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The hydrogen challenge: addressing storage, safety, and environmental concerns in hydrogen economy

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A R T I C L E I N F O

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A B S T R A C T

As part of global decarbonization efforts, hydrogen has emerged as a key energy carrier that can achieve deep emission reductions in various sectors. This review critically assesses the role of hydrogen in the low-carbon energy transition and highlights the interlinked challenges within the Techno-Enviro-Socio-Political (TESP) framework. It examines key aspects of deployment, including production, storage, safety, environmental impacts and socio-political factors, to present an integrated view of the opportunities and barriers to large-scale adoption. Despite growing global interest, over 90 % of the current global hydrogen production originated from fossil-based processes, resulting in around 920 Mt of CO_2 emissions, two-thirds of which were attributable to fossil fuels. The Life Cycle Assessment (LCA) shows that coal-based electrolysis resulted in the highest GHG emission (144 - 1033 g CO_2-eq/MJ) and an energy consumption (1.55–10.33 MJ/MJ H_2). Without a switch to low-carbon electricity, electrolysis, cannot deliver significant climate benefits. Conversely, methanol steam reforming based on renewable feedstock offered the lowest GHG intensity (23.17 g CO_2-eq/MJ) and energy demand (0.23 MJ/MJ), while biogas reforming proved to be a practical short-term option with moderate emissions (51.5 g CO_2-eq/MJ) and favourable energy figures. Catalytic ammonia cracking, which is suitable for long-distance transport, represents a compromise between low energy consumption (2.93 MJ/MJ) and high water intensity (8.34 L/km). The thermophysical properties of hydrogen, including its low molecular weight, high diffusivity and easy flammability, lead to significant safety risks during storage and distribution, which are exacerbated by its sensitivity to ignition and jet pulse effects. The findings show that a viable hydrogen economy requires integrated strategies that combine decarbonised production, scalable storage, harmonised safety protocols and cross-sector stakeholder engagement for better public acceptance. This review sets out a multi-dimensional approach to guide technological innovation, policy adaptation and infrastructure readiness to support a scalable and environmentally sustainable hydrogen economy.

1. Introduction

Driven by the increasing urgency of the climate crisis, a growing number of countries have set net-zero emissions targets, reflecting a global shift towards climate action. In April 2022, 131 countries, accounting for 88 % of global greenhouse gas emissions, had announced commitments to achieve net zero emissions. Human-induced emissions have already led to a global temperature increase of 1.1 °C above pre-industrial levels and there is a broad consensus that achieving net zero emissions by 2050 is essential to limit warming to 1.5 °C [1]. To achieve this goal, emissions must be reduced in all sectors. While strategies such as energy efficiency, electrification and renewables can deliver around 70 % of the required reductions, hydrogen will play a crucial role in decarbonising sectors where alternatives are currently limited or economically unviable, e.g. heavy industry, long-distance transport and seasonal storage. In this context, hydrogen is expected to contribute around 10 % of the emission reductions required under the International Renewable Energy Agency's (IRENA) 1.5 °C scenario and 12 % of total final energy demand [1,2].

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List of acronyms

AG2S	Acid Gas to Syngas process
ALK	Alkaline Electrolysis
ATR	Autothermal Reforming
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CGH_2	Compressed Gaseous Hydrogen
COG	Coke Oven Gas
COP26	26th UN Climate Change Conference of the Parties
DBDE	Dichlorobenzene Equivalent (used in toxicity metrics)
ESG	Environmental, Social, and Governance
EU27	European Union (27 member states)
FCEV	Fuel Cell Electric Vehicle
FCV	Fuel Cell Vehicle
GEP	Green Energy Park
GH2	Green Hydrogen
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
H_2	Hydrogen
H_2-DRI	Hydrogen-based Direct Reduced Iron
HFC	Hydrogen Fuel Cell
HFCEV	Hydrogen Fuel Cell Electric Vehicle
HFCHEV	Hydrogen Fuel Cell Hybrid Electric Vehicle
HRS	Hydrogen Refuelling Station
ICEV(s)	Internal Combustion Engine Vehicle(s)
IEC	International Electrotechnical Commission
IEA	International Energy Agency
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LAC	Latin America and Caribbean
LCA	Life Cycle Assessment
LCC	Life Cycle Cost Assessment
LH_2	Liquid Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
MJ	Megajoule
MOF	Metal–Organic Framework
Mt	Million Tonnes
MTPA	Million Tonnes Per Annum
NA	Not Available
NH_3	Ammonia
NZE	Net Zero Emissions
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
SCZONE	Suez Canal Economic Zone
SDG	Sustainable Development Goals
SPIC	State Power Investment Corporation
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SSHS	Solid-State Hydrogen Storage
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TTW	Tank-to-Wheel
UGS	Underground Gas Storage
WTW	Well-to-Wheel

In response to rising global temperatures, increasing energy demand and growing concerns over fossil fuel depletion, the search for sustainable alternatives has become increasingly urgent. Hydrogen (H_2) has gained attention as a viable energy carrier due to its high specific energy, elevated combustion temperature, and substantial storage capacity, offering a clean, emission-free option [3,4]. It is being integrated into national and international energy strategies and adopted across sectors such as manufacturing and transportation [5]. Despite its potential, the environmental sustainability of hydrogen remains contested. Nevertheless, as a carbon-free molecule with the highest energy content per unit mass, hydrogen is positioned to play a pivotal role in future low-carbon energy systems and the realisation of a hydrogen economy [6]. Its high energy density and clean combustion enhance its appeal for applications in transportation, power generation, and industrial processes. Moreover, its lightweight nature and availability in both gaseous and liquid forms make it especially advantageous for weight-sensitive transport modes. The renewed interest in hydrogen reflects its strategic importance in decarbonization and the advancement of technologies aimed at unlocking its full potential.

Furthermore, hydrogen fuel cells generate electricity with high efficiency, emitting only water vapor as a byproduct, making them a sustainable energy solution [7–9]. Given its versatility and unique characteristics, hydrogen is poised to become a cornerstone of future global energy landscape. However, due to its broad flammability range and high explosive potential (4–74 % in air), hydrogen poses substantial safety hazards during production, storage, transportation, and use. Even a minimal energy input is sufficient to ignite hydrogen, which increases the risk of accidental combustion or explosions [10]. These challenges are further amplified under cryogenic conditions, as hydrogen must be stored at extremely low temperatures (−253 °C) to remain in liquid form, complicating containment and handling procedures [11,12]. Although hydrogen oxidation yields only water, making it an environmentally clean fuel, the element's low volumetric energy density even in its liquid state limits its storage efficiency relative to conventional hydrocarbon-based transportation fuels [7–9,13]. Despite its high gravimetric energy density, the energy content per unit volume remains a key barrier to large-scale deployment. These physical and chemical limitations must be addressed through technological innovations to ensure hydrogen's safe integration into a sustainable and resilient energy system.

