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IOP Publishing Environ. Res.: Energy **3** (2026) 025024 https://doi.org/10.1088/2753-3751/ae69e3

ENVIRONMENTAL RESEARCH
ENERGY

Check for updates

OPEN ACCESS

RECEIVED
5 January 2026

REVISED
10 April 2026

ACCEPTED FOR PUBLICATION
7 May 2026

PUBLISHED
29 May 2026

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PAPER

Global hydrogen emissions and air pollutants from the hydrogen economy: scenario analysis with the GAINS model

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Keywords: hydrogen emissions, hydrogen leakage, air pollutant emissions, hydrogen production, hydrogen economy, emission inventory

Supplementary material for this article is available online

Abstract

The deployment of hydrogen offers significant opportunities for decarbonization and advancing the energy transition. However, hydrogen itself acts as an indirect greenhouse gas (GHG) by extending methane's atmospheric lifetime, contributing to tropospheric ozone and stratospheric water vapour formation. Currently, the primary anthropogenic source of hydrogen emissions is the incomplete combustion of fossil fuels, biomass and waste. However, the development of a hydrogen economy might lead to significant amounts of hydrogen emissions due to leakage throughout the value chain. Additionally, hydrogen production, storage, transport, and end-use can lead to emissions of GHGs and ambient air pollutants. This study employs the gas—air pollution interactions and synergies model to quantify global emissions of hydrogen, from combustion sources and leakages, as well as GHG and air pollutants associated with the hydrogen economy. We apply a range of energy demand scenarios and evaluate the sensitivity to different hydrogen production methods and emission control strategies. Our results indicate that anthropogenic hydrogen emissions in 2020 were approximately 10 Mt H_2, primarily from the incomplete combustion of gasoline and fuelwood. Projections indicate that anthropogenic hydrogen emissions could increase to up to 20 Mt H_2 by 2050, driven by both incomplete combustion and fugitive sources. Increased air pollutant emissions related to the hydrogen economy are generally easier to manage than hydrogen emissions using existing control technologies and regulatory frameworks. The study also provides a comprehensive documentation of the integration of emissions related to the hydrogen-economy into a modelling framework to support further analysis and potential policy implications.

1. Introduction

Increasing the use of hydrogen (H_2) across the economy is currently seen as an important strategy for the decarbonization of fossil fuel-dependent and hard-to-abate sectors such as transport, heavy industries (e.g. steel, cement, aluminium, glass) and chemicals (e.g. petrochemical, fertilizers) (IRENA 2024, UNFCCC 2024, Hossain Bhuiyan and Siddique 2025). Hydrogen demand exceeded 97 Mt in 2023, with the majority concentrated in traditional applications such as oil refining and industrial uses, particularly for fertilizer production (IEA 2024b).

However, hydrogen's potential extends far beyond these sectors, offering opportunities to replace fossil fuels across a wide range of applications. Due to hydrogen's high energy density, it can be used as a green alternative to fossil fuels for high-temperature processes (Marocco *et al* 2023) or for electricity generation in backup power systems (Rikabi *et al* 2023). Similarly, hydrogen can support residential and commercial sectors by providing both heat and power. In the transport sector—one of the most

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promising areas for hydrogen—fuel cell electric vehicles can be used across various modes, including passenger cars, freight vehicles, buses, trucks, and potentially even ships and aircraft (Elgendi *et al* 2025).

Various strategies are available for expanding hydrogen use. However, since hydrogen is a very small and volatile molecule, some applications require the replacement or significant modification of current energy infrastructure and end-use appliances (Esquivel-Elizondo *et al* 2023). Transport, storage and consumption of hydrogen in end-use requires its physical (compression, liquefaction or adsorption) or chemical (conversion to ammonia or liquid organic carriers) transformation (Hossain Bhuiyan and Siddique 2025). Hydrogen can also be blended into natural gas and used in existing devices, such as boilers, heaters, furnaces and turbines (Penchev *et al* 2022). These aspects result in complex trade-offs and pose challenges and limitations to the hydrogen supply-chain, which tends to intensify as the hydrogen economy develops and expands.

The deployment of hydrogen can lead to a variety of environmental implications. Producing hydrogen from fossil fuel sources, such as oil, natural gas or coal, may result in net greenhouse gas (GHG) emissions if used without carbon capture and storage (CCS) technologies (E4tech 2019). Also, air pollutants can be released during hydrogen production, transportation, and storage. Hydrogen emissions to the atmosphere are a growing concern because it acts as an indirect GHG by extending the atmospheric lifetime of methane and affecting ozone and stratospheric water vapour levels (Ocko and Hamburg 2022). The burning of fossil fuels, biomass and waste with insufficient oxygen leads to hydrogen emissions, alongside other harmful air pollutants (Paulot *et al* 2024). Fugitive emissions refer to intended (venting) or unintended hydrogen leaks throughout the value chain, including production, storage, transportation, and distribution (Esquivel-Elizondo *et al* 2023, Sand *et al* 2023). Finally, even though hydrogen combustion does not emit CO_2, it can still emit nitrogen oxides (NO_x), especially under high-temperature conditions (Gogolek 2021, Wright and Lewis 2022). Understanding and managing these impacts is essential for ensuring that the deployment of hydrogen contributes effectively to climate goals without introducing unnecessary and undue environmental risks.

This study evaluates emissions related to the hydrogen flow under different demand scenarios. We quantify global anthropogenic hydrogen-related emissions over the period 1990–2050, providing a comprehensive assessment across key sectors. We estimate hydrogen emissions from leakage and incomplete combustion of fossil fuels, biomass and waste. We also assess co-emissions of GHGs and air pollutants arising from hydrogen storage, distribution, combustion, and from various methods of hydrogen production, including fossil-based and low-carbon technologies. Although we recognize hydrogen's potential for decarbonizing hard-to-abate sectors, our analysis does not engage in the broader debate over hydrogen's role in replacing other fuels or the relative benefits of different production methods. Additionally, issues related to grid balancing and electricity system expansion fall outside the scope of this paper.

By contributing to the emerging literature on the environmental implications of a hydrogen economy, this work enhances the understanding of hydrogen's potential impacts on the climate and on air quality. In this way, it extends the knowledge base for directing efforts to mitigate emissions arising from the hydrogen economy. The novelty of this study lies in providing the first integrated global estimates of hydrogen emissions from both incomplete combustion and fugitive sources, alongside associated pollutant emissions from various hydrogen production methods. Furthermore, we introduce a comprehensive structured emissions modelling framework to support the development of emission inventories, atmospheric modelling and policy assessment of activities related to the hydrogen economy.

In the next section, we provide an overview of the scientific foundation for assessing the environmental and climate impacts of the hydrogen economy, focusing on potential sources of emissions. Section 3 describes the GHG—air pollution interactions and synergies (GAINS) model framework and the methodology used to quantify hydrogen-related emissions. It outlines how various scenarios based on fuel consumption trends, hydrogen production methods, and emissions control policies are combined to estimate future emissions. Sections 4 and 5, respectively, present and discuss the main results, including hydrogen emissions from incomplete combustion and fugitive sources, nitrogen oxide emissions from hydrogen combustion, ammonia emissions related to hydrogen storage and transport, and other pollutants associated with different hydrogen production pathways. Section 6 summarizes the study's conclusions, provides policy recommendations, and highlights areas for further research on the environmental implications of a hydrogen economy. The supplementary material provides additional details on the GAINS model extension for hydrogen, including sectoral definitions, emission factors, control options, extended results and uncertainty analysis.

2. Environmental impacts of the hydrogen economy

There is a wide range of feedstocks and technologies available for hydrogen production. One of the most common forms is when hydrogen is a by-product of refining processes, particularly during catalytic reforming of low-octane hydrocarbons and the gasification of heavy oil (He *et al* 2023). Coal gasification is another major method, particularly in China, accounting for approximately 21% of the current global hydrogen production (IEA 2023). These methods of hydrogen production are often referred to as black or brown hydrogen due to their association with high carbon dioxide (CO_2) emissions, when CCS is not applied.

In the steam methane reforming (SMR) method, methane (CH_4), usually obtained from natural gas, reacts with water vapour (H_2O) at high temperatures (500 °C–900 °C) and pressures (above 20 bar) to produce hydrogen, along with carbon monoxide (CO) and carbon dioxide (CO_2) (Narváez-Romo *et al* 2024). This process is referred to as grey hydrogen when CCS is not applied, and as blue hydrogen when CCS is in place. Methane can also serve as a feedstock for hydrogen production through pyrolysis, a process in which it is split into hydrogen gas and solid carbon by way of high temperatures, with minimal CO_2 emissions. This method is commonly referred to as turquoise hydrogen (Alhamed *et al* 2024)

In the electrolysis method, water molecules are split into hydrogen and oxygen by using electricity. When the electricity for this process originates from renewable sources, such as solar or wind energy, it can be considered a low-carbon production method, referred to as green hydrogen (Ishaq *et al* 2022). Another emerging method involves the use of nuclear power, referred to as pink hydrogen, to supply electricity for electrolysis and to provide the high temperatures required for thermochemical water splitting (Constantin 2023).

Gasification technologies can also be applied to renewable biomass feedstocks, such as lignocellulosic materials, algae, food waste, and municipal solid waste, enabling a potentially low-carbon hydrogen pathway (Cao *et al* 2020). Due to the potential for zero or even negative CO_2 emission (if CCS is applied), they are often referred to as moss hydrogen or ultra-green hydrogen.

Finally, orange hydrogen can be extracted from natural sources through a stimulated oxidation of ferrous minerals in geological formations (Osselin *et al* 2022). Subsurface hydrogen also occurs naturally, primarily as a result of anoxic and abiotic oxidation of ferrous iron, a form commonly referred to as white hydrogen. According to the U.S. geological survey (Ellis and Gelman 2024), global reserves of natural hydrogen may total up to 100 billion metric tons, which could supply current global hydrogen demand for approximately 1000 years (Blay-Roger *et al* 2024). Several natural hydrogen hotspots have already been identified worldwide (Blay-Roger *et al* 2024).

2.1. Climate impacts of hydrogen

The hydrogen economy might interfere with the climate system through the emission of GHGs released during its production phase. For instance, CO_2 is emitted during the combustion of fossil fuels (typically oil-based liquids and natural gas) in order to produce process heat in refineries (e.g. for partial oxidation or catalytic reforming) or to generate high-temperature steam used for SMR. Another source of CO_2 is fuel combustion needed to produce H_2 via the gasification of coal, biomass and waste. In addition, SMR and gasification techniques are associated with fugitive emissions of CH_4 and CO_2 (Alhamdani *et al* 2017).

Hydrogen can also have an indirect effect on the climate due to reactions with other gases in the troposphere and stratosphere (Warwick *et al* 2022, Sand *et al* 2023). It can react with hydroxyl ions (OH–), producing free hydrogen atoms and water vapour. Atmospheric OH– oxidizes about 90% of methane (CH_4) and is considered its primary sink (Saunois *et al* 2020). Thus, when hydrogen molecules consume the naturally occurring hydroxyl ions, the lifetime of CH_4 in the atmosphere is prolonged (Ocko and Hamburg 2022). This effect is problematic because methane is the second most important GHG contributing to global warming, according to the IPCC. Free hydrogen atoms (H) can also lead to the formation of ozone (O_3) at the tropospheric level, which, besides contributing to warming, can also cause damage to human health and crop losses. Finally, an elevated water vapour concentration in the stratosphere increases infrared radiative capabilities, intensifying overall climate warming (Ocko and Hamburg 2022).

Hydrogen has a shorter lifetime in the atmosphere than methane. To account for complex interactions between both species, various studies have sought to estimate hydrogen's global warming potential

Table 1. Hydrogen and GHG global warming potentials.

Species	GWP 100	GWP 20	References
Hydrogen (H_2)	11.6 ± 2.8	37.3 ± 15.1	Sand *et al* (2023)
Hydrogen (H_2)	11.5 ± 5.5	34.2 ± 16	Warwick (2023)
Hydrogen (H_2)	8 ± 2	N/A	Derwent (2023)
Hydrogen (H_2)	10.8	32.2	Warwick (*et al* 2022)
Hydrogen (H_2)	12.8 ± 5.2	40.1 ± 24.1	Hauglustaine (*et al* 2022)
Fossil Methane (CH_4)	29.8 ± 11	82.5 ± 25.8	IPCC AR6 Forster *et al* (2023)
Non-fossil Methane (CH_4)	27.0 ± 11	79.7 ± 25.8	
Nitrous Oxide (N_2O)	273 ± 130	273 ± 118	

(GWP)[3] under different time spans. As shown in table 1, hydrogen's GWP has been estimated in current literature to range from 6 to 18 for the 100 years span (GWP-100), and from about 16–64 for the 20 years span (GWP-20). Although hydrogen's indirect global warming effect is much lower than the direct effect of methane or nitrous oxide (N_2O), its future climate impact could become significant in scenarios with high levels of hydrogen consumption.

