chain in both 2050 scenarios, with leakage rates of 2% to 4% for electrolysis, and 0.5% to 1.5% for SMR.[40] If these estimations are proven true with empirical measurements, any strategy to mitigate H_2 emissions should consider upstream emissions carefully. Thus incentives, regulatory nudges or obligations to invest in technologies to reduce emissions could have a significant impact.

A straightforward solution would be to **expand the scope of the Industrial Emissions Directive** (IED) to encompass H_2 emissions. Following its recent revision, the IED applies to all SMR plants as well as to electrolysers with a capacity above 50 tonnes per day. An alternative but rather unlikely approach would be to include H_2 emissions from these activities into the EU ETS. Pricing H_2 emissions within the EU would support efforts to address H_2 emissions embedded in basic products imported into the EU through the Carbon Boader Adjustment Mechanism (CBAM). However, incorporating H_2 emissions into the EU ETS by the 2026 revision round – which will define the rules for the trading period that starts in 2030 – does not seem feasible.[41] Hydrogen is not yet classified as a GHG at the international level and in the EU legal framework, and adequate MRV systems for H_2 emissions remain undeveloped. The next viable opportunity may not arise until the mid to late 2030s. In contrast, expanding the IED appears to be more expedient pathway and could also address some of the downstream emissions discussed

---

[40] By contrast, in a workshop organised by the European Commission's Joint Research Centre (see: JRC: 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. https://publications.jrc.ec.europa.eu/repository/handle/JRC130362), a much lower range has been assumed: 0.03 % to 0.2% for electrolysis and zero H_2 emissions from SMR. However, these figures rely solely on estimates from one or two industry experts. In any case, this discrepancy points to the importance of investing in improved monitoring of H_2 emissions from hydrogen production facilities. It also suggests that H_2 emission intensities may vary widely across different electrolysers and SMR installations, which strengthens the benefit of introducing BAT-oriented emissions limits.

[41] In a recent paper, we argued that introducing CH_4 emissions in the next EU ETS revision round is both desirable and potentially feasible, provided immediate action is taken. However, given the less developed level of MRV for H_2 emissions, applying the same timeline for H_2 emission is not realistic. See: R. Piria, B. Görlach (2024): Pricing methane emissions from the energy sector: consideration of options, for the EU. Ecologic Institute. https://www.ecologic.eu/de/19826

below in Chapter 2.3.3. Alternatively, the European Commission could propose a **specific regulation on H_2 emissions**, a possibility now available **under Article 9(6) of the recently adopted EU Gas Internal Markets Directive**, as elaborated above in Chapter 2.2.2.

Any upcoming regulatory framework for mitigating upstream H_2 emissions should **make a distinction between SMR and electrolysers**, to avoid unintended consequences. Coal gasification is not considered here, as it is irrelevant to hydrogen production in Europe.

On the path to climate neutrality, the EU should phase out its SMR facilities, replacing them with electrolysers. This transition requires minimal, if any, investment in new SMR capacity. Consequently, any improvements in H_2 emission intensity from SMR would need to come from retrofitting existing plants. When designing **regulations to reduce H_2 emissions from SMR**, policy makers **should avoid** two key **unintended consequences**:

- First, safety: some of the venting and purging activities today are done to ensure safe operations. Regulations to reduce H_2 emissions should not inadvertently cause any safety concern.
- Second, if technical measures to reduce H_2 emissions decrease the material efficiency of the SMR process, they would lead to higher specific natural gas consumption and, consequently, to higher CO_2 and CH_4 emissions, potentially resulting in a negative net climate impact. This is a speculative hypothesis, as researching the technical options to reduce H_2 emissions from SMR is beyond the scope of this paper.
- Third, most hydrogen demand currently supplied by SMR is isolated, provided by individual SMR plants and not connected to hydrogen grids. Initially, the supply of electrolysers may be insufficient to meet demand. If this issue persists when H_2 emissions limits are introduced, and if compliance costs under H_2 emission regulations are too high, industries dependent on hydrogen but unable to install on-site electrolysers could be forced out of the market. TO mitigate this risk, early-stage H_2 emission regulations should prioritise achievable improvements within existing SMR facilities. Adopting a phased approach would allow time for the expansion of hydrogen grids and electrolysis capacity, enabling a smoother transition to low-emission hydrogen production. Once hydrogen grids and electrolysers are adequately developed, progressively ambitious H_2 emission standards could be introduced, further incentivising a shift to electrolysers, and delivering additional reductions in CO_2 and CH_4 emissions.