Assessing the long-term sustainability of hydrogen production and utilization requires systematically evaluating various production pathways and their environmental implications. Hence, the holistic assessment must consider hydrogen's entire life cycle, including production, storage, distribution, and end-use. Life cycle assessment (LCA), as proposed by Osman et al. [14] and Weidner et al. [15], provides a systematic approach to evaluating hydrogen's environmental footprint. This methodology enables a deeper understanding of different hydrogen production pathways, associated life cycle inventories, and potential environmental consequences. Beyond production, LCA also examines storage and distribution methods, assessing infrastructure requirements, energy inputs, and environmental trade-offs. Furthermore, evaluating the environmental impact of hydrogen across various applications, including power generation and transportation, is essential for determining its role in a sustainable energy future.

Transitioning to a hydrogen economy has the potential to significantly reduce CO_2 emissions and support global energy sustainability goals [16]. Conducting environmental assessment enables researchers and relevant stakeholders to link a system's elementary flows to its environmental burdens, facilitating a more accurate evaluation of sustainability [17,18]. Numerous studies have explored various hydrogen production methods, including conventional steam methane reforming (SMR) [19], renewable alternatives [20], and emerging production routes [21]. Research has also extensively analysed hydrogen storage and transportation challenges [22]. Key topics in the hydrogen research landscape include technological barriers, recent advancements, safety considerations, and the reliability of hydrogen technologies, with storage being a particularly critical area of focus. While technical efficiency and economic feasibility assessments are well established, environmental sustainability evaluations require further refinement. However, it is worth noting that hydrogen production pathways evaluated in these studies often focus primarily on environmental impacts, with safety considerations rarely included in the analysis.

This review provides a timely and multidimensional reassessment of the global hydrogen energy system by examining not only the technological and environmental challenges, but also the interplay of production pathways, storage modalities, safety risks and sustainability metrics. In contrast to previous studies that focus narrowly on individual components such as hydrogen production technologies or life cycle emissions [15,23–32], this work adopts a system-oriented synthesis that situates hydrogen deployment within a broader Techno-Enviro-Socio-Political (TESP) framework. The TESP framework is a comprehensive, interdisciplinary approach to assessing complex energy systems that incorporates technological, environmental, social and political dimensions. This framework is particularly well suited for analysing sustainable energy transitions, where decision-making must go beyond technical performance and cost considerations and consider public acceptance, regulatory alignment, geopolitical dynamics and environmental impacts. By applying the TESP perspective, this study captures the interdependencies and trade-offs associated with large-scale hydrogen deployment, providing a more holistic basis for strategic planning and policy design. Through its integrative approach, the review provides a basis for assessing the overall sustainability and long-term viability of hydrogen. It advances the discourse by proposing multi-level strategies that balance technological innovation with policy structures and stakeholder engagement, providing a holistic roadmap for a climate and socially responsible hydrogen deployment. Given the increase in global hydrogen production from 85 Mt in 2016 to 97 Mt in 2023 [33][34], predominantly from fossil sources, the study underlines the urgency of transitioning to harmonised, sustainability-focused energy systems.

1.1. Hydrogen colour spectrum: production pathways and environmental implications

Hydrogen is classified into various "colours" based on its production method and environmental impact (Fig. 1). Grey hydrogen is the most common and carbon-intensive form, produced via steam methane reforming (SMR) or coal gasification, where methane or coal is converted into hydrogen without capturing the carbon dioxide (CO_2) emissions. Blue hydrogen is produced using the same SMR or gasification methods but incorporates carbon capture and storage (CCS) technologies to trap 85–95 % of the CO_2, making it less harmful to the environment. Turquoise hydrogen, an emerging decarbonization option, is produced through methane pyrolysis, which thermally splits methane into hydrogen and solid carbon rather than CO_2, offering a potentially lower-emission route if powered by clean energy. Green hydrogen is the most sustainable option, generated via electrolysis of water using renewable electricity such as solar or wind, resulting in zero greenhouse gas emissions [35–38]. While grey and blue hydrogen depend on fossil fuels like methane or coal, turquoise hydrogen provides a cleaner alternative with manageable solid carbon byproducts. Green hydrogen, however, is central to future decarbonization strategies due to its alignment with renewable energy (RE) use and climate goals.

Like electricity, hydrogen is an energy carrier rather than a direct energy source. Its ability to be stored, transported, and utilized efficiently makes it an essential component in renewable energy storage, minimizing waste during periods of low energy demand. However, the conventional colour-based (grey, blue, turquoise, and green) classification of hydrogen production oversimplifies its environmental impact [39]. Most of the global hydrogen is derived from fossil fuels, with 76 % obtained via steam methane reforming (SMR) of natural gas and 22 % through coal gasification. Only about 2 % is produced through water electrolysis [40], highlighting a major sustainability challenge. Fossil fuel-based hydrogen production contributes significantly to greenhouse gas emissions, particularly CO_2, and has other detrimental environmental effects, making grey hydrogen the least sustainable option. Among the various hydrogen production methods, green hydrogen-generated through water electrolysis powered by renewable energy and blue hydrogen produced via steam methane reforming (SMR) with carbon capture are gaining momentum in the transition toward sustainable and energy-efficient hydrogen production. Green hydrogen, in particular, is at the forefront of large-scale renewable energy projects [41,42], while blue hydrogen serves as an interim solution bridging the gap between fossil fuel dependency and a hydrogen-based economy.

While green hydrogen is generally considered the cleanest option, its carbon footprint can vary, particularly when biomass feedstocks or thermochemical conversion processes are involved. Additionally, despite public concerns regarding its safety, blue hydrogen undergoes carbon capture and storage (CCS), significantly reducing its emissions. It is also important to recognise that renewable energy technologies, such as photovoltaic (PV) panels essential for green hydrogen production, have environmental drawbacks. Manufacturing PV panels involves resource extraction, energy-intensive production, and hazardous waste generation, contributing to their overall carbon footprint. Moreover, solar panels have an operational lifespan of approximately 30 years, after which they require specialised waste management and disposal

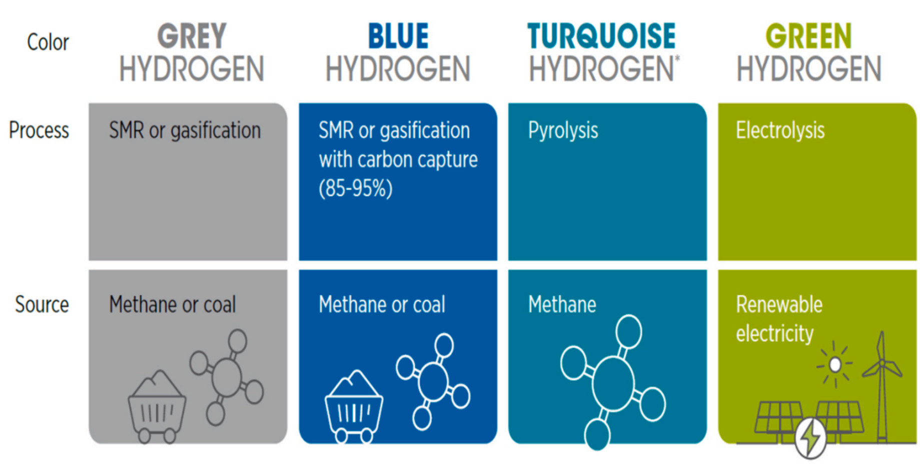

Fig. 1. Various hydrogen production methods and their environmental impacts. Adapted from Ref. [37].