2.2. Sources of hydrogen emissions

Current hydrogen emissions originate primarily from natural and anthropogenic sources (Ehhalt and Rohrer 2009). Natural sources include nitrogen fixation in both terrestrial and marine environments, and photochemical production, where H_2 is formed during the oxidation of methane (CH_4) and non-methane volatile organic compounds (NMVOCs) in the atmosphere. Across various studies, atmospheric photochemical production is consistently identified as the largest source of hydrogen formation, ranging from approximately 30–48 Mt H_2 per year, while nitrogen fixation ranges from 3 to 22 Mt H_2 per year, although some studies have narrowed down its contribution to about 9 Mt H_2 per year (Xiao *et al* 2007, Yashiro *et al* 2011, Yver *et al* 2011). The present study, however, focuses specifically on anthropogenic sources, including incomplete combustion of fossil fuels, biofuels and waste, as well as fugitive emissions, as detailed in the following sections.

2.2.1. Incomplete combustion

Combustion sources have been dominating anthropogenic emissions of H_2, including incomplete combustion of fossil fuels (e.g. from transportation, residential heating, and industrial processes), biomass burning (such as forest fires and agricultural residue burning), biofuel use and waste burning (Bousquet *et al* 2011, Yver *et al* 2011). During combustion, H_2 is released as a by-product alongside other gases like carbon monoxide (CO) (Vollmer *et al* 2012, Paulot *et al* 2024). Hydrogen emission factors from incomplete combustion can be inferred by applying a CO/H_2 conversion ratio, based on the specific fuel and sector in which the combustion occurs, as described by Paulot *et al* (2024).

2.2.2. Fugitive emissions

As hydrogen use expands over time, leakages are expected to become a more prominent source of emissions. Such emissions can occur in any step of the supply and demand chains of hydrogen, and can be either intentional (venting, purging) or unintentional (boil-off, residual, leakages through pipes and equipment) (Esquivel-Elizondo *et al* 2023). Literature sources estimate potential leakage rates by consultations with industry or governmental experts (Fan *et al* 2022, Frazer-Nash Consultancy 2022), or by drawing proxies with reported natural gas leak rates (Cooper *et al* 2022, Frazer-Nash Consultancy 2022). These estimates are rather uncertain due to the unavailability of measurement data.

2.3. Air quality impacts

In some sectors, the hydrogen economy might lead to changes in emissions of nitrogen oxides (NO_x), ammonia (NH_3), and sulphur dioxide (SO_2) compared to a situation of no hydrogen use. These pollutants play critical roles in the formation of secondary particulate matter ($PM_{2.5}$) and tropospheric ozone (O_3) (Ying and Kleeman 2003, Qiu *et al* 2023), both of which are harmful to human health and ecosystems (Amann *et al* 2008, Kiesewetter *et al* 2015, Burnett *et al* 2018, Nuvolone *et al* 2018). Hence, it is

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[3] Global warming potential (GWP) is typically reported over 20- or 100 year time horizons and expressed relative to CO_2. GWP20 emphasises short-lived climate pollutants such as methane, while GWP100 is the standard metric used in international climate policy frameworks such as the Paris Agreement and the Kyoto Protocol, as well as the Intergovernmental Panel on Climate Change (IPCC) assessments and national reports.

essential to examine each pollutant individually for developing effective emission control strategies and accurately assessing the co-benefits of policies aimed at decarbonization and air quality improvement.

2.3.1. Air pollutant emissions from hydrogen production

Hydrogen production methods as outlined in section 2 are linked to distinct air pollutant emission profiles depending on their feedstocks and chemical processes. The emissions in this section refer exclusively to the production stage and do not account for the full lifecycle impacts of feedstocks or technologies. Oil- and coal-based methods emit not only CO_2, but also CO, PM, SO_2 and NO_x. E4tech (2019), Mneimneh *et al* (2023). SMR emits NO_x specifically from the high-temperature combustion of natural gas in the furnaces (Edwards *et al* 2014, Young *et al* 2017). Biomass and waste gasification can also release NO_x, PM, and SO_2 (Miller *et al* 2017). In contrast, electrolysis represents the cleanest production pathway, generating no direct air pollutants during operation.

2.3.2. NO_x emissions from hydrogen combustion

Hydrogen can be combusted as a fuel in power plants (turbines) or in end-use devices (e.g. internal combustion engines) in its pure form or as a mix with other gaseous fuels. It is reported that hydrogen combustion under lean air conditions leads to higher thermal formation of NO_x than from the combustion of natural gas (Frazer-Nash Consultancy 2018, NETL 2022, Mitchell and Hobson 2023). NO_x poses a direct risk to human health and acts as a precursor to the formation of O_3 and PM (Lewis 2021). The amount of NO_x from the combustion of hydrogen-gas mixes depends on the burner type, load, and hydrogen blending ratio. Thermal NO_x is formed by the oxidation of nitrogen in the air under high temperatures (above 1,500 °C). Gogolek (2021) concludes that a blended hydrogen content of up to 20% in volume of gas could increase NO_x emission by 12%–17% in industrial boilers and heaters compared to burning natural gas, while the combustion of pure hydrogen in appliances is estimated to increase NO_x emissions by 23% when compared to pure natural gas. Combustion with pure oxygen (oxy-fuel[4]) to reduce NO_x emissions is technically possible, but this solution requires specifically designed turbines/boilers (Liu *et al* 2012, NETL 2022).

2.3.3. Ammonia leakages

Increased reliance on hydrogen in the energy system is expected to accelerate ammonia (NH_3) production because ammonia is likely to serve as one of the main carriers and storage forms for hydrogen (Spatolisano *et al* 2024). In the coming years, ammonia is considered a key hydrogen carrier due to its high hydrogen content, relative ease for liquefaction for storage, and the existence of a well-established global infrastructure for its production, transport, and distribution (Chatterjee *et al* 2021, Kojima 2023). While fugitive hydrogen emissions can occur during both the Haber–Bosch process (converting H_2 to NH_3) and ammonia cracking (converting NH_3 back to H_2), ammonia itself is also prone to leakage. Such leaks can lead to significant environmental impacts, including air and water pollution as well as health hazards (Klimont and Winiwarter 2011, Guthrie *et al* 2018, Ma *et al* 2021, Rathod *et al* 2023).

3. Methodology and data

3.1. Hydrogen module in GAINS

The GAINS model is a technology process-based model that quantifies air pollutants and GHGs from 1990–2070 in five-year intervals for about 185 regions[5], which can be individually evaluated or aggregated up to the global level (Amann *et al* 2011). It uses emission factors and activity data from publicly available databases and calculates emission control costs from policymakers' perspectives. GAINS models emissions from various activities, many of which are not related to hydrogen.

Current air pollutants represented in GAINS include SO_2, CO, NO_x, NMVOCs, NH_3, mercury (Hg), and various size fractions of particulate matter (e.g. PM_1, $PM_{2.5}$, PM_{10}). GAINS also calculates emissions of GHGs, namely CO_2, CH_4, N_2O, and a wide range of fluorinated gases (F-gases). To quantify anthropogenic hydrogen emissions into the atmosphere, the GAINS model has been expanded by the authors

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[4] In this process, fuel is burned using nearly pure oxygen instead of air. In addition to improving combustion efficiency, this approach also reduces the formation of thermal NO_x, which typically occurs when nitrogen and oxygen in the air react at high temperatures (Liu *et al* 2012).

[5] In GAINS, some regions represent whole countries, others represent a group of countries and others represent sub-national divisions. Those regions reflect the global coverage of the GAINS model and account for a total of 178 countries. Some countries or regions, generally very small countries/islands, are not represented in GAINS. A full listing of countries in the GAINS model is available at: http://gains.iiasa.ac.at/models/.

with the hydrogen module, which is described in detail in the supplementary material. The module links all activities and sectors along the hydrogen value chain to all direct and indirect related emissions. New activities, sectors and technologies have been introduced to reflect hydrogen-related developments which were not previously included in the modelling framework, as described in the supplementary material.

The GAINS hydrogen module is represented in figure 1, which shows that H_2 emissions from incomplete combustion are computed across a wide range of fuels, including varieties of coal (brown, derived and hard coal), heavy fuel oil, diesel oil, gasoline, kerosene, natural gas, biogas, charcoal, agricultural residues and waste. Fugitive hydrogen emissions are estimated throughout hydrogen's full supply and demand chain segments ranging from production, transmission and storage, distribution networks, and final use. The model also allows for the estimation of emissions from hydrogen production (CO, PM fractions, SO_2, NO_x, CH_4, CO_2), storage (NH_3) and hydrogen combustion (NO_x). The estimation of sinks for hydrogen, as well as for other pollutants and GHGs, lies outside the scope of the GAINS model. Nevertheless, we acknowledge that these sinks may vary over time and affect the impact of emissions within the period considered in this analysis.

3.2. Emissions estimation

We estimate global emissions of H_2, GHGs and air pollutants using equation (1).

$$E_i = \sum_m A_{i,k} ef_{i,k,m} x_{i,k,m} \tag{1}$$

where:

E_i denotes the emissions from country/region i;

$A_{i,k}$ denotes the activity level of type k in country/region i;

$ef_{i,k,m}$ denotes the emission factor of activity type k after application of control measure m in country/region i;

$x_{i,k,m}$ denotes the application rate of control measure m to activity k in country/region i, where $\sum x_{i,k,m} = 1$;

Emission factors for GHGs and air pollutants associated with hydrogen production are based on values provided by the E4tech (UK) report on H_2 emission potential literature review (E4tech 2019). Storage and handling emissions related to the conversion of hydrogen to ammonia are calculated based on the H_2 energy input, assuming NH_3 losses of 1% (Chatterjee *et al* 2021).

For estimating NO_x emissions from hydrogen combustion, this study follows the EMEP/EEA Air Pollutant Emission Inventory Guidebook (Mitchell and Hobson 2023). The guidebook recommends using NO_x emission factors for hydrogen combustion that are comparable to those for natural gas. This is largely due to the mitigating effects of existing emission regulations applied to gas turbines in power generation, internal combustion engines, such as compressed natural gas (CNG) vehicles, and commercial heating systems. However, the guidebook advises increasing the emission factor for hydrogen-fired domestic boilers by a factor of three compared to natural gas, due to their higher combustion temperatures and NO_x formation potential. When hydrogen is blended with methane, the NO_x emission factors are calculated based on a maximum blend ratio of 20% hydrogen by volume (Jia *et al* 2023). Full details on the emission factor assumptions used in this study are provided in the supplementary material.

For hydrogen emissions from the land-based incomplete combustion of fossil fuels, biomass and waste, we calibrate our emissions factors by a ratio of H_2 per CO as estimated by Paulot *et al* (2024). Emissions from international shipping are derived from the CO emission data provided by the ECLIPSE V6b (evaluating the climate and air quality impacts of short-lived pollutants) Project (Klimont and Heyes 2019). Hydrogen emission from the international aviation sector were not considered in this work. The supplementary material presents the methodology for converting CO emission factors into H_2 emission factors.