When considering **H_2 mitigation measures for electrolysers**, EU policy makers should on one hand consider that H_2 emissions can be reduced at a lower cost than at other stages of the value chain, and on the other hand recognise that high compliance costs could hinder the necessary market scale-up. If the compliance costs limit the availability of green hydrogen for applications where electrification is not viable, they may inadvertently lead to substantially higher overall GHG emissions associated with fossil-based hydrogen production. While minimising H_2 emissions from electrolysers is not a priority today, it will gain importance over time. Assuming a 20-year lifespan, an electrolyser commissioned in 2025 will operate primarily during a period when its H_2 emissions are a minor concern compared to the CO_2 and CH_4 emissions it prevents by displacing fossil-based hydrogen or fossil fuels directly. However, an electrolyser commissioned in 2040 will operate during the decade in which the EU aims to achieve climate neutrality and beyond, making H_2 emissions a critical consideration. Therefore, to strike a good balance between compliance costs and the climate mitigation advantage of regulating H_2 emissions from electrolysers, policy makers should be mindful of the timing with regard to the level of market ramp-up of electrolysers.

In the initial phase, policy makers should consider using pull measures. For example, additional financial incentives could be offered for electrolysers with below-average or BAT-levels of H_2 emission intensity. If H_2 emission limits for electrolysers are introduced, they should be set at a level that does not hinder market expansion, with scope for gradual tightening over time. When designing measures to reduce H_2 emissions from electrolysers, policy makers should consider that certain types of electrolysers are more capable than others of operating flexibly, adapting to a power system with high shares of wind and solar generation. **Flexible electrolysers** not only substitute fossil-based hydrogen production but also enable faster displacement of fossil-based power generation. This added value may justify more relaxed rules concerning their H_2 emissions.

In addition, the EU should consider addressing the H_2 emissions embedded in **imported products** as it intends to import substantial quantities of hydrogen, hydrogen derivatives (such as ammonia), and other products whose production may involve hydrogen (such as iron or steel). One approach could be to develop provisions similar to those in the recently adopted EU Methane Emissions Regulation (EU-MER),[42] which could impose MRV obligations on the importers of specific products with embedded H_2 emissions. This could form part of a potential legislative proposal under Article 9(6) of the new EU Directive on Gas Internal Markets. Alternatively, embedded H_2 emissions in imports could be addressed through the CBAM. However, as previously discussed, this would require the EU to establish a domestic H_2 pricing scheme, which is unlikely to be feasible before the mid-2030s at earliest. Furthermore, unless hydrogen is recognised as a GHG under the UNFCCC, imposing hydrogen mitigation measures on exports from third countries - such as measures akin to EU-MER provisions on imports or integrating hydrogen emissions into the CBAM framework – might pose legal challenges.

2.3.2 Midstream hydrogen emissions

Midstream refers to all stages between the hydrogen producer and the end user. This includes all components of hydrogen transmission systems, such as pipelines and compression stations, hydrogen storage, hydrogen distribution systems, whether by pipeline, truck or rail. It also includes hydrogen fuelling stations.

In Chapter 2.2.2, we have discussed how the recently updated EU Gas Directive has introduced monitoring and reporting as well as leak detection and repair (LDAR) obligations for hydrogen networks, terminals and storage. Article 9(6) further empowers the Commission to submit a legislative proposal to introduce measures to reduce H_2 emissions, which could also address midstream emissions.

However, the monitoring and reporting and LDAR provisions of the Gas Directive do not cover midstream supply chains involving **truck-transported hydrogen**, which are considered to have substantially **higher leakage rates** than pipelines and storage systems. The JRC report quoted in footnote 37 estimates leakage rates of approximately 4.2% for compressed hydrogen and 10-20% for liquefied hydrogen, with potential reductions to 3% and 4.5%, respectively, by 2030. The Columbia University report, referenced in Figure 1, projects a leakage range of 2.5% to 5% by 2050, without differentiating between liquefied and compressed hydrogen.