[14]. Although green and the emerging turquoise hydrogen is expected to dominate future sustainable energy systems, blue hydrogen remains a crucial transitional energy source facilitating a smoother shift toward sustainability [42]. Achieving a sustainable hydrogen economy requires a comprehensive evaluation of hydrogen's environmental impact and long-term viability.

2. Overview of global hydrogen market

Hydrogen production is transforming significantly as nations strive for cleaner energy solutions. While fossil fuel-based hydrogen still dominates, advancements in electrolysis and renewable energy integration accelerate the shift toward low-carbon and green hydrogen. In 2023, global hydrogen production totalled 97 million tonnes (Mt), with low-emissions hydrogen accounting for less than 1 % of that volume. However, if current project announcements are realized, the output of low-emissions hydrogen could grow to 49 million tonnes per year by 2030, an increase from the 38 Mtpa projected in the *Global Hydrogen Review 2023* IEA [34]. Policy support, technological innovations, and investment initiatives drive global hydrogen expansion (Fig. 2). This progress positions hydrogen as a key enabler of the energy transition and decarbonization efforts.

2.1. Hydrogen demand and consumption

The COVID-19 pandemic caused a global decline in hydrogen demand in 2020, primarily due to reduced transportation activities and lower refinery and fertilizer production [44]. Despite this setback, the long-term outlook for hydrogen remains strong, driven by climate change concerns and supportive government policies aimed at scaling up decarbonized hydrogen production. Blue hydrogen, derived from fossil fuels with carbon capture, and green hydrogen, produced via water electrolysis using renewable energy, are gaining traction. Hydrogen demand is expected to grow at a ~5 % CAGR between 2016 and 2025, driven by fuel cell vehicles, refineries, and ammonia production. North America currently leads the hydrogen market due to its robust petrochemical and ammonia sectors, while Asia led by China, Japan, India, and South Korea is rapidly advancing through technological innovation and infrastructure development [45] (Fig. 3a). Europe, including Germany, France, the UK, and others, also remains a significant player, with emerging markets like Saudi Arabia, Brazil, South Africa, and Argentina showing potential. Globally, the hydrogen generation market is projected to grow from USD 135.5 billion in 2018 to USD 199.1 billion by 2023, with the Asia-Pacific region leading this growth [44]. China's investment in hydrogen cities and refuelling stations, and the leadership of Japan and South Korea in fuel cell vehicle (FCEV) development with 60 % of global FCEV sales from South Korea highlight the growing global push toward a low-carbon hydrogen economy.

As the energy landscape evolves, global hydrogen demand is expected to reach around 660 million tonnes by 2050, according to the IEA's Net Zero Emissions (NZE) scenario, which models a pathway consistent with limiting global warming to 1.5 °C [46–49]. This projection assumes widespread electrification, rapid deployment of low-emission hydrogen technologies, and stringent policy interventions to phase out unabated fossil fuels. The Sixth Assessment Report of the International Panel on Climate Change (IPCC AR6) pathways similarly emphasise the role of hydrogen in decarbonising sectors where direct electrification is a challenge, including heavy industry and long-distance transport, and other key industries serving as a feedstock in sectors such as food processing, glass, fertilizer, and steel production [50]. It will also be vital for producing synthetic fuels used in maritime and aviation transport, for backup power generation, and for enabling clean mobility through its use in heavy-duty vehicles, long-range passenger transport, and trains (Fig. 3b). Additionally, hydrogen will support high-temperature industrial heating applications [3,47,51]. According to International Renewable Energy Agency (IRENA), hydrogen could meet up to 12 % of global final energy demand by mid-century, with a quarter of this demand being met through international trade, if costs are reduced, and infrastructure is developed. These scenarios highlight the strategic importance of hydrogen in creating a zero-emission energy system, while emphasising the need for coordinated global action to scale up the production and distribution of clean hydrogen.

Fig. 4 shows the overview of different methods of hydrogen production, distribution, and storage; different energy supply by sources and hydrogen applications and utilisations based on sectors (Fig. 4a–d).

2.2. Current development and status of global hydrogen production

Hydrogen has emerged as a pivotal driver in global energy transition efforts, increasingly recognized for its strategic role in advancing decarbonization across multiple sectors. As of 2023, worldwide hydrogen production reached approximately 97 million tonnes, yet the vast majority of over 99 % was derived from fossil fuel-based methods,