Hydrogen leakage rates applied in this study and summarized in the tables from the supplementary material are derived from the most recent literature and represent the best estimations currently available (Bond *et al* 2011, Van Ruijven *et al* 2011, Arrigoni and Bravo Diaz 2022, Cooper *et al* 2022, Fan *et al* 2022, Frazer-Nash Consultancy 2022, Ocko and Hamburg 2022, Warwick *et al* 2022). Hormaza Meijia *et al* (2020) also find the same leakage rates for 100% hydrogen, blended hydrogen and pure natural gas in experiments using typical low-pressure infrastructure. Equation (2) converts the leakage rate into

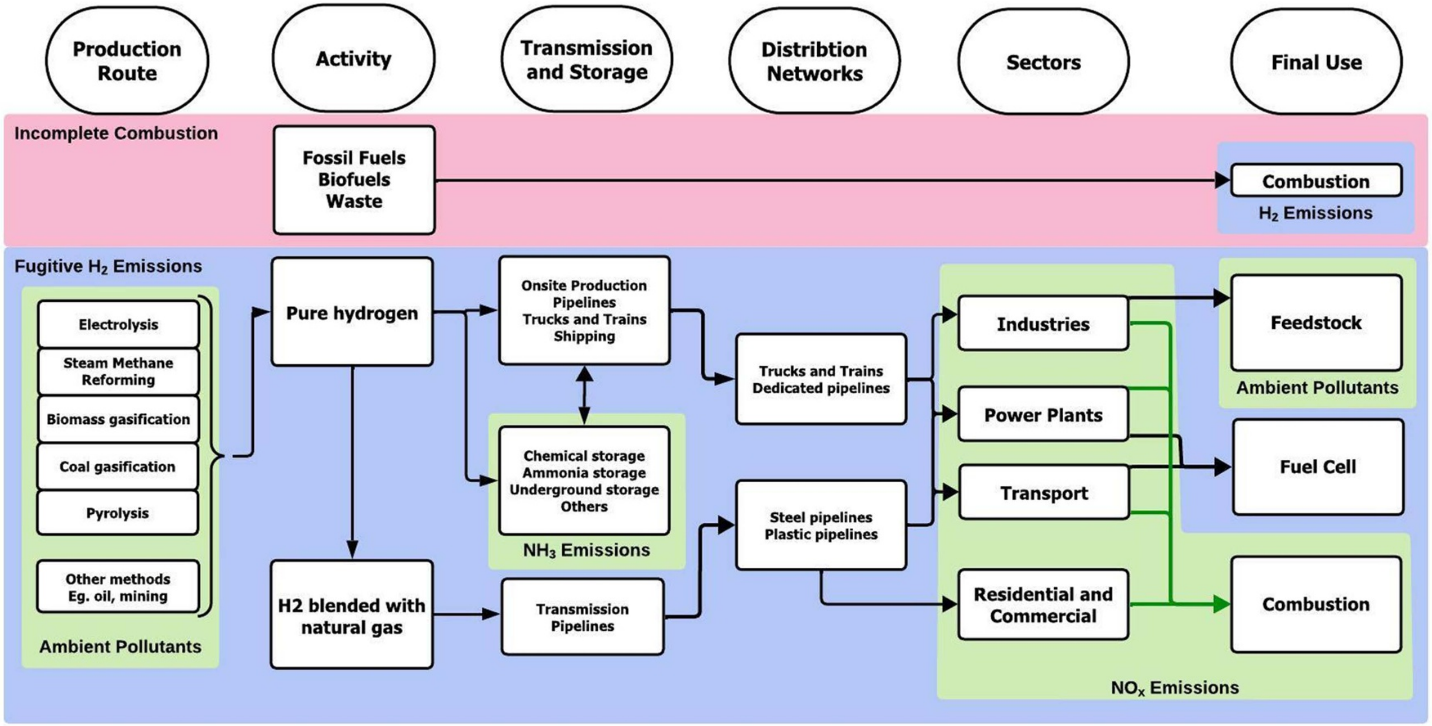

Figure 1. Key sources of hydrogen emissions and associated pollutant emissions within the hydrogen economy reflected in the GAINS model.

GAINS emission factors, in ktH_2/PJ.

$$EF_{H_2} = \frac{L}{LCV_{H_2}} \times 10^3 \tag{2}$$

where:

EF_{H2} denotes the estimated emission factor for fugitive hydrogen (in ktH_2/PJ)

L denotes the assumed leakage rate (in %) from hydrogen activity (Mt Mt^{-1})

LCV_{H2} denotes the lower calorific value of hydrogen (120 PJ Mt^{-1})

It is assumed that emissions associated with hydrogen production, transmission, and storage are allocated to the country or region where hydrogen is ultimately consumed. While this consumption-based attribution approach facilitates a global assessment, we acknowledge that, in the future, hydrogen is increasingly traded and transported across borders, introducing spatial decoupling between production and end-use that may influence emission accounting frameworks.

For fugitive hydrogen emission factors from distribution networks, we apply a method based on Höglund-Isaksson *et al* (2023), which takes into account network length and total throughput of gas, in this case hydrogen. We assume that only relined steel and PE/PVC pipelines are used to distribute blended and pure hydrogen. Residential/building distribution networks have a higher leakage propensity than other sectors, such as industry, power generation and vehicle refuelling stations (Dennett and Vallender 2011). Fugitive hydrogen emission factors for networks are given by equation (3).

$$e_i^{\mathrm{R}} = \frac{1}{d} \times M_i \times \frac{L^{\mathrm{R}}}{A^{\mathrm{R}}} \times s \tag{3}$$

where:

e_i^R is the country-specific hydrogen emission factor from distribution networks by material type i in residential or non-residential sector R (in kt PJ^{-1}),

d is a factor adjusting for the higher leakage propensity in residential networks relative to non-residential networks ($d = 0.23$ for residential and $d = 1$ for non-residential),

M_i is the material-specific emission rate,

L^R is the country-specific total network length,

A^R is the amount of hydrogen (in PJ) projected to be used in 2050,

s is the scaling factor (=3).

A detailed description of the methodology and country-specific emission factors is presented in the supplementary material (tables 8–10).

3.3. Energy activity data

In this study, we adopt fuel consumption and hydrogen production projections reported by the world energy outlook 2024 (WEO) from the international energy agency (IEA 2024c). Their estimates reflect one of several possible perspectives on how the hydrogen economy may evolve under current climate policies and prevailing techno-economic assumptions. At the same time, they provide projections with sufficient spatial, temporal, and sectoral resolution to enable consistent implementation within the GAINS modelling framework. The IEA-WEO provides projections for 30 regions, which are downscaled to align with the 185 regions in the GAINS model, potentially introducing minor variations. For our purposes, it is essential that the WEO scenarios place the hydrogen economy within the broader energy and climate policy context of each region, thereby allowing for the quantification of emissions of pollutants beyond hydrogen.

Our baseline (BL) projections follow the trends of IEA's stated policies scenario, which provides a conservative outlook by assessing the likely outcomes of energy and climate policies already implemented or under development, with few improvements in current energy policies and without assuming full achievement of government targets or future policy strengthening (IEA 2024a, 2024c).

The mitigation (MT) projections align with the IEA's Announced pledges scenario, which assumes that all national climate pledges, such as goals for universal electricity access and clean cooking, are fully

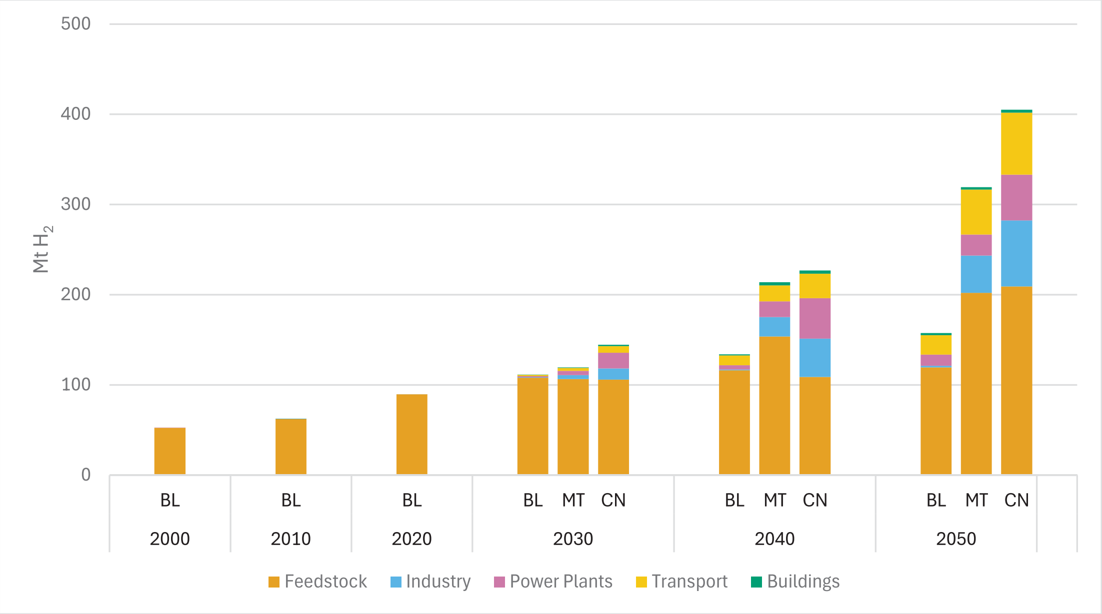

Figure 2. Evolution of hydrogen demand by sector from 2000 to 2050. *Source*: IEA (2024b).

implemented on schedule. This scenario explores how the realization of these commitments would influence global energy demand, particularly affecting the role of fossil fuels and accelerating the adoption of low-emission alternatives like hydrogen (IEA 2024a, 2024c).

Finally, the carbon neutral (CN) projection is largely based on IEA's net zero emissions scenario by outlining a pathway for the global energy sector to reach net zero CO_2 emissions by 2050. It assumes the achievement of the sustainable development goals, especially related to universal energy access, and broad deployment of clean energy technologies by taking into account costs, technology maturity, market conditions, existing infrastructure and policy orientations (IEA 2024a, 2024c).

Historical data and projections for agricultural waste burning are derived from the model's internal BL framework, which incorporates country-specific policy developments, expert consultations, satellite data and activity trends informed by estimations from the IEA and Food and Agriculture Organization (Klimont *et al* 2025).

Since hydrogen is considered to be an alternative to fossil fuels within a global decarbonization strategy, its demand is expected to increase in the overall energy mix. Figure 2 presents projected global hydrogen demand and indicates that historical (from 2000 to 2020) hydrogen consumption takes place primarily for non-energy purposes, such as feedstock for fertilizers, hydrocarbons and other chemical industries. Projections that seek higher decarbonization (MT and CN) intensify the use of hydrogen as feedstock, now expanded to heavy industries such as cement and steel. Other key sectors using hydrogen include high heat industrial combustion, power generation, fuel cell vehicles, maritime and aviation transport, and residential/commercial applications (buildings). According to figure 2, global hydrogen consumption is estimated at 158 Mt in 2050 (2.6% of total demand) in the BL, 319 Mt (6.2% of total demand) in the MT, and 405 Mt (9.1% of total demand) in the CN projections. They represent increases in hydrogen consumption of 76%, 257% and 353%, respectively, relative to the global demand in 2020.

Figure 3 illustrates total energy consumption by fuel type and sector in 2050 across the three projections. The consistent decline in liquid fossil fuel use in the MT and CN projections is particularly pronounced in the transport sector, largely due to an increase in electricity consumption primarily sourced from renewables. It is also important to note that the scenarios assume a rapid shift towards renewables (solar and wind) and nuclear in the power generation sector. This low-carbon electricity production balances an increased demand in sectors such as transport and electricity consumption in the buildings sector.

3.4. Definition of emissions scenarios

In GAINS, an emission scenario combines energy demand projections (as presented earlier) with emission factors and control strategies, which represent the technical measures and policies applied to reduce

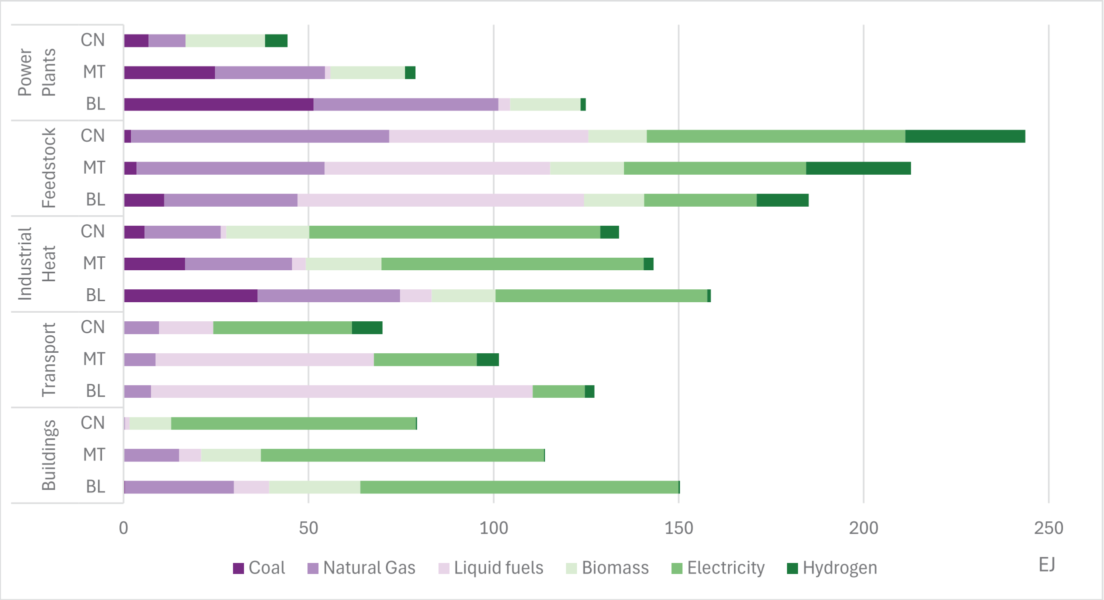

Figure 3. Fuel Consumption by Sector and scenario in 2050. *Source*: IEA (2024b).