The **primary future use of truck-transported hydrogen** may be to supply refuelling stations for road transport. The high hydrogen leakage rates associated with truck-transported hydrogen reinforce arguments (see Chapters 1 and 2.1) against the widespread use of hydrogen in road transport, which would require an extensive network of refuelling stations. Widespread market

---

[42] Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942. See: http://data.europa.eu/eli/reg/2024/1787/oj

adoption of hydrogen for light-duty vehicles appears unlikely, also for economic reasons. However, where hydrogen is transported by trucks, mandatory emission limits should be considered.

Policies that encourage or mandate the adoption of BAT could be highly effective. Even with ambitious BAT levels, imposing H_2 emission limits on truck-transported hydrogen is unlikely to result in significant economic drawbacks. Large hydrogen consumers would generally remain unaffected, as they typically rely on on-site production and are expected to connect to hydrogen pipelines in the future. Strict measures on H_2 leakages from truck-transport, including compressors or liquefiers, would support the strategic aim of restricting hydrogen use to applications where it delivers distinct benefits.

Other users of truck-supplied hydrogen include **industries,** laboratories, and research institutes that consume small quantities insufficient to justify on-site production. Unless connected to hydrogen pipelines in the future, these users would bear the compliance costs associated with emission limits for truck-transported hydrogen. This seems reasonable, given that the climate impact of hydrogen is not reflected in any pricing mechanism.

Hydrogen leakages from **hydrogen fuelling stations** are regulated by the Directive on equipment and protective systems intended for use in potentially explosive atmospheres, commonly known as the ATEX Directive.[43] While its scope addresses health and safety, it does not encompass climate mitigation. Consequently, it focuses on the prevention of explosions and fires. It can be assumed that there is a considerable gap between the limits set by the ATEX Directive and the lower leakage levels that could be achieved through the application of BAT to minimise H_2 emissions. As the ATEX Directive focuses on explosion prevention, expanding its scope to address lower levels of leakage relevant for climate change mitigation would likely be impractical. This task would be more effectively addressed by the new, dedicated legal instrument to reduce H_2 emissions, as envisaged in Art. 9(6) of the Gas Internal Markets Directive.

2.3.3 Downstream hydrogen emissions

Today and in the future, a substantial portion of hydrogen will be consumed in **large-scale facilities** subject to both the EU IED and the EU Emissions Trading System (ETS). These include sectors such as **steelmaking, ammonia production, refineries**, as well as **industrial processes and power plants** with large combustion installations. In some of these applications, hydrogen leakage rates could be significant.[44] For these applications, the same considerations apply as for SMR and electrolysers discussed in Chapter 2.3.1 above.

Smaller-scale but potentially widespread hydrogen applications such as road vehicles, forklifts, trains, other non-road vehicles, and heating systems cannot be covered by the IED or the ETS. For such small-scale applications, monitoring minor hydrogen leaks – those below the thresholds of safety regulations but still relevant for climate mitigation – can present technical challenges.[45] The following discussion also touches on **hydrogen applications we recommended avoiding** in Chapter 2.1., such as hydrogen-based light-duty vehicles and space

---

[43] Directive 2014/34/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres. http://data.europa.eu/eli/dir/2014/34/oj

[44] Fan et al. 2022, quoted above, assumes a 1.5% to 3% leakage rate for hydrogen-based power plants, 0,2%- 0,5% in other industries.

[45] This paper does not aim to assess the current or future technical feasibility of such monitoring, nor of technical mitigating measures. Instead, the following considerations should be read as a call to explore possible measures and implement them if reliable methods for quantifying and controlling hydrogen emissions are or become available. Research and technical development, as briefly discussed in Chapter 2.4, may enhance this feasibility.

heating systems. Proposing H_2 emission limits for these applications does not contradict this general recommendation.