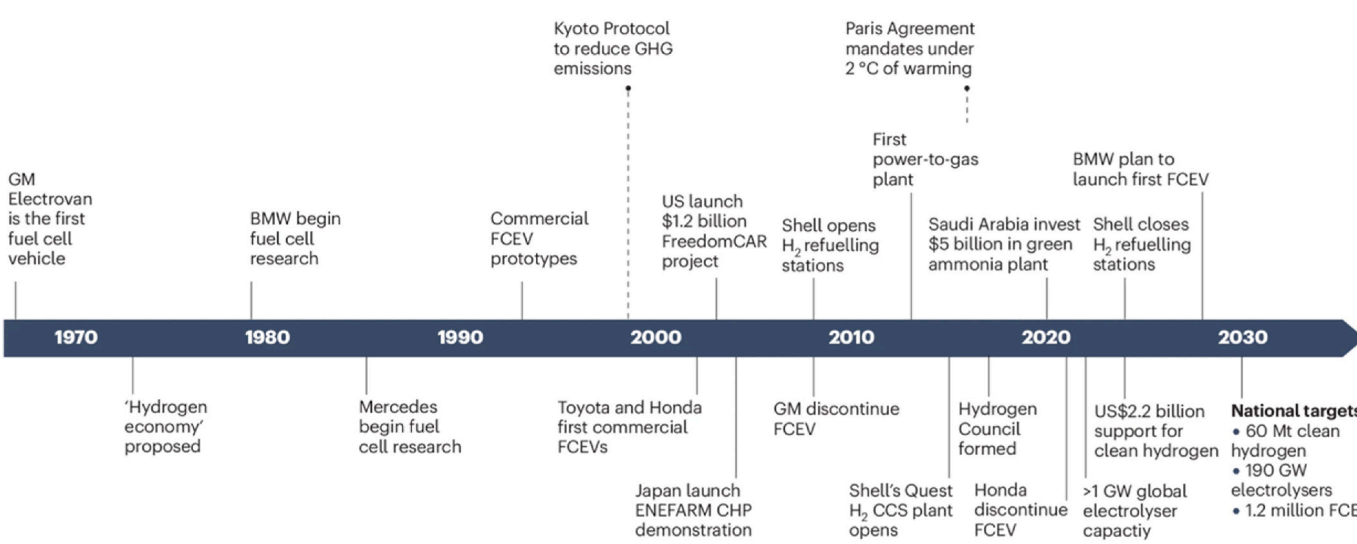

Fig. 2. Chronological overview of notable developments in the hydrogen energy sector, compiled from publicly accessible sources (reproduced from Ref. [43] with permission from Springer Nature, copyright 2025). The growth of the hydrogen industry has experienced fluctuating levels of enthusiasm, with projections and strategic goals differing significantly across regions. (*CCS - carbon capture and storage, FCEV - fuel cell electric vehicle, and GHG - greenhouse gas.*

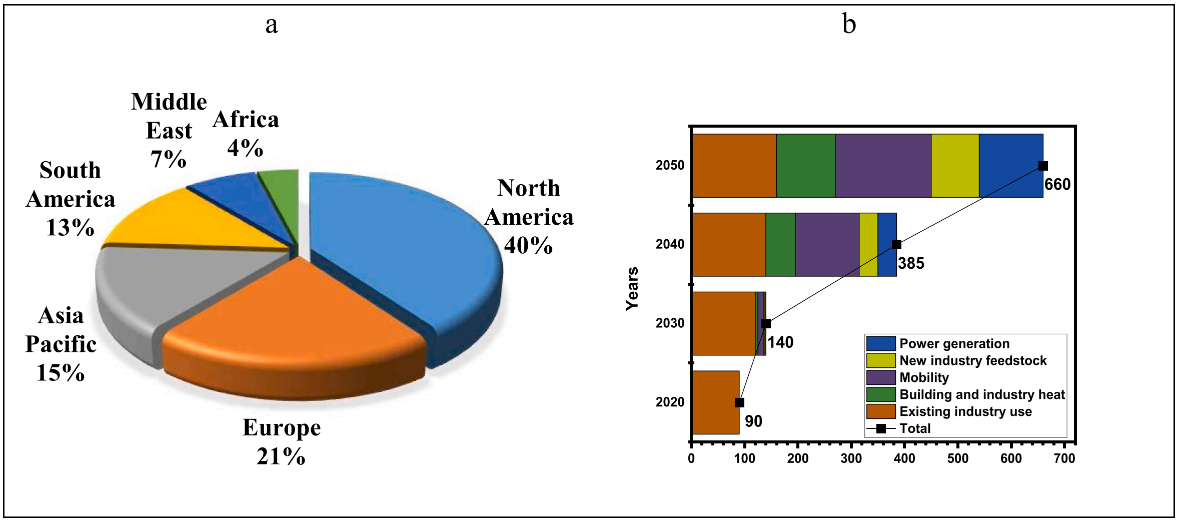

Fig. 3. (a). Regional overview of the global hydrogen market (b) Sectoral demand for hydrogen: end users, modified from Ref. Ref. [4,44] respectively.

primarily through steam methane reforming [34]. This underscores the pressing need for a shift toward cleaner alternatives. On the development front, countries and regions are actively investing in low-emission hydrogen technologies, including green hydrogen via electrolysis and turquoise hydrogen through methane pyrolysis. The ongoing, announced and proposed hydrogen projects in Table 1 indicate that low-emission hydrogen capacity could rise to 49 million tonnes per year by 2030, marking a substantial increase from previous estimates. This global surge in development highlights a growing recognition of hydrogen's role in decarbonizing hard-to-abate sectors such as industry and heavy transport [34]. Green hydrogen is expected to play a crucial role in achieving these objectives. It is primarily produced via electrolysis using renewable energy sources such as solar, wind, hydropower, and biomass gasification. This method provides sustainable, emission-free alternatives to fossil fuels, making green hydrogen a key component in transition to a low-carbon economy [52].

2.2.1. North America

North America is poised to lead the global hydrogen economy, with projections suggesting the market could exceed $140 billion annually by 2030. By 2022, the region had 33 green hydrogen plants with a combined capacity of 691,000 tons annually [53]. The U.S. produces around 10 million metric tons (MMT) of hydrogen annually, mainly for petroleum refining and ammonia production. However, barriers such as high production costs, infrastructure limitations, and low demand incentives hinder progress. Reducing costs through better electricity pricing, enhanced electrolyser performance, and longer equipment lifespans is crucial for scaling up blue and green hydrogen, enabling the shift from pilot to commercial projects [53]. North America benefits from a robust oil and gas industry, rich energy resources, and a diverse demand base. Unlike other regions focusing solely on green hydrogen, North America is developing both blue and green hydrogen infrastructure. The U.S. leads in hydrogen pipeline infrastructure, especially along the Gulf Coast, while Canada hosts the world's two largest hydrogen projects, totalling 86 MTPA, accounting for 88 % of the region's planned capacity. Still, over 95 % of U.S. hydrogen is grey, emitting ten times more CO_2 per unit of hydrogen [54]. Canada's Hydrogen Strategy of 2020 targets supplying 30 % of its energy demand with hydrogen by 2050, aiming to be among the top three clean hydrogen producers [55]. Environmental concerns play a central role in Canada's energy policies. The country ratified the Kyoto Protocol in 2002, but after the election of Prime Minister Stephen Harper in 2006, emissions reduction efforts stalled. Despite its innovation and R&D leadership, Canada's fragmented policy landscape exacerbated by its withdrawal from the Kyoto Protocol in 2012 has slowed cohesive progress [56]. Significant policy coordination and investment are essential for this region to achieve hydrogen sector leadership.