Table 2. Control strategies and associated energy projections.

Control strategy	Energy demand projections		
	Baseline (BL)	Mitigation (MT)	Carbon neutral (CN)
Current legislation (CLE)	X	X	X
Maximum feasible reduction (MFR)	—	X	X

emissions. Pollutant control strategies can be categorized as, but are not limited to: a) end-of-pipe technologies, such as filters for PM, reducing agents for CO and NO_x, and desulfurization sorbents for SO_2; b) infrastructure and installation improvements, such as replacing steel pipelines with polyethylene (PE) or polyvinyl chloride (PVC) as well as leakage detection and controls to minimize hydrogen leakage; c) adoption of industrial best practices, including reducing venting from electrolysers and implementing leak detection and repair programs to control hydrogen emissions; and d) vehicle regulations, such as the EURO standards, which, among other requirements, impose emission limits on CO, indirectly reducing hydrogen formation from incomplete combustion in the transport sector.

We assume two sets of control strategies (which assumes no control as a strategy) and combine them with our energy demand projections as presented by table 2.

The 'Current Legislation' (CLE) represents a set of strategies that seek to capture the expected emission levels based on the implementation of existing and announced policies targeting emissions from hydrogen production, leakage, and combustion. The 'Maximum Feasible Reduction' (MFR) strategy reflects the lowest achievable emission levels, assuming full deployment of best available technologies for leakage prevention and combustion control, without financial or regulatory constraints. We apply MFR control strategy to MT and CN projections. These control strategies help to define a high and low range of projected emissions of H_2 and other pollutants in the model, providing a useful basis for comparison with previous studies.

To assess the sensitivity of emission scenario results to assumptions about hydrogen production, we expand the energy demand projections by incorporating three distinct hydrogen production pathways, as detailed in table 3. For the BL projection, we assume a continuation of the current mix (CM) for hydrogen production, which is dominated by fossil fuels and includes only a small share of electrolysis (IEA 2024c, 2025). This CM pathway is also applied to compute historical H_2 emissions. For the MT and CN energy demand projections, we introduce two additional production pathways to compare with the BL. On the one hand, the no fossil (NF) pathway assumes that hydrogen is produced exclusively from renewable electricity and biomass, eliminating fossil fuel inputs entirely. On the other hand, the clean production (CP) pathway envisions low-emission hydrogen production through a combination of renewable electricity and natural gas supplemented with CCS. These sensitivity cases only consider impacts

Table 3. Hydrogen production pathways.

		Energy demand projection		
Production pathway	Key assumptions[a]	Baseline (BL)	Mitigation (MT)	Carbon neutral (CN)
Current mix (CM)	62% SMR, 21% coal, 16% oil, 1% electrolysis	X	—	—
No fossil (NF)	50% biomass, 50% electrolysis	—	X	X
Clean production (CP)	50% electrolysis, 50% SMR with CCS	—	X	X

[a] Current mix shares estimated from (IEA 2024b, 2025).

Table 4. Summary of emission scenarios for this study.

Energy demand projection	Control strategy	Production pathway	Emissions scenarios
Baseline (BL)	Current legislation (CLE)	Current mix (CM)	BL_CLE_CM
Mitigation (MT)	Current legislation (CLE)	No fossil (NF)	MT_CLE_NF
Mitigation (MT)	Maximum feasible reduction (MFR)	No fossil (NF)	MT_MFR_NF
Mitigation (MT)	Current legislation (CLE)	Clean production (CP)	MT_CLE_CP
Mitigation (MT)	Maximum feasible reduction (MFR)	Clean production (CP)	MT_MFR_CP
Carbon Neutral (CN)	Current legislation (CLE)	No fossil (NF)	CN_CLE_NF
Carbon Neutral (CN)	Maximum feasible reduction (MFR)	No fossil (NF)	CN_MFR_NF
Carbon Neutral (CN)	Current legislation (CLE)	Clean production (CP)	CN_CLE_CP
Carbon Neutral (CN)	Maximum feasible reduction (MFR)	Clean production (CP)	CN_MFR_CP

of varying H_2-production patterns while feedback on emissions from the changed electricity demand or fuel mix changes in the power sector is not considered.

Adopting different hydrogen production pathways enhances the assessment of future trends of H_2–emissions as well as of other key pollutants such as CO, $PM_{2.5}$, SO_2 CO_2, NO_x and CH_4. Emission factors for each pollutant from hydrogen production are presented in the supplementary material (table 2). Variations in production technology also influence direct hydrogen (H_2) emissions; for instance, electrolysis processes may involve routine venting and purging of hydrogen during start-up and shut-down cycles, contributing to fugitive emissions.

Table 4 provides a summary of the nine scenarios developed in this study, each representing a unique combination of energy demand projections, control strategies, and hydrogen production pathways. The BL_CLE_CM scenario stands out as the sole reference scenario, reflecting a continuation of current energy consumption trends, established control policies (CLE), and conventional hydrogen production methods (CM). It serves as the BL against which other scenarios are compared. The MT and CN projections combine either CLE or MFR control strategies with alternative hydrogen production pathways, either NF or CP. These scenarios do not include the CM production pathway, as maintaining the current hydrogen mix would contradict the fundamental goals of emissions reduction embedded in MT and CN assumptions.

3.5. Uncertainties

Although the literature shows strong agreement regarding hydrogen emissions from incomplete combustion, fugitive hydrogen emission rates remain highly uncertain. According to a review by Esquivel-Elizondo *et al* (2023), the largest uncertainties are associated with hydrogen liquefaction, transport, handling, and refuelling, where leakage rate estimates range widely, from 0.15% to 20% of total hydrogen volume. Emissions during production processes also vary considerably, from 0.0% to 9.2%, depending on technology type and operational conditions. For hydrogen transported in non-liquid forms, leakage rates are reported between 0.0003% and 6.5%, while end-use losses typically do not exceed 3%.

In order to account for these uncertainties, we perform an uncertainty analysis using a Monte Carlo simulation approach (Rubnstein and Kroese 2008). The analysis consists of 10 000 repeated simulations in which emission factors are randomly varied to reflect the wide range of hydrogen leakage rates reported in the literature, as summarized in supplementary material (table 19). The analysis focuses on the CN_CLE_CP scenario, which exhibits the highest level of hydrogen activity by 2050.

Emissions of air pollutants from the hydrogen production and combustion also remain uncertain, despite ongoing efforts reported in the literature to assess and review the current state of knowledge. In this study, we do not conduct a formal uncertainty analysis of the air pollution estimates primarily due to the lack of comprehensive uncertainty ranges across pollutant species, as well as the limited empirical data available for emerging hydrogen technologies. Instead, we focus on a comparative scenario-based assessment to highlight the potential range of outcomes under different policy and technology pathways.

4. Results

4.1. Historical emissions of hydrogen (1990-2020)

Global hydrogen emissions from fuel combustion decreased from 13.0 in 1990 to 10.4 Mt H_2 in 2020, as shown by figure 4. The main primarily anthropogenic sources of those emissions are driven by residential fuelwood use and gasoline consumption by passenger cars. For open burning of biomass (e.g. forest and grassland fires) (green bars), we include estimates from Vollmer *et al* (2012) for 1990–2010 and from Paulot *et al* (2021) for 2020. Anthropogenic sources of incomplete combustion, such as coal, oil products, biofuels, and other combustion-related activities, contributed approximately 40% to 70% of total hydrogen emissions during this period, while agricultural open burning accounted for an additional 14% to 19%. By 2020, incomplete combustion of fuels and agricultural waste made up nearly 90% of total anthropogenic hydrogen emissions, with the remainder attributed to fugitive emissions. Section 5.1 discusses these historical emission results modelled in GAINS with previous hydrogen emissions inventories.

4.2. Future emissions of hydrogen (2020-2050)

Figure 5 shows that total hydrogen emissions are projected to increase alongside hydrogen use, especially in scenarios where hydrogen replaces fossil fuels, such as MT_CLE_NF and CN_CLE_NF[6] (solid lines). In these scenarios, global annual emissions may reach up to 17.1 Mt H_2 and 20.4 Mt H_2, respectively in 2050. The widespread adoption of best available technologies to control hydrogen leakages, as shown in the MT_MFR_NF and CN_MFR_NF scenarios (dashed lines), could reduce emissions in 2050 by 64% and 75%, respectively, compared to their CLE counterparts[7]. Leakage control technique for hydrogen include end-of-pipe technologies, infrastructure and installation improvements, industrial best practices, and vehicle regulations. When compared to the BL scenario (BL_CLE_CM), these reductions amount to 44% and 53%, respectively.

Climate impacts of the selected scenarios can be examined by adopting hydrogen's GWP of approximately 12 (Sand *et al* 2023 in table 1)[8]. Resulting annual emissions of H_2 from all anthropogenic sources (fossil fuels, biomass, other combustion and leakages) are estimated to have decreased from 155.9 Mt of CO_2 equivalent (CO_{2eq}) in 1990–124.4 Mt CO_{2eq} in 2020. Given that global GHG emissions were 50.6 Gt CO_{2eq} in 2020 (Ritchie and Roser 2024), hydrogen emissions (excluding aviation) would represent roughly 0.31% to 0.26% of the global emissions, in 1990 and 2020, respectively. In 2050, emissions could range from 87.6 to 245.0 Mt CO_{2eq} per year, depending on control strategies. This would correspond to approximately 0.17% to 0.48% of current global CO_{2eq} emissions.

Figure 6 shows that anthropogenic hydrogen emissions from incomplete combustion decrease across all CLE scenarios, as households shift from fuelwood to cleaner fuels and stricter emission regulations for vehicles are gradually implemented. Hydrogen emissions from anthropogenic sources of incomplete fuel combustion are projected to decline by 18% (to 6.0 Mt H_2 yr^{-1}) until 2050 in the BL_CLE scenario and by 73% (to 2.0 MtH_2 yr^{-1}) in the CN_CLE scenario, compared to 2020. Emissions from agricultural open burning tend to stay stable around 2.0 Mt H_2 per year throughout the period.

Compared to 2020, fugitive emissions are projected to increase by a factor of 4, 11 and 16 in BL_CLE, MT_CLE and CN_CLE, respectively. Figure 7 shows that hydrogen intensive scenarios, MT_CLE and CN_CLE, lead to increased fugitive emissions, primarily driven by expansions in transmission and distribution segments of the energy supply chain, including new pipelines and alternative transport methods such as liquefied hydrogen transport by land and sea.

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[6] Since the assumed H_2 emission factors for biomass gasification and SMR are nearly identical, both the NF and CP pathways result in equivalent hydrogen leakage estimates. Therefore, only the NF scenarios are presented in this section.

[7] Tabulated values underlying these results are available in the Open Data file.

[8] Although we estimate the CO_2-equivalent impact of hydrogen using its GWP100, we acknowledge that global warming potentials can vary with location. Therefore, spatial differences in hydrogen emissions could influence the resulting CO_2-equivalent estimates and their overall effectiveness.

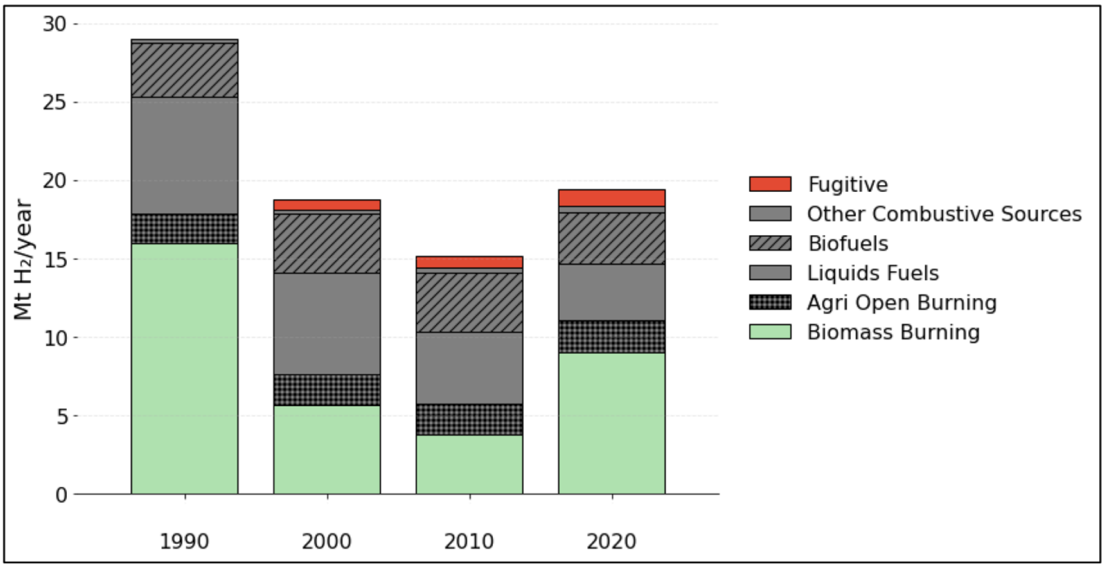

Figure 4. Global hydrogen emissions from 1990–2020 by source. Biomass burning obtained from Vollmer *et al* (2012) and Paulot *et al* (2021).