The current EU legal framework includes various measures to limit emissions from **road vehicles** for climate protection and air quality. The framework should be expanded to also cover H_2 emissions. This could involve updating the **Regulation for vehicle type approval**[46] to establish rules for accurately determining H_2 emissions from leaks and unburned fuel, similar to the existing rules for determining the emissions of other GHGs. The same regulation mandates that manufacturers provide an Environmental Vehicle Passport (EVP) containing information on pollutant emissions. According to Article 14(4), the form and data requirements for the EVP will be set by the European Commission in an implementing act. This presents an opportunity to ensure that H_2 emissions are included, as the EVP may also include non-toxic greenhouse gases. In addition, onboard monitoring systems could track H_2 emissions to the extent technically feasible. Moreover, the **Emission Performance Standards (EPS)** for light-duty[47] and heavy-duty[48] vehicles fleets should be expanded to include H_2 emissions.

Similarly, the EU emission standards for trains, ships, other **non-road vehicles**, and mobile machinery currently do not regulate H_2 emissions. Moreover, the relevant EU Regulation[49] only covers internal combustion engines, thereby excluding fuel cells-powered engines. Introducing H_2 emission limits, including from fuel cells, is therefore advisable, especially in market segments where hydrogen-based engines are more likely to gain significant market shares in the EU, such as forklifts and, potentially, ships.

If hydrogen-based **space heating and domestic hot water devices** are introduced into the EU market, they would fall under the EU Sustainable Products Regulation (ESPR) adopted in June 2024[50], which builds on and expands the scope of the Ecodesign Directive, ultimately replacing it.

However, neither the ESPR nor the Ecodesign Directive currently addresses H_2 emissions in their implementing regulations for specific products.[51] This omission persists despite the ESPR's stated objective to "*reduce the overall carbon footprint and environmental footprint of products over their life cycle (…)*". Extending the ESPR's scope to include hydrogen at the next opportunity is a low-effort, no-regret option. Developing specific rules on H_2 emissions in the implementing regulations for individual products may be unnecessary if those products fail to gain traction in the EU market or are not marketed at all. Avoiding hydrogen-based space

---

[46] Regulation (EU) 2024/1257 of the European Parliament and of the Council of 24 April 2024 on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7). http://data.europa.eu/eli/reg/2024/1257/oj (consolidated version).

[47] Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles. Consolidated text: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R0631-20240101 (consolidated version).

[48] Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO_2 emission performance standards for new heavy-duty vehicles. https://eur-lex.europa.eu/eli/reg/2019/1242/oj

[49] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery. http://data.europa.eu/eli/reg/2016/1628/2022-07-17v (consolidated version).

[50] Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products. https://eur-lex.europa.eu/eli/reg/2024/1781/oj

[51] For example, the Commission Regulation (EU) No 813/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1521111746792&uri=CELEX:32013R0813 Similar implementing regulations exist for other products which could conceivably burn hydrogen, such as water heaters.

heating is preferable and should be the main focus of EU policy making, as discussed in further detail in Chapter 2.1.

2.4 Research and technological development

This chapter briefly outlines the research and technological development (RTD) areas that should be supported by EU RTD programmes to advance the hydrogen-specific elements of the agenda discussed in this paper. Here, "specific" indicates that this section concentrates on the technologies and research infrastructure necessary to pursue the strategic goals presented in Chapter 2.2 (classifying hydrogen as a precursor gas in the UNFCCC reporting framework and establishing EU H_2 emission monitoring and reporting systems) and Chapter 2.3 (reducing the H_2 emission intensity of relevant equipment and processes). The RTD requirements related to the first strategic goal discussed in Chapter 2.1 – limiting hydrogen use to beneficial applications – are not covered here, as this would require widening the scope to encompass broader energy research, without adding specific value to this paper.

This chapter draws on the technological analyses provided by two reports: one from the European Commission's Joint Research Centre (JRC) and the other from the Center on Global Energy Policy at the Columbia University In New York.[52]

Summary of recommendations:

The main recommendation from this chapter is:

- **Include RTD on H_2 emissions in the successor programme to Horizon Europe':** The EU can contribute to these strategic goals by incorporating RTD on hydrogen emissions into its main research and innovation programme. While strategic decisions for the remaining duration of Horizon Europe have been made, the priorities for its successor programme, starting in 2028, remain open.

2.4.1 Key RTD topics on hydrogen's role as an indirect GHG

The following RTD areas can enable more rapid progress in building the scientific knowledge needed to support the IPCC discussion on classifying hydrogen as a precursor gas (see Chapter 2.2.1). They can likewise contribute to macro-level H_2 emission monitoring, which could inform potential target setting.