2.2.2. European Union (EU)

Hydrogen is integral to Europe's transition to clean energy, net-zero targets, and broader sustainability objectives. The EU aims to reduce Liquefied Natural Gas (LNG) imports by expanding hydrogen market. In 2022, hydrogen contributed to less than 2 % of Europe's total energy use, primarily serving as a raw material for chemical industries such as plastics and fertilizer production. However, 96 % of this hydrogen originated from natural gas, resulting in significant CO_2 emissions [57]. To counter this, the REPowerEU Strategy of 2022 set an ambitious goal: by 2030, the EU aims to generate 10 million tonnes of renewable hydrogen domestically while importing an additional 10 million tonnes. In view of its far-reaching potential, almost all EU member states have recognized green hydrogen as an important component of their energy and climate strategies. The EU has set itself the target of installing at least 6 GW (GW) of renewable hydrogen electrolyser capacity by 2024 and increasing this to 40 GW by 2030 [58]. In 2025, EU plans to deploy 17.5 GW of electrolyser capacity to produce 10 million tonnes of renewable hydrogen per year, with a further 10 million tonnes to be imported by 2030, bringing the planned total use to 20 million tonnes per year [58,59]. Looking ahead to 2050, renewable hydrogen is expected to supply roughly 10 % of the EU's energy needs, crucial in reducing emissions from energy-intensive sectors and transportation [57]. Hydrogen is integral to Europe's transition to clean energy, net-zero targets, and broader sustainability objectives. The EU's hydrogen policy framework was introduced in July 2021 as part of the Fit-for-55 package, establishing legally binding targets for adopting renewable hydrogen in industry and transport by 2030 [57]. The EU Clean Hydrogen Partnership (2021–2027) and the European Clean Hydrogen Alliance support the large-scale deployment of hydrogen under Horizon Europe and the EU Hydrogen Strategy. With six thematic roundtables and a project pipeline published in 2021, major efforts such as the Electrolyser Partnership are targeting an annual production capacity of 17.5 GW by 2025. These initiatives reflect the EU's strong commitment to hydrogen as a cornerstone of the clean energy transition and its potential to decarbonise industry and transport [57]. Europe is the world leader in planned hydrogen investments and in the number of announced projects covering the entire hydrogen value chain.

2.2.3. Asia Pacific

In Asia, China leads in hydrogen production, generating

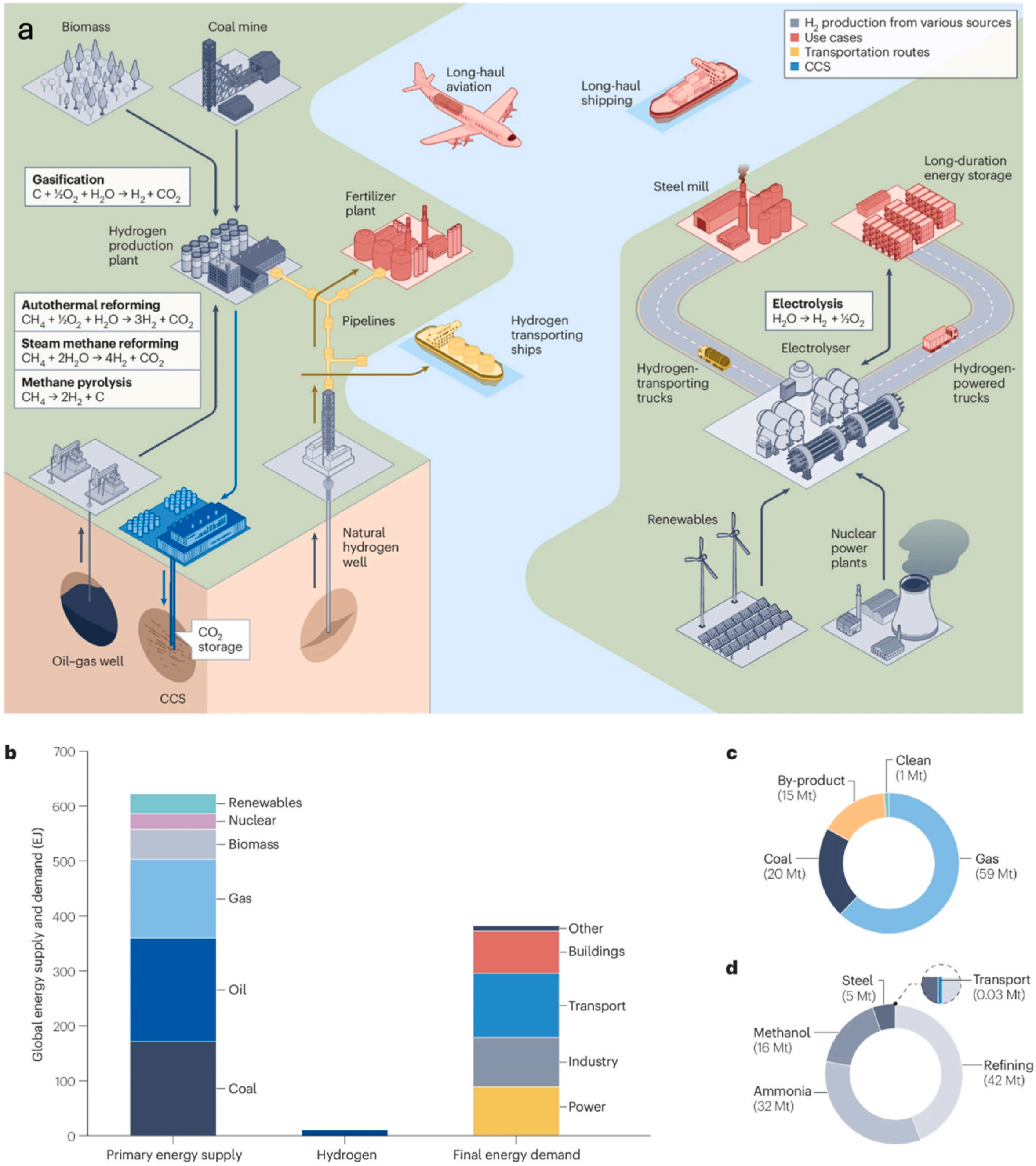

Fig. 4. **(a)** Outlines the primary methods of hydrogen production, distribution, and storage, along with notable applications. **(b)** Presents a breakdown of global primary energy supply by source, the total hydrogen output from all production methods, and the global final energy demand by sector as of 2022. **(c)** Shows the global distribution of hydrogen production sources, with color coding corresponding to the supply categories shown in part (b). **(d)** Illustrates the proportion of hydrogen consumption across end-use sectors, again color-matched to the energy demand in part (b), emphasising that industrial applications currently dominate hydrogen use. Reproduced from Ref. [43] with permission from Springer Nature, copyright 2025. *Hydrogen serves as a flexible energy carrier with multiple pathways for production and utilization, yet it remains a minor contributor to the global energy mix and is still predominantly derived from fossil fuel sources. CCS (carbon capture and storage) is a key technology associated with reducing emissions from fossil-based hydrogen production.* (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

approximately 34.1 million tons in 2020, a 2 % increase from 33.4 million tons in 2019. However, the vast majority, 96 % of hydrogen production is derived from fossil fuels such as coal, natural gas, and oil. Electrolysis, including chlor-alkali by-production and water electrolysis, accounts for just 4 % of national output [60]. Coal remains the dominant feedstock for hydrogen production in China, with coal gasification contributing 14.4 million tons, coke production yielding 10.4 million tons, and chlor-alkali manufacturing providing 1.0 million tons in 2020 [60]. Renewable hydrogen production via water electrolysis in remains limited, with only 510 thousand tons annually generated from demonstration projects and 925 thousand tons from chlor-alkali by-production [60]. On the demand side, the ammonia industry is China's largest hydrogen consumer, followed by methanol synthesis, petroleum refining, and chlor-alkali manufacturing. These industries often utilize hydrogen as feedstock or process heat. A production-consumption gap of 4.5 million tons per year leads to hydrogen waste, as some hydrogen-rich gases, such as coke oven gases and coal gasifier synthesis gases, are combusted onsite or vented due to economic constraints [60].