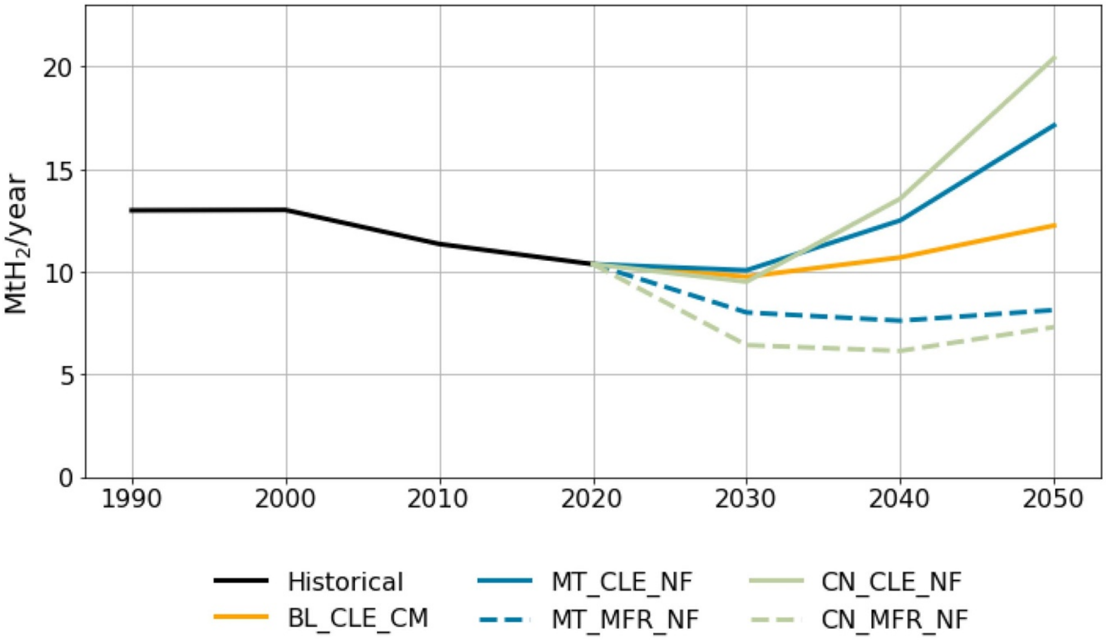

Figure 5. Global hydrogen emissions from anthropogenic sources: historical and by scenario. Solid lines represent scenario under CLE strategy, while dashed lines represent scenarios under MFR strategy. Colours represent historical (black) and BL (orange), MT (blue) and CN (green) energy demand projections under the NF hydrogen production pathway.

4.3. Uncertainty analysis results

Figure 8 presents the results of the Monte Carlo simulation, while the detailed numerical outputs are available in Table 20 of the supplementary material. When accounting for uncertainties, specifically those related to hydrogen leakage, total hydrogen emissions in the CN_CLE_CP scenario could range from as low as 12 Mt H_2 yr^{-1} (equivalent to 144 Mt CO_2eq) to as high as 42 Mt H_2 yr^{-1} (504 Mt CO_{2eq}) by 2050. The highest uncertainty ranges are associated with distribution networks, transmission, and storage, while industrial combustion exhibits the lowest relative error margins.

4.4. Nitrogen oxide emissions from the H_2 combustion

By 2050, NO_x emissions from hydrogen combustion under the CLE strategy are projected to reach globally approximately 0.3 Mt in the BL_CLE_CM scenario, 1.6 Mt in MT_CLE_NF, and 2.5 Mt in CN_CLE_NF, as shown in figure 9. To set these values in context, these emissions are equivalent

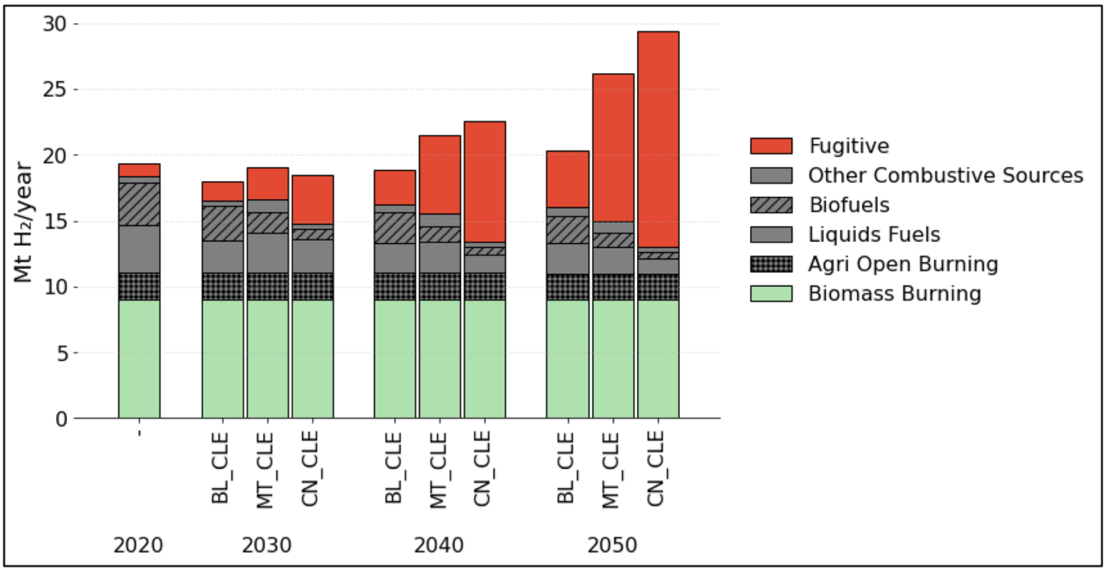

Figure 6. Global hydrogen emissions by source and activity. Future emissions from open biomass burning are assumed to remain the same as in 2020. Grey shade columns: hydrogen emissions from incomplete combustion by fuel type (hashes). 'Other Combustive Sources' include coal, natural gas and municipal solid waste.

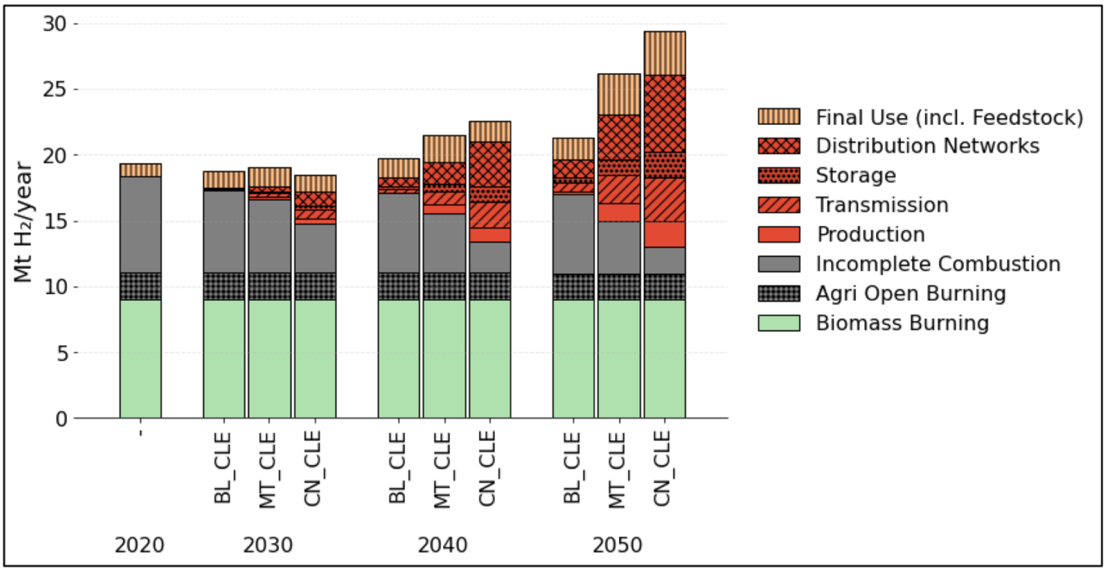

Figure 7. Global hydrogen emissions by sector. The future emissions from the open biomass burning are assumed to remain the same as in 2020. Bright red columns: hydrogen leaks from the supply chain. Orange columns: fugitive hydrogen emissions from industry (combustion and feedstock) and other end uses (transport, residential, power plants).

to roughly half of the global NO_x emissions from buses in 2020 (5.3 Mt), as estimated by GAINS (2025)[9]. While these figures represent significant relative increases compared to 2020 levels, they would account, in the BL_CLE_CM scenario, for only 0.4% of projected global NO_x emissions in 2050, when considering emissions from other combustion sources of NOx (e.g. fossil fuels in transport and industry). In the MT_CLE_NF and CN_CLE_NF scenarios, the relative contribution of hydrogen combustion to global NO_x emission in 2050 increases to 2.5% and 7%, respectively. This difference is explained by the overall decline in total NO_x emissions, driven by reductions in the combustion of fossil fuels in the low-carbon scenarios. In Because of fuel switches towards electricity many end-use sectors, as well as a rapid deployment of non-biomass renewables in power generation, the share of NO_x emissions from the hydrogen combustion compared to other sources increases.

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[9] The public scenarios and results from the GAINS model can be accessed at: https://iiasa.ac.at/models-tools-data/gains

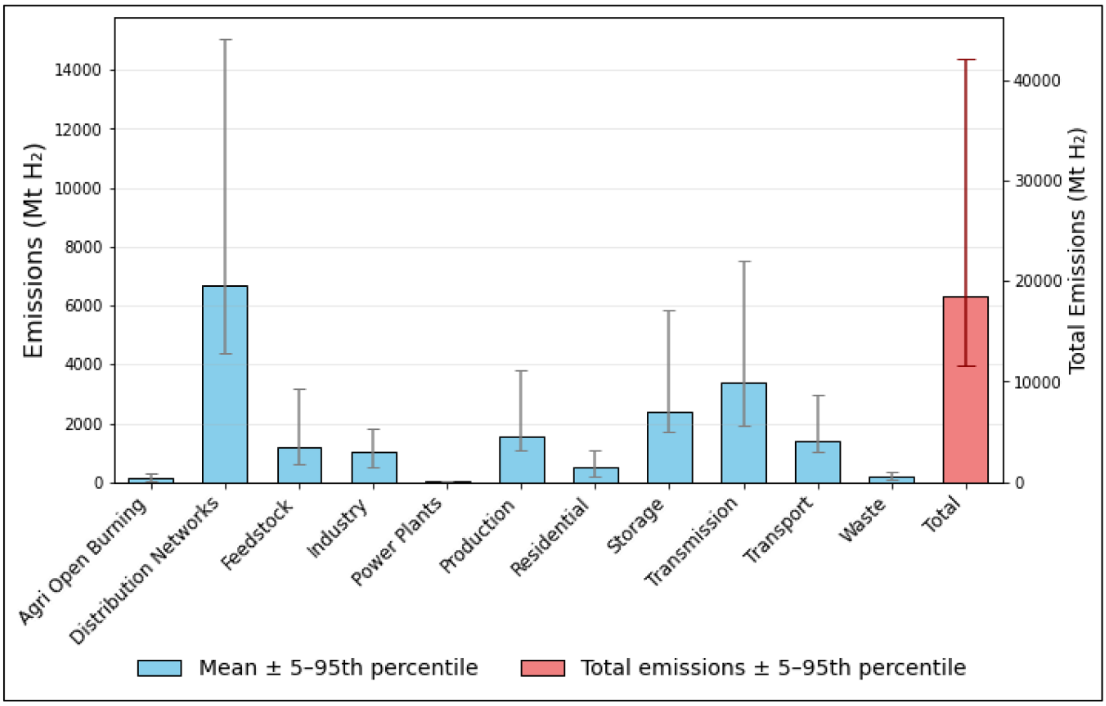


Figure 8. Uncertainties in global hydrogen emissions by sectors in the CN_CLE_CP scenario in 2050. Values expressed as Mt of H_2. Bars represent mean emission from all 10 000 simulations. Ranges represent 95% confidence interval, considering a log-normal distribution. Comparison between GAINS emissions and error ranges presented in Table 20 in the supplementary material.