- **Natural hydrogen sources and sinks**: Geological hydrogen sources, the behaviour of hydrogen-consuming organisms in the soil, and their responses to changing conditions.
- **Anthropogenic hydrogen sources and impacts**: Measurement-based quantification of upstream, midstream and downstream emissions, impact of potential use of hydrogen in aviation on contrails.
- **Development of macro-level hydrogen monitoring technologies**: Development of techniques to continuously monitor hydrogen concentrations in the atmosphere, and for real-time hydrogen concentration measurement near facilities to quantify facility-level

---

[52] For easier reading, these reports are referenced here again although previously mentioned:
Joint Research Centre (2022): 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. https://publications.jrc.ec.europa.eu/repository/handle/JRC130362
Z. Fan et al (2022): Hydrogen leakage: a potential risk for the hydrogen economy. Center on Global Energy Policy, Columbia-SIPA. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/Hydrogen-LeakageRegulations_CGEP_Commentary_070722_0.pdf

emissions. Theoretical and empirical work to establish how methods used to measure and monitor other GHGs can be adjusted to hydrogen.

- **Experimental and modelling approaches**: Understanding the dispersion of hydrogen and hydrogen-methane blends in the atmosphere through experimental and modelling methods.
- **Expansion of research infrastructure for hydrogen observation**: In 2022, only three hydrogen observation stations existed in the northern hemisphere. The high expectations set by the JRC in 2022 regarding the efforts of the National Oceanic and Atmospheric Administration under the US Department of Commerce may require reassessment in light of the recent political change in the US.
- **Inclusion of H_2 emissions in the major climate models**: Beginning with models run by or in collaboration with, EU-based research institutions, it is necessary to support the investment necessary to expand the major climate models to consider H_2 emissions.

2.4.2 Key RTD topics on technologies to detect hydrogen leakages

Existing technologies for detecting hydrogen leaks are designed to identify concentrations that could pose a fire or explosion risk, typically in the range of 1,000–10,000 ppm. However, to address the climate impact of H_2 emissions, detection at much lower concentrations – around 0.01 to 1 ppm – will be necessary. This requires the development of new technologies suitable for use across various environments.

Based on the sources mentioned above, the following technology areas may be relevant for this purpose. This list is illustrative and may not be exhaustive.

- **Chemochromic coatings**: These are thin films of vacuum-deposited pigment that alters both its colour and resistance upon exposure to hydrogen. This makes them compatible with wireless radio-frequency identification sensors for remote monitoring.
- **Sensors with continuous monitoring capability**: These sensors enable the assessment of cumulative, annual leakage rates.
- **Optical hydrogen gas imaging cameras**: These technologies require enhancements to improve accuracy and reliability. Improvements should address external conditions such as wind direction and speed, plume polarity, ambient temperature, and background complexity.
- **Reducing operational and maintenance efforts**: Certain technologies currently in use, such as thermal conductivity, semiconducting oxides, ultrasonic physical principle require continual maintenance or skilled operators. Reducing these requirements could enable wider and more cost-effective deployment.

2.4.3 Opportunities in Horizon Europe and its successor programme

The EU’s central research and innovation programme, Horizon Europe, has already invested in research related to hydrogen emissions. Under the Horizon Europe work programme for 2023-2024, there was an €8 million call for proposals on the “climate impacts of a hydrogen economy,” which included the potential climate impact of hydrogen emissions, as well as the improvement of monitoring tools for detecting and quantifying sources. This call represented about 3% of the overall funding for the “climate, energy and mobility” cluster in 2023-2024. Additionally, within its Clean Hydrogen Joint Undertaking, Horizon Europe provided €3 million for pre-normative research on H2 emissions from the hydrogen value chain.

However, the recently adopted strategic plan for 2025-2027 does not specifically address hydrogen emissions. Nonetheless, it may be possible to include some of the RTD topics mentioned above within the individual work programmes for specific years. The most significant opportunity to anchor H_2 emission topics will arise during the discussion of strategic research priorities for the successor programme to Horizon Europe, which will cover the period from 2028 onwards.