Table 1
Some notable global hydrogen projects showing the production capacity and technologies.

Project name/Ownership/Partnership	Countries	Start/announced or commission date	Technologies/Energy sources	Estimated NH_3 or H_2 Production Capacity (tons/year)	Refs.
North America					
Air Products and AES Corporation's Green Hydrogen Facility	United States	2027	Electrolysis (Solar & Wind)	57,476.46	[53]
Advanced Clean Energy Storage Project	United States	2025	Renewable energy	28,734.57	[53]
Vallera Renewables Hydrogen Plant	United States	2025	Electrolysis	22,943.52	[53]
The Wind-to-Hydrogen Project	United States	2026	Wind	20,070.84	[53]
ZIP Hydrogen facility, phase 1	United States	2017	PEM	350.40	[69,70]
SunLine Transit Agency, Palm Springs	United States	2018	PEM	324.12	[69–71]
NEL - Nikola	United States	2020	NA	174,060.20	[70,71]
Nikola	United States	2020	ALK	359.16	[69–71]
Naval Facilities Engineering Command, Engineering and Expeditionary Warfare Centre	United State	2016	SOEC	10.95	[69–71]
Lake Charles Methanol	United States	2022	Fossil	198,873.36	[70,72]
Submarines	United States		PEM		[69–71]
St. Gabriel Green Hydrogen Plant (Hidrogenii)	United States	2025	Renewable energy	182,500	[53]
Kingsland Green Hydrogen Plan	United States	2025	Renewable energy	4303.47	[53]
Casa Grande Green Hydrogen Plant	United States		Renewable energy	2866.47	[53]
Donaldsonville Green Hydrogen Project	United States	2025	Alkaline H_2O Electrolysis	5,723,179.20	[53]
Sauk Valley Green Hydrogen Plant by Invenergy	United state	2025	Electrolysis (Solar)	18,980	[53]
Enbridge P2G Toronto	Canada	2017	PEM	327.63	[70,73]
Markham Energy Storage, Ontario	Canada	2018	PEM	409.98	[70,71,74]
Northwest Sturgeon refinery	Canada	2019	Fossil	133,764.96	[69–71]
Nutrien (former Agrium) fertilizer	Canada	2019	Fossil	33,228.88	[69–71]
Air Liquide Becancour	Canada	2020	PEM	3279.19	[70,71,75]
Asia Pacific					
2 Yanqing Renewable Energy Hydrogen Production Project - State Power Investment Corporation (SPIC)	China	2022	Wind, Solar & Hydro	980	[60]
Yumen Oilfield 160 MW Renewables Hydrogen Production Demonstration Project	China	2023	Solar	7000	[60]
Zhangjiakou Green Hydrogen Energy Integration Demonstration Base Project	China	2022	Wind	2800	[60]
Huajiu Rooftop Solar PV Power to Hydrogen Project - Huajiu Hydrogen Energy (Henan)	China	2023	Solar	153	[60]
Henan Pingmei Shenma Group Kaifeng Dongda Chemical 16 MW Solar to Hydrogen Demonstration Project	China	2023	Solar	2157	[60]
Sinopec Ordos Green Power Hydrogen Production Project - Sinopec	China	2023	Solar & Wind	10,000	[60]
Narisong Solar to Hydrogen Industrial Demonstration Project	China	2023	Wind	10,000	[60]
ABC Cleantech – Green Hydrogen and Ammonia	India	2022	Solar & Wind	200,000	[76]
ACME - Green Hydrogen and Green Ammonia Plant Rajasthan	India	2022	Solar	314	[76]
ACME- IHI Corporation Green H2 and Ammonia Facility	India	2024	Renewable energy	229,600	[76]
AVAADA & Tata Steel Special Economic Zone Ltd (TSSEZL)	India	2023	Solar	130,000	[76]
BPCL - Electrolyser and Blending	India	2021	Electrolysis	785	[76]
GAIL- GH_2 Project	India	2024	PEM electrolyser	1570.542	[76]
Greenko - Green Hydrogen Production Plans	India	2025	Renewable energy	540,000	[76]
HLC - Himachal Green Hydrogen and Ammonia Plant	India		Renewable energy	300,000	[76]
HPCL - Andhra Pradesh Green Hydrogen Project	India	2023	Renewable energy	7300	[76]
Samcheok Green Hydrogen Plant	South Korea	2021	Electrolysis - Renewable energy	~365	[77]
North Gyeongsang Nuclear H_2 Project	South Korea	2024	SMR + Nuclear	~10,000	[78]
ENEOS Hydrogen Project	Japan	2020	Electrolysis (Solar-powered)	~10,000	[79]
African Region					
Mauritania's AMAN project	Mauritania	2022–2029	Solar & Wind	1,700,000	[80]
Nour Electrolyser Project	Mauritania	2024	Electrolysis	1,200,000	[80]
Masdar-Infinity-Conjuncta green hydrogen project	Mauritania	2023	Electrolysis	1,360,000	[80]
Tsau Khaeb project	Namibia	2021–2026	Solar & Wind	300,000	[80]
Daures Green Hydrogen Village	Nambia	2022 -	Renewable energy	31	[80]
Swakopmund project	Nambia	2022–2025	Solar PV & Electrolysis	1400	[80]
Green Ammonia Plant by Hive Hydrogen	South Africa	2021–2028	Electrolysis - Renewable energy	300,000	[80]
IPM/NCP H_2 Refuelling Stations deployment	South Africa	2025	Renewable energy	2500	[81]

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Table 1 (*continued*)