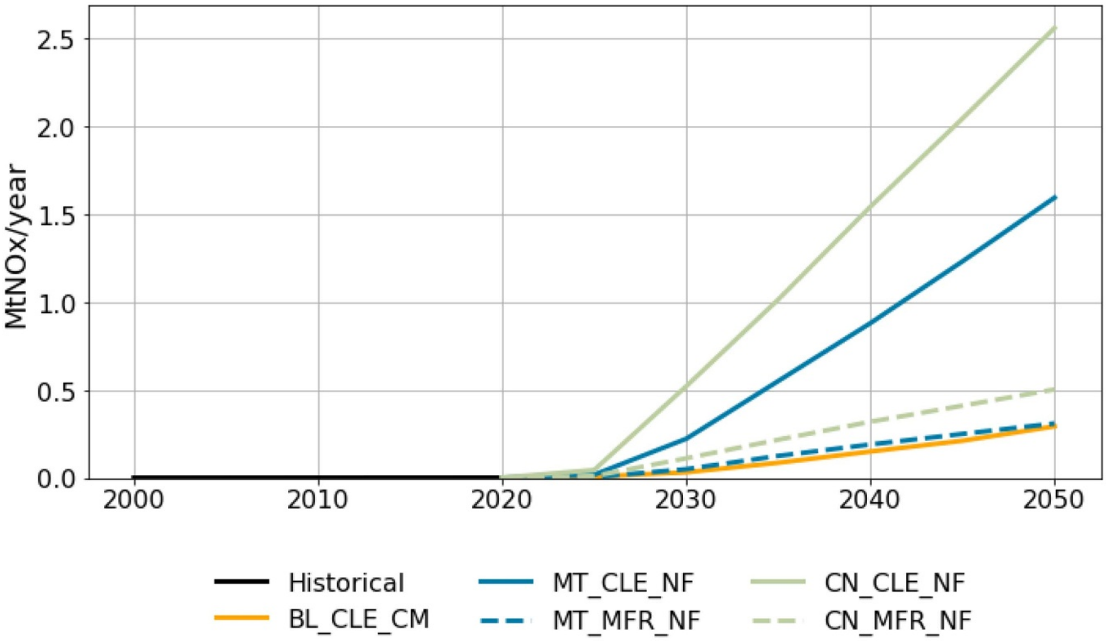
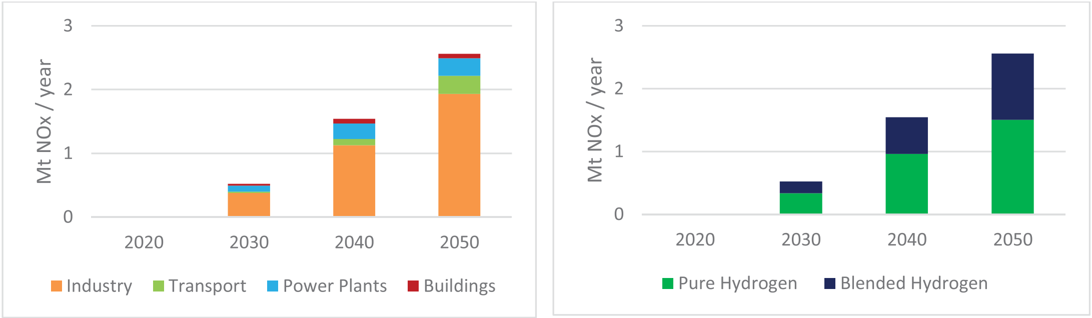


Figure 9. Global NO_x emissions from the hydrogen combustion by scenario.

Our estimations assume that NO_x emissions from hydrogen combustion can be controlled by the same technologies as applied for engines and turbines burning natural gas, such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), an assumption that is supported by Lewis (2021). These technologies can reduce NO_x emissions by up to 80%, leading to projected totals of 309–502 kt NO_x by 2050 in the MT_MFR_NF and CN_MFR_NF scenarios. Despite the resulting reductions, NO_x emissions in the H_2-intensive scenarios remain higher than those in the BL_CLE_CM scenario (292 kt NO_x).



a) NO_x emissions by sector b) NO_x emissions by activity

Figure 10. NO_x emissions from hydrogen combustion in the CN_CLE_NF scenario.

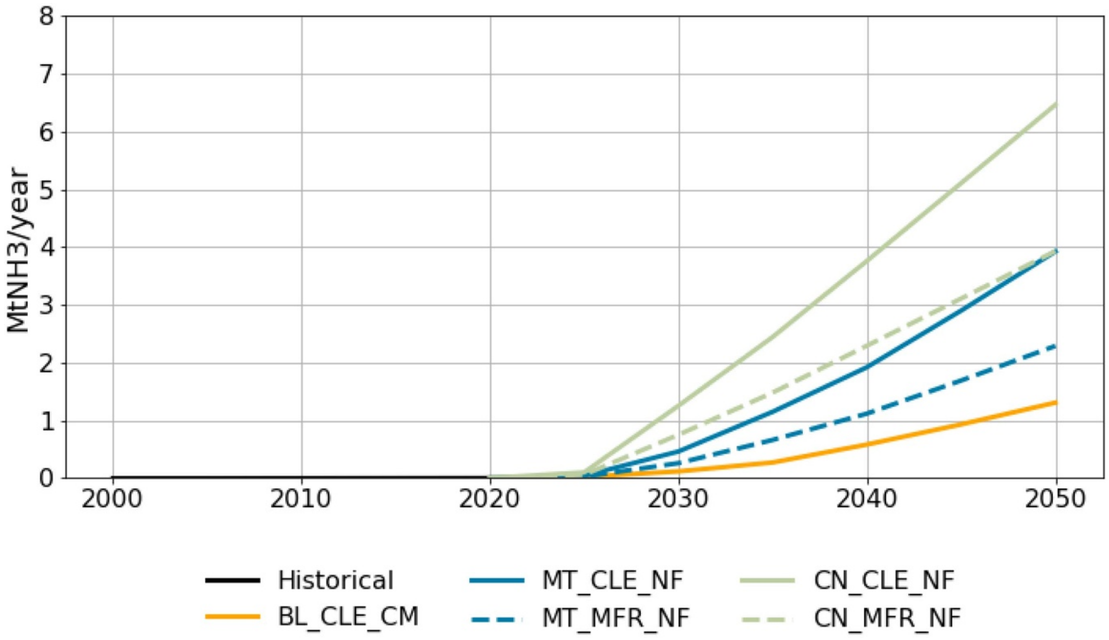


Figure 11. Global fugitive NH_3 emissions from hydrogen stored as ammonia.

Figure 10(a) shows the sectoral split of NO_x emissions from hydrogen combustion for the CN_CLE_NF scenario. By 2050, the industrial sector accounts for roughly 75% of total emissions, followed by power plants and transport sectors. Figure 10(b) indicates that the combustion of pure hydrogen will be responsible for 60% of total NO_x emissions from hydrogen combustion in 2050. This reflects a significant shift in hydrogen use toward high-temperature industrial processes, which are harder to electrify and where hydrogen combustion is often proposed as a decarbonization strategy.

It is important to note that due to data limitations, this study assumes that whenever pure hydrogen is used in power plants, it is combusted. Nevertheless, the GAINS H_2-module allows for both combustion of H_2 and the use of H_2 in fuel cells, in which case direct NO_x emissions would be minimized. In the transport sector (and in non-fuel cells vehicles), GAINS assumes that hydrogen is exclusively combusted in a blend with natural gas (e.g. CNG vehicles). Hence, future improvements in emission standards and technologies beyond CLE could further reduce emissions in these applications.

4.5. Ammonia emissions from hydrogen storage

Figure 11 shows that global fugitive ammonia emissions related to the H_2 supply chain grow consistently, mainly due to an increased hydrogen demand. By 2050, NH_3 emissions may reach 1.3 Mt in the BL_CLE_CM scenario, 4.0 Mt in the MT_CLE_NF scenario, and 6.5 Mt in the CN_CLE_NF scenario, which would correspond to an increase by 2%–11% of current global ammonia emissions (dominated by agricultural sources) or about half of the current global ammonia emissions from cattle manure

(13 Mt) (GAINS 2025). Control technologies for reducing ammonia releases comprise the improvement of storage and handling or good operational practices, with a removal efficiency of up to 50%. Their full application reduces NH_3 emissions to 2.3 Mt and 3.9 Mt by 2050 in the MT_MFR_NF and CN_MFR_NF scenarios, respectively.

4.6. Emissions associated with various hydrogen production pathways

4.6.1. Methane emissions

Current direct emissions of methane from the hydrogen production chain are estimated at approximately 157 kt per year (figure 12(a)). Maintaining the current production mix (BL_CLE_CM scenario) could lead to an increase to 209 kt CH_4 by 2050. Future methane emissions are strongly associated with hydrogen production via biomass gasification, reaching approximately 1069 kt by 2050 in the CN_CLE_NF scenario. In the CN_CLE_CP scenario, which favours the SMR production method with CCS, emissions reach about 320 kt CH_4 by 2050. It is important to note that these emissions refer only to methane leaks occurring during the hydrogen production process, and not to the full life cycle of methane-based hydrogen. Nor are they associated with the indirect effect of hydrogen emissions on the prolonged atmospheric lifetime of methane. As such, they are negligible, with 2050 emissions corresponding to roughly 0.3% of global anthropogenic methane emissions in 2020 (Höglund-Isaksson *et al* 2020) across the scenarios. Full adoption of good practices can reduce methane emissions by roughly 25% in both the CN_MFR_NF and CN_MFR_CP scenarios.

4.6.2. Carbon monoxide emissions

Figure 12(b) indicates that future CO emissions vary greatly according to the production method assumed in scenarios. Historical upstream emissions range from approximately 40 kt CO in 2000 to 68 kt in 2020. Maintaining a similar production mix as in the BL_CLE_CM scenario could result in emissions exceeding 103 kt per year by 2050. Such amounts can be considered negligible when compared to total global CO emissions, which accounted for more than 442 Mt in 2020 according to the GAINS model estimate (GAINS 2025). The CN_CLE_NF, which heavily relies on biomass feedstocks, may also lead to higher CO emissions as hydrogen demand increases, reaching around 2.3 Mt by 2050. A similar amount emitted globally by industrial furnaces fired by fossil fuels (2.1 Mt) in 2020 (GAINS 2025). In contrast, the CN_CLE_CP scenario, where SMR remains the predominant production method, shows lower CO emissions, estimated at 238 kt by 2050. For CO emissions, the application of control technologies, mainly SCR in the production process provides an 8% emission reduction, as shown by the CN_MFR_CP and CN_MFR_NF lines in figure 12.

4.6.3. Carbon dioxide emissions

Results presented in figure 12(c) indicate that the past CO_2 emissions from hydrogen production were approximately 1.2 Gt in 2020, which aligns with estimates reported by the IEA (2024b) and corresponds to roughly 3% of global CO_2 emissions (Ritchie and Roser 2024). If the current production patterns continue, emissions could rise to 1.8 Gt by 2050 in the BL_CLE_CM scenario—a figure comparable to total CO_2 emissions from cement production (1.7 Gt CO_2) in 2020. As the GAINS model treats hydrogen production coupled with CCS as a sector rather than as an abatement technology, hence, there is no MFR strategy defined for CO_2. A transition to hydrogen production based on electrolysis and biomass (CN_CLE_NF scenario), and the application of CCS technologies (CN_CLE_CP scenario) by 2050 could reduce CO_2 emissions by at least 75% compared to the BL.

4.6.4. Nitrogen oxides emissions

As shown in figure 12(d), NO_x emissions from hydrogen production are primarily linked to coal-based methods and biomass gasification. Historical NO_x emissions show an increase from 857 kt in 1990 to 1.5 Mt in 2020. Under the BL_CLE_CM scenario, NO_x emissions are projected to reach nearly 1.9 Mt by 2050, while in the CN_CLE_NF scenario, they may rise to almost 3.0 Mt. These levels are comparable to current global NO_x emissions from household biomass combustion (1.8 Mt) and agricultural machinery (3.0 Mt) (GAINS 2025). The CN_MFR_NF scenario, however, suggests a significant potential for NO_x reduction through applying best available technologies (e.g. SCRs, commonly used to control NO_x from fuel combusting sectors. In such a case, NO_x emissions from hydrogen production can be reduced by up to 92% compared to the CN_CLE_NF scenario, and by 87% relative to the BL_CLE_CM scenario.

4.6.5. Fine particulate matter emissions

Figure 12(e) shows that hydrogen production based on coal and oil has led to a steady increase in $PM_{2.5}$ emissions, rising from approximately 4 kt in 2000 to 7 kt in 2020, which represent a relatively small

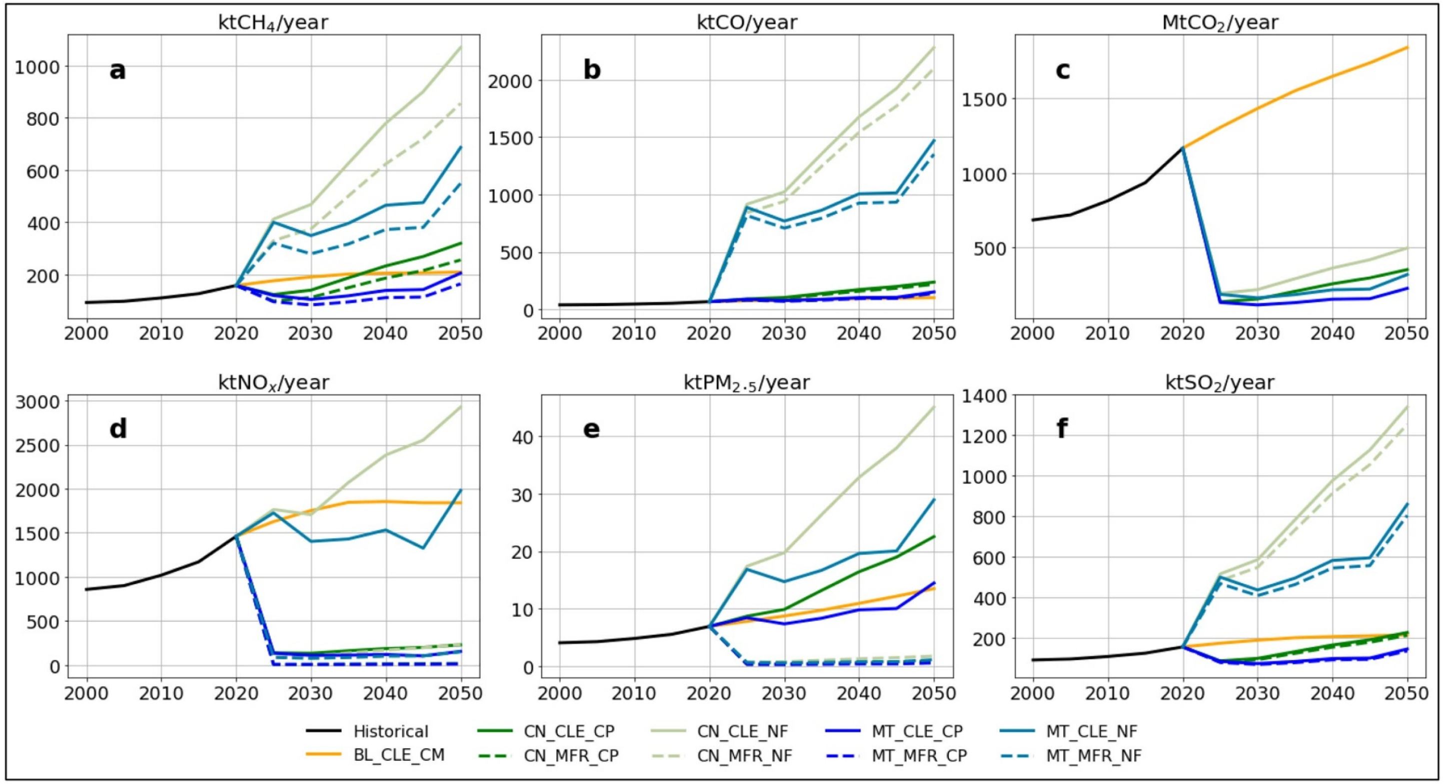


Figure 12. Global emissions of selected air pollutants and GHGs related to hydrogen production.

share (0.02%) of $PM_{2.5}$ totals, which accounted for about 34 Mt in 2020 (GAINS 2025). While in the BL_CLE_CM scenario the $PM_{2.5}$ emissions can reach up to 13.5 kt per year in 2050, the CN_CLE_NF scenario leads to roughly 45 kt $PM_{2.5}$ by 2050. These emissions are more than twice the amount released by the global pig iron production (21 kt $PM_{2.5}$) in 2020, as estimated by the GAINS model (GAINS 2025). The CN_CLE_CP scenario also results in an increase compared to the BL, reaching 22 kt of $PM_{2.5}$ emissions by 2050. This increase is primarily due to the lack of clearly differentiated emission factors for pollutants in the literature for the H_2-production methods with and without CCS (E4tech 2019). Such emissions, however, can be almost completely removed (99% reduction) if the best control strategies, such as high efficiency dedusters, are fully applied, as shown by the MFR scenarios.

4.6.6. Sulphur dioxide emissions

Figure 12(f) shows that SO_2 emissions from hydrogen production reached approximately 157 kt in 2020, primarily driven by oil- and coal-based production, which represents about 0.3% of total global emissions in that year (51 Mt SO_2). If current trends continue (BL_CLE_CM scenario), emissions could rise to around 215 kt by 2050, still accounting for less than 1% of the projected global emissions from all sources. The use of biomass in the CN_CLE_CP scenario contributes to the growth in SO_2 emissions, which can reach 1.3 Mt in 2050, comparable to emissions from the brick production (1.5 Mt SO_2) in 2020 (GAINS 2025). A modest share of these emissions (around 6.4%) could be mitigated in the case of application of best available technologies for the sulphur control in industry as shown in the CN_MFR_NF and CN_MFR_CP scenarios. This indicates that current desulfurization technologies are already effective, and emissions are inherently low compared to other sectors.

5. Discussion

The transition to a widespread hydrogen usage is expected to reduce dependency on carbon-intensive fuels and processes, however, this strategy is linked with important challenges and trade-offs due to changes in the energy system and emission profiles. A key concern is whether the induced emission releases could offset some of the anticipated climate benefits of the planned large scale H_2-deployment (Sun *et al* 2024). The findings of this study contribute to the ongoing discussion by offering insights into these and other potential implications of a hydrogen-based economy.

5.1. Hydrogen emission inventories

Previous studies have aimed to estimate the sources and sinks of hydrogen emissions using a variety of models and measurement datasets. Table 5 compiles results from those studies on the average estimates of past H_2 releases from the key sources, including fossil and non-fossil fuel combustion, open biomass burning, as well as emissions from N_2-fixation (from both ocean and land) and photochemical production (from methane and other VOCs). These assessments are based on diverse methodologies and data sources, resulting in significant variability across outcomes and underscoring the complexity of accurately quantifying emissions of atmospheric hydrogen.

Differences in results stem mainly from diverging treatments of non-anthropogenic sources, different energy accounting/modelling approaches, and the use of top-down atmospheric measurements versus bottom-up inventories of anthropogenic emissions from sectoral activities. For example, Vollmer *et al* (2012) estimated that hydrogen emissions from incomplete combustion averaged 16.6 Mt H_2 per year between 2000 and 2010, by relying on data from the EDGAR inventory, while Paulot *et al* (2024) estimated that anthropogenic hydrogen emissions from fossil fuel burning averaged 14. Mt H_2 per year between 2010 and 2019 by using CO emissions from the 2021 version for the Community Emissions Data System (CEDS). Estimations vary, however, due to different database coverage and versions. For example, the updated CEDS database of the year 2025 reports on average approximately 100 Mt less CO emissions annually than the earlier CEDS 2021 version (Hoesly *et al*, 2025). By applying the same CO-to-H_2 conversion ratio, this would eventually result in lower associated hydrogen emissions than computed previously.

Total hydrogen emissions from incomplete combustion range across studies, mostly between 26 and 40 Mt H_2 yr^{-1}. Earlier studies such as Sanderson *et al* (2003) and Price *et al* (2007) estimate the highest values, around 33–40 Mt H_2 yr^{-1}, largely due to strong contributions from both fossil fuel and open biomass burning. Emissions from fossil fuel combustion show substantial variation between studies, with values ranging from 3.2 to 22 Mt H_2 per year, reflecting differences in methodologies, years covered, and assumptions about emission factors. Emissions from biomass burning, which mostly refer to forest fires but may also include biomass-fuels in some studies, are estimated to range between 2.8–20 Mt H_2 yr^{-1}.

Table 5. Comparison of global hydrogen inventories averages by source (in Mt H_2 yr^{-1}).

Source	Years	Fossil fuel	Biofuels and waste[b]	Total Combustive	Fugitive	Total Anthropogenic	Biomass burning	N_2 fixation (ocean and land)	Photochemical production
Novelli *et al* (1999)	1990–1996	15 ± 10	—	**15 ± 10**	—	**15 ± 10**	16 ± 5	6 ± 3	40 ± 7
Hauglustaine and Ehhalt (2002)	[a]	16	—	**16**	—	**16**	13	10	—
Sanderson *et al* (2003)	1994–1995	20	—	**20**	—	**20**	20	8	30.2
Rhee *et al* (2006)	2000	15 ± 6	—	**15 ± 6**	—	**15 ± 6**	16 ± 3	12 ± 10	—
Price *et al* (2007)	2001	18.3	4.4	**22.7**	—	**22.7**	10.1	6	34.3
Xiao *et al* (2007)	[a]	15 ± 10	—	**15 ± 10**	—	**15 ± 10**	13 ± 3	9 ± 4	41 ± 11
Ehhalt and Rohrer (2009)	[a]	11 ± 4	—	**11 ± 4**	—	**11 ± 4**	15 ± 6	9 ± 4	—
Bousquet *et al* (2011)	1991–2004	22 ± 3	—	**22 ± 3**	—	**22 ± 3**	10 ± 2	—	48 ± 4
Yver *et al* (2011)	2006–2009	18.5	—	**18.5**	—	**18.5**	7.8	9.4	46.5 ± 0.2
Yashiro *et al* (2011)	1997–2005	15.2 ± 0.1	—	**15.2 ± 0.1**	—	**15.2 ± 0.1**	11 ± 3	9	38.5
Pieterse *et al* (2011)	[a]	17	—	**17**	—	**17**	15	8	37.3
Vollmer(2012)	2000	8.3 ± 2.1	2.7 ± 0.7	**11.0 ± 2.2**	—	**11.0 ± 2.2**	5.7 ± 1.4	—	—
	2005	5.9 ± 1.5	8.4 ± 2.1	**14.3 ± 2.6**	—	**14.3 ± 2.6**	2.8 ± 0.7	—	—
	2010	3.9 ± 1.0	9.4 ± 2.3	**13.3 ± 2.5**	—	**13.3 ± 2.5**	3.0 ± 0.8	—	—
Pieterse *et al* (2013)	[a]	13.9 ± 3.2	—	**13.9 ± 3.2**	—	**13.9 ± 3.2**	15	8	36.8
Paulot *et al* (2021)	2010–2019	14.3	—	**14.3**	—	**14.3**	9	6	42.1
Paulot *et al* (2024)	2004–2019	[a]	[a]	**13**	—	**13**	8	9	44
This study	1990	7.7	5.3	**13.0**	0.00	**13.0**	—	—	—
	2000	6.8	5.6	**12.4**	0.59	**13.0**	—	—	—
	2010	5.0	5.7	**10.6**	0.70	**11.4**	—	—	—
	2020	4.1	5.2	**9.4**	1.01	**10.4**	—	—	—

[a] Not specified.

[b] Includes agricultural open burning.

In comparison, our estimates suggest that total hydrogen emissions (including combustion and fugitive emissions) declined from approximately 13.0 Mt to 10.4 Mt between 1990 and 2020. The differences between our results and those from previous studies can be attributed to variations in the emission factors used to convert H_2/CO ratios, as well as to differences in the underlying emissions inventory models. Notably, our analysis does not account for hydrogen emissions from forest/savanna/grassland fires, as this source is not covered explicitly by the GAINS framework. Despite these differences, most studies consistently identify gasoline-powered road transport and fuelwood in households as the major contributors to anthropogenic hydrogen emissions.

5.2. Comparative overview of global hydrogen emissions across scenarios

Table 6 summarizes the results for all emission species analysed in this work across each scenario in years 2020 and 2050. In the BL scenario, where hydrogen does not play a significant role in decarbonization, H_2 emissions are projected to rise by approximately 20%, primarily due to continued incomplete combustion. In contrast, the development of a hydrogen economy is expected to increase fugitive emissions, with levels rising by a factor of 1.7 in the MT scenario and 2.0 in the CN scenario. However, the implementation of best available control strategies can lead to a reduction in emissions compared to 2020 levels by 22% to 30% despite increased use of hydrogen in the MT and the CN scenario. Even in the most optimistic scenarios, total hydrogen-related emissions remain below 1% of global CO_2-equivalent emissions in 2050.