Project name/Ownership/Partnership	Countries	Start/announced or commission date	Technologies/Energy sources	Estimated NH_3 or H_2 Production Capacity (tons/year)	Refs.
HySHiFT Secunda	South Africa	2026	Renewable energy	16,400	[81]
Ubuntu Green H_2: Phase 1	South Africa	2026	Renewable energy	7000	[81]
Atlanthia Green NH_3/H_2: Phase 1	South Africa	2027	Solar and wind	7300	[81]
Electrolyser plant at the Suez Canal Economic Zone (SCZONE) by Masdar & Hassan Allam Holding Group	Egypt	2022	Electrolysis - Renewable energy	890,000	[80]
Fortescue-Egypt-gH2 project	Egypt	2022	Electrolysis	300,000	[80]
Ain Sokhna Green Hydrogen Plant	Egypt	2026	Solar and Wind	100,000	[82]
ACME green ammonia project	Egypt	2023	Renewable energy	400,000	[80]
Amun project by CWP Global and engineering	Morocco	2019–2025	Solar & Wind	900,000	[80]
Independent power producer (IPP) Total Eren - green hydrogen project	Morocco	2024	Solar & Wind	710,000	[80]
Hevo Ammonia Morocco project	Morocco	2021	Renewable energy	31,000	[80]
Masen Green Hydrogen project	Morocco	2020	Electrolysis - Renewable energy	8400	[80]
Ben Guerir project.	Morocco	2017	Solar & Wind	125	[80]
Green hydrogen hub by CWP Global	Djibouti	2022	Solar & Wind	300	[80]
Europe					
HyDeal Ambition	Spain France	2030	Solar PV & electrolyser	3600	[83]
Cerulean Winds - North Sea	UK	2024	Offshore Wind	259.88	[83]
Sines refinery (phase 2)	Portugal	2025	Electrolysis	155.93	[83]
SALCOS - first expansion	Germany	2025	NA	136	[83]
Deltaurus 3	Netherlands	2027	NA	121.28	[83]
HySynergy, phase 3	Denmark	2030	NA	121.28	[83]
Sreen Hydrogen Hub, phase 2	Germany Denmark	2031	NA	121.28	[83]
SravitHy	France	2027	NA	120.00	[83]
IPCEI Black Horse (40 electrolysis production sites)	Poland Czech Republic Slovakia Hungary	2030	NA	116.80	[83]
Westkuste l00 (Phase 2)	Germany	2028	NA	116.08	[83]
NorthH2, phase l	Netherlands	2027	Offshore Wind	173.25	[83]
Esbjerg green ammonia plant	Denmark	2027	NA	173.25	[83]
Iberdrola - H2 Sreen Steel	Spain	2026	NA	173.25	[83]
NeptHyne, phase 2	Poland	2030	NA	173.08	[83]
Solar PV Plant port of Sines	Portugal	2030	Solar PV	171.52	[83]
Dylan, phase 2	UK	2030	NA	121.28	[83]
Deltaurus 3	Netherlands	2027	NA	121.28	[83]
HySynergy, phase 3	Denmark	2030	NA	121.28	[83]
Green Hydrogen Hub, phase 2	Germany Denmark	2031	NA	121.28	[83]
SravitHy	France	2027	NA	120.00	[83]
IPCEI Black Horse (40 electrolysis production sites)	Poland Czech Republic Slovakia Hungary	2030	NA	116.80	[83]
Westkuste l00 (Phase 2)	Sermany	2028	NA	116.08	[83]
Herning Electrolyser Plant	Denmark	2023–2025	Electrolysis - Renewable energy	15.0	[84]
Belfort Alkaline Electrolyser Gigafactory	France	2023–2024	Alkaline Electrolysis	30	[84]
Blanquefort Hydrogen Fuel Cell Manufacturing Facility	France	2023–2023	Solar & Wind	3.0	[84]
Lysekil Green Hydrogen Plant	Sweden	2023–2024	Electrolysis - Renewable energy	15.0	[84]
Stuttgart-Münster Hydrogen Power Plant	Germany	2023–2026	Gas turbine	1.5	[84]
Latin America and Caribbean (LAC)					
Cerro Pabellón	Chile	2017	PEM electrolyser	10	[85]
Haru Oni, HIF's operational pilot project	Chile	2021	Electrolysis, Wind	NA	[85,86]
Anglo American pilot project	Chile	2021	Renewable energy	0.73	[85,87]
Ecopetrol's Cartagena refinery	Colombia	2018	PEM electrolyser	7.3	[85]
Promigas pilot project	Colombia	2019	PEM electrolyser	1.5	[85]
Ad Astra Pilot Project	Costa Rica	2013	PEM electrolyser	0.8	[85]
Helax-Isthmus Facility	Mexico	2026	Solar & Wind	900,000	[88]
French Developer HDF Projects	Mexico	2024	Renewable energy–solar PV	5700	[89]
Vale and Green Energy Park (GEP) Partnership	Brazil	2024	Renewable energy	Not specified	[90]
Unigel Green Hydrogen Plant	Brazil	2023	Renewable energy	100,000	[91]
Middle East Region					
NEOM Green Hydrogen Project	Saudi Arabia	2022/2026	Electrolysis (Solar & Wind)	1,200,000	[65]
Saudi Aramco Blue NH_3	Saudi Arabia	2022–2030	SMR + CCUS	11,000,000	[92]
Ruwais Blue Ammonia Plant	UAE	2027	SMR + CCUS	1,000,000	[93]
Dubai Green Hydrogen Project	UAE	2021	Electrolysis (Solar)	~90	[94]
Masdar Green Hydrogen	UAE	2025	Electrolysis - Renewable energy	1,000,000	[82,95]
Green Energy Oman (GEO)	Oman	2021–2032	Electrolysis (Solar & Wind)	1,800,000	[96]

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Table 1 (*continued*)

Project name/Ownership/Partnership	Countries	Start/announced or commission date	Technologies/Energy sources	Estimated NH_3 or H_2 Production Capacity (tons/year)	Refs.
Hydrom Block Allocations	Oman	2023–2030	Electrolysis (Solar & Wind)	1,500,000	[66]
AMEA Power Hydrogen Project	Jordan	2022	Electrolysis - Renewable energy	40,000	[82]

PEM: Proton Exchange Membrane, PEM: Proton Exchange Membrane, ALK: Alkaline, SOEC: Solid Oxide Electrolysis Cell, NA: Not Available, RE: Renewable Energy.

Optimizing the supply chain could significantly enhance hydrogen efficiency in China. Additionally, Japan aims to consume 3 million tons annually by 2030 and 20 million tons by 2050 to advance a hydrogen- and ammonia-based economy [61]. India has set ambitious energy targets, aiming for energy independence by 2047 and net-zero emissions (NZE) by 2070 [52]. Green hydrogen, produced via renewable-powered electrolysis and biomass gasification, is key to India's low-carbon future. These methods offer clean alternatives to fossil fuels, advancing national decarbonization goals [52].

2.2.4. Latin America and caribbean (LAC) (south and central America)

LAC has strong potential for low-emission hydrogen production, benefiting from abundant renewable energy and a largely decarbonized electricity mix. In 2023, hydrogen demand reached 4 Mt, mainly for refining and chemicals, but 90 % was produced from natural gas, increasing reliance on imports. The region imports 80 % of its nitrogen-based fertilizers, contributing to a trade deficit of up to 0.4 % of GDP. Expanding domestic low-emission ammonia production could reduce costs, enhance energy security, and stabilize prices. LAC also holds 20 % of the world's iron ore reserves, with high-grade ores suited for hydrogen-based direct reduced iron (H_2-DRI), which could lower reduced iron production costs for importers by nearly 30 %. Opportunities vary by country. Mexico and Colombia could leverage existing refinery demand, Chile's mining sector could adopt hydrogen for decarbonization, and Brazil, responsible for 90 % of LAC's iron ore trade, could lead in H2-DRI production. Panama, targeting 5 % hydrogen-based shipping fuel by 2030, aims to become a regional fuel hub. Despite potential 7 Mtpa hydrogen production by 2030, only 0.1 % of projects are operational. High capital costs and the need for a 140 % increase in renewable capacity pose challenges. Immediate action is needed to scale production, reduce imports, and develop hydrogen hubs to position LAC in the global hydrogen economy [62].

2.2.5. African region

Africa faces significant energy challenges, with approximately 600 million people lacking access to electricity [63]. The continent's anticipated population and economic growth will require substantial energy expansion. By utilizing renewable resources for green hydrogen production, African nations can meet this demand sustainably. Additionally, the continent holds vast reserves of critical minerals, such as platinum and platinum group metals, essential for fuel cells and next-generation hydrogen technologies. Africa has substantial export potential for green hydrogen. The European Investment Bank estimates that the continent's green hydrogen production capacity could surpass 50 million tons per annum by 2035, with production costs projected at just €2 per kilogram, making it competitive with global oil prices of approximately €90 per barrel [63]. Proximity to Europe allows Morocco, Mauritania, and Egypt to integrate production into the European Hydrogen Backbone initiative. Other African nations can leverage existing maritime infrastructure to export derivative products such as green ammonia, further enhancing Africa's role in the global hydrogen economy [63].

2.2.6. Middle East region

The Middle East is rapidly emerging as a global hub for low-carbon hydrogen production, leveraging its abundant renewable resources, strategic export positioning, and substantial capital investment. As of 2025, countries such as Saudi Arabia, the United Arab Emirates (UAE), Oman, and Egypt have announced giga-scale projects aimed at producing green and blue hydrogen for both domestic use and international export. Saudi Arabia's NEOM Green Hydrogen Company is constructing a 4 GW renewable energy facility targeting 1.2 million tonnes per annum (Mtpa) of green ammonia by 2026, while the UAE's Masdar aims to produce 1 Mtpa of low-carbon hydrogen by 2030 [64,65]. As part of its Hydrom initiative, Oman has allocated land for projects aimed at achieving the 2030 target of producing up to 1.5 million tonnes of green hydrogen (gH2) per year (Mtpa) [66]. These developments are supported by regional roadmaps such as the World Economic Forum's "Enabling Measures for Low-Carbon Hydrogen in MENA," which identifies key policy enablers and infrastructure priorities [64]. The region's focus spans export-oriented strategies, decarbonization of existing industrial uses, and novel applications in green steel, sustainable aviation fuel, and maritime shipping. With over 23.5 Mtpa of hydrogen pipeline capacity planned across the Middle East and Africa1, the region is strategically positioned to supply Europe and Asia with competitively priced clean hydrogen, reinforcing its role in the global energy transition [67].

It can be inferred that there are clear regional differences in the development of hydrogen production, characterised by different project deployment and preferred technologies (Table 1). These differences are driven by factors such as resource availability, energy market structures, infrastructure maturity, policy incentives and national decarbonization priorities. In 2023, hydrogen production remains largely fossil, with 4687.3 kt of blue hydrogen from natural gas with carbon capture, compared to only 147.6 kt of green hydrogen from electrolysis with renewables (Fig. 5). North America and the Asia-Pacific region led the way in blue hydrogen production with over 2000 kt each, while the Middle East produced 621.9 kt, almost exclusively from non-renewable sources. In contrast, green hydrogen production was minimal in most regions, with Asia-Pacific leading the way with 93.6 kt, followed by Europe with 31.6 kt. Africa and South America produced negligible amounts of green hydrogen, highlighting the regional disparities in clean energy infrastructure [68]. The dominance of blue hydrogen reflects the continued dependence on existing natural gas networks and the cost advantages of fossil fuel production. However, this trend underscores the urgent need to accelerate investment in renewable energy and electrolyser deployment to meet decarbonization goals. Without a significant shift toward green hydrogen, the climate benefits of hydrogen as an energy carrier remain limited.

3. Environmental assessment of hydrogen

The integration of hydrogen into clean energy systems is accelerating, driven by its versatility and decarbonization potential. As its role expands, evaluating the environmental sustainability of both its production, utilization and storage becomes increasingly critical, particularly given the wide range of pathways from fossil-based to renewable sources. Green hydrogen, produced via electrolysis using renewable energy, offers the lowest environmental footprint. Storage and transportation, however, pose challenges due to hydrogen's low density and

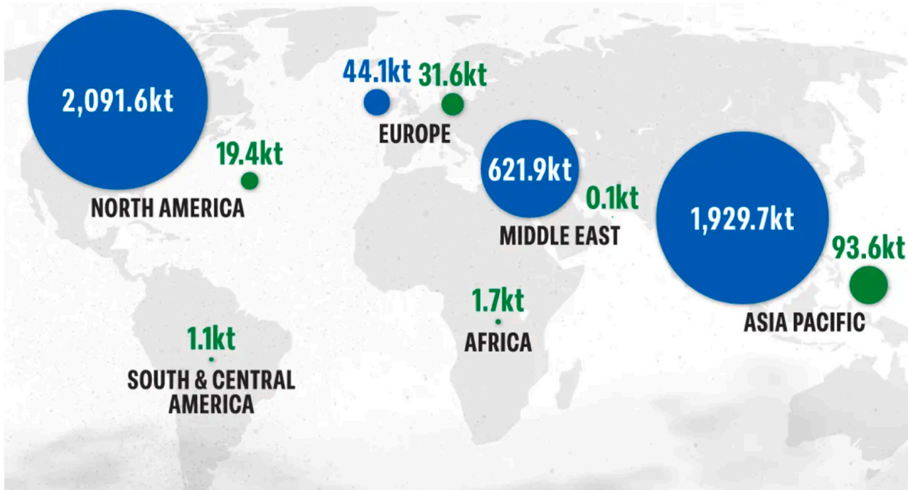

Fig. 5. Global hydrogen production by region in 2023 totalled approximately 4834.9 kilotons, comprising 4687.3 kt from blue hydrogen (SMR + CCUS) and 147.6 kt from green hydrogen (produced via electrolysis powered by RE). (1000 kt = 1 ton). Adapted from Ref. [68]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

high diffusivity. These stages can introduce energy losses and safety concerns, impacting overall sustainability. A holistic