Emissions of NO_x and NH_3 notably increase compared to 2020 levels. This increase is driven by the expanded use of hydrogen combustion in industry and power generation, as well as the storage and transport of hydrogen in the form of ammonia. The implementation of effective control strategies is crucial to mitigate these emissions and reduce their potential impacts on human health and ecosystems.

Table 6 also summarizes the results for each scenario with varying production pathway and control strategy considered in this study. Compared to other GHG emissions, methane emissions from different hydrogen production methods are generally negligible. However, attention should be directed more towards the entire natural gas supply chain to prevent leakages, rather than focusing solely on hydrogen production via SMR or biomass gasification (Höglund-Isaksson *et al* 2023). In contrast, CO_2 emissions from hydrogen production currently account for approximately 3% of global CO_2 emissions and could rise to 5% in 2050, relative to 2020 levels (IEA 2024b). These emissions should not be overlooked, and it is essential to consider the full life cycle of hydrogen production and its associated feedstocks when evaluating environmental impacts, as well as the deployment of CCS technologies.

As shown by our results, hydrogen production may lead to increased emissions of pollutants such as CO, $PM_{2.5}$, NO_x and SO_2, depending on the production method. Even renewable-based options like biomass gasification can contribute to higher levels of air pollutants. These emissions can be considerable in the context of global totals, suggesting that future hydrogen production paths have an environmental and health impact that needs to be quantified. For instance, the total NO_x emissions from both hydrogen demand and supply might reach 5.5 Mt by 2050 in the CN_CLE_NF scenario, which is a figure similar to current NO_x emission emitted globally by conventional buses (5.4 Mt NO_x), as estimated by the GAINS model (GAINS 2025).

Therefore, efforts to minimize emissions through the adoption of effective control technologies and best practices should be encouraged and adopted in the legislation. Additionally, further studies are needed to combine the measurement of the hydrogen and air pollutants in exhaust gases, which will help to refine emission factors and enhance the accuracy of scenario assessments. Therefore, it is essential that hydrogen deployment strategies consider not only GHG reductions but also co-pollutant emissions.

5.3. Future fugitive emissions of hydrogen

For fugitive emissions, this study applies recent leakage rate assumptions from the literature to evaluate the potential future impacts under various hydrogen demand scenarios. Table 7 shows that existing estimates for global hydrogen demand vary widely, with more recent studies assuming future hydrogen demand above 500 Mt per year. This directly affects the amount of fugitive emissions in 2050, which ranges from 5.9 to 95.5 Mt. These results highlight the considerable uncertainty surrounding hydrogen leakage rates and the expansion of a future hydrogen economy. In comparison, this study estimates that fugitive hydrogen emissions could range from 0.9 to 16.4 Mt H_2 per year by 2050, based on country and sector-specific emission factors, as detailed in the supplementary material.

Hydrogen total emissions (fugitive and incomplete combustion—table 6) are projected to reach 20.4 Mt H_2 in 2050 in the CN scenario—or about 245 Mt CO_{2eq}. This represents 0.5% of global GHG

Table 6. Overview of total global emissions by scenario, in 2050.

			Emissions along the Hydrogen Value Chain									
			Incomplete combustion and leakage		Hydrogen Combustion	Storage	Hydrogen Production					
Scenario	Pathway	Control Strat.	H_2 (Mt)	CO_{eq} (Mt)[b]	NO_x (Mt)	NH_3 (Mt)	CH_4 (Mt)	CO (Mt)	CO_2 (Mt)[b]	NO_x (Mt) ‡	$PM_{2.5}$ (Mt)	SO_2 (Mt)
Reference Year - 2020	Current Mix	CLE	10.4	124.4	0.0	0.0	0.2	0.1	1165.6	1.5	0.01	0.2
Baseline	Current Mix	CLE	12.3	147.0	0.3	1.3	0.2	0.1	1841.6	1.8	0.01	0.2
Mitigation	No Fossil	CLE	17.1	205.7	1.6	3.9	0.7	1.5	318.5	2.0	0.03	0.9
		MFR	8.1	97.6	0.3	2.3	0.5	1.4	NA	0.1	0.00	0.8
Mitigation	Clean Prod.	CLE	[a]	[a]	[a]	[a]	0.2	0.2	225.5	0.2	0.01	0.1
		MFR	[a]	[a]	[a]	[a]	0.2	0.1	NA	0.0	0.00	0.1
Carbon Neutral	No Fossil	CLE	20.4	245.0	2.6	6.5	1.1	2.3	496.1	2.9	0.05	1.3
		MFR	7.3	87.6	0.5	3.9	0.9	2.1	NA	0.2	0.00	1.3
Carbon Neutral	Clean Prod.	CLE	[a]	[a]	[a]	[a]	0.3	0.2	351.3	0.2	0.02	0.2
		MFR	[a]	[a]	[a]	[a]	0.3	0.2	NA	0.0	0.001	0.2

[a] Same values as in the No Fossil pathway.

[b] CO_2 equivalent emission of H_2, considering a GWP of 12.

Table 7. Overview of hydrogen emission from leakages: literature and current findings.

Publication	Demand in 2050 (MtH_2)	Emissions in 2050 (MtH_2) Min	Emissions in 2050 (MtH_2) Max	Leakage Rates[a] Min	Leakage Rates[a] Max
Warwick *et al* (2023)	859	8.7	95.5	1.0%	10.0%
Fan *et al* (2022)	528	15.3	29.6	2.9%	5.6%
Ocko and Hamburg (2022)	590	5.9	64.9	1.0%	10.0%
Cooper *et al* (2022)	550	2.6	23.8	0.5%	4.3%
Bond *et al* (2011)	225	1.3	6.1	0.1%	2.0%
This Study		**Emissions in 2050 (MtH_2) MFR**	**Emissions in 2050 (MtH_2) CLE**	**Losses[b] MFR**	**Losses[b] CLE**
Baseline (BL)	155	—	4.2	—	2.9%
Mitigation (MT)	319	2.2	11.2	0.7%	3.5%
Carbon Neutral (CN)	405	3.3	16.4	0.8%	4.1%

[a] Relative to total hydrogen demand for the respective study.

[b] Relative losses, considering the ratio of fugitive emissions to total hydrogen demand.

emissions in 2023 as reported by Ritchie and Roser (2024). It is important to note that the CN scenario assumes a substantial reduction in fossil fuel consumption, which also contributes to lower hydrogen H_2 emissions from incomplete combustion. Hence, transitioning to a hydrogen-based economy is expected to deliver meaningful climate benefits, despite hydrogen's indirect contribution. Nevertheless, further research is needed, particularly on atmospheric chemistry and hydrogen soil sinks, to deepen our understanding of hydrogen's broader climate impacts and which measures to pursue in order to mitigate hydrogen-related emissions.

5.4. Policy recommendations and future research

Despite growing interest in the hydrogen economy and its implications, several uncertainties and limitations remain. Future hydrogen demand is difficult to predict due to its strong dependence on interconnected energy systems and emerging technologies in initial stages of their deployment, such as the development of decentralized energy systems and the need for storage capacities and grid balancing. Although many projections assume that hydrogen for decarbonization will primarily be produced through electrolysis powered by clean electricity to achieve minimal CO_2 emissions, the current energy system still relies on fossil-fuel based power generation. The associated emissions might offset hydrogen's climate benefits unless CCS-technologies are widely adopted. Additionally, hydrogen production via electrolysis must consider environmental impacts beyond the GAINS model scope, such as freshwater consumption (Bianco *et al* 2023, Kumar *et al* 2024).

Fugitive emissions are expected to grow with expanded hydrogen infrastructure and, by 2050, may exceed emissions from incomplete combustion. The hydrogen supply chain and infrastructure for transmission, distribution and storage are the components where most hydrogen leakage occurs. These sources should become the subject of regulations for leakage monitoring and emission standards along the entire value chain. The application of hydrogen in industry is expected to continue, as feedstock or fuel, by providing high-temperature heat and backup power solutions, and for decarbonizing energy-intensive sectors such as steel and cement production. For this reason, the use of best practices and advanced leakage control technologies offers substantial potential for emission abatement. Transport is a key end-use sector where hydrogen fuel cells can play a significant role in reducing both GHGs and ambient air pollutants. Future policies and regulations should address both types of emissions to ensure an integrated approach for decarbonization and air quality improvement.

Accurate data and measurements, such as the ones conducted by Westra *et al* (2024), are essential for assessing future emissions from hydrogen production. Current fossil-based supply methods using natural gas, oil, or coal generate additional emissions of GHGs, and even hydrogen produced from biomass can lead to emissions of CO, $PM_{2.5}$ and SO_2. While these pollutants are technically manageable through existing regulatory mechanisms and technologies, these controls must be expanded to cover hydrogen-related activities explicitly. There is also a need for precise measurement techniques to calibrate emission factors for hydrogen leakages and to represent the environmental impacts of hydrogen under various control policies more accurately. On-site, high-resolution measurements of hydrogen leakages across the value chain are currently carried out within several research activities (HYDRA 2024, HYway 2024, NHyRA 2024).

Future development within the GAINS framework will focus on refining emissions and cost factors, exploring a broader range of hydrogen production mixes, and enhancing scenario analysis. The integrated modelling approach enables flexible and spatially explicit impact assessment of various energy demand and production pathways. Upcoming improvements will also include the spatial distribution of emissions sources (0.1 x 0.1-degree resolution), the consideration of regional specifics of hydrogen production, transmission, distribution, and end-use. These enhancements will support an integration with atmospheric chemistry models to assess hydrogen's effects on the global climate system, as well as the health and ecosystem impacts of associated pollutants.

6. Conclusions and policy recommendations

This study presents a comprehensive overview and quantification of emissions associated with the hydrogen economy using the GAINS framework. In this work, we analyse anthropogenic GHG and air pollutant emissions according to historical estimates and future scenarios. This includes hydrogen emissions from the incomplete combustion of fossil and biogenic fuels as well as emissions along the hydrogen value chain including hydrogen production, transport, distribution and storage, and end-use. We also estimate NO_x emissions from hydrogen combustion, fugitive NH_3 emissions from the hydrogen storage, as well as GHGs and air pollutant emissions from various policy scenarios and hydrogen production pathways.

In future projections about the application of hydrogen and replacement of other fuels and feedstocks with hydrogen, we consider BL, MT and CN projections. Simultaneously, we consider different assumptions on how hydrogen is produced: the CM, NF with production from biomass and electrolysis, and CP from SMR with CCS and electrolysis. We also evaluate the effect of control strategies according to current legislation (CLE) and maximum feasible reduction (MFR). The CLE strategy assumes that air pollution control policies will proceed according to countries' implementation schedules, offering meaningful reductions in air pollutants and hydrogen emissions from incomplete combustion.

Our results confirm that incomplete combustion currently represents the largest source of hydrogen emissions and continues to play an important role also in the hydrogen-intensive scenarios, primarily from the use of fossil fuels and biomass. We estimate a substantially lower global warming and air pollution impact of the application of hydrogen as a fuel and industrial feedstock than from fossil alternatives. However, estimated emissions are still significant. Because the CP as well as MT measures along the value chain have a large potential of reducing emissions by up to 75%, there is a strong rationale to consider both components within control policies.

As the hydrogen economy is still emerging, there are currently no specific national or regional regulations addressing hydrogen leakages or fugitive emissions, besides safety standards in installations. Most existing policies focus on promoting hydrogen deployment rather than managing its environmental risks. We recommend that hydrogen-related policies incorporate in their formulation requirements and standards for technologies, materials, and best practices aimed at minimizing hydrogen leakage.

Acknowledgment

This research has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101137582 (HYway). We also acknowledge the International Energy Agency for providing energy scenarios and trends through the collaborative work on the World Energy Outlook, which were processed to derive underlying activity projections used in this study. Thanks to colleagues from Pollution Management (PM), specially to Wolfgang Schöpp, and Integrated Assessment on Climate Change (IACC) groups at the International Institute for Applied System Analysis (IIASA), as well as colleagues from the HYway project for their support and fruitful discussions and feedback.

Data availability statement

Data sets generated during the current study are available as a data file for this submission. Original energy projections from the 2024 World Energy Outlook (WEO) are partially available from the International Energy Agency (IEA 2024c) as a free dataset at:

- www.iea.org/reports/world-energy-outlook-2024.
- www.iea.org/data-and-statistics/data-product/world-energy-outlook-2024-extended-dataset.

Additional input data were used under an IEA license and partially are not publicly available.

All data that support the findings of this study are included within the article (and any supplementary information files).

Supplementary Material available at: https://doi.org/10.1088/2753-3751/ae69e3/data1.

Supplementary Data available at: https://doi.org/10.1088/2753-3751/ae69e3/data2.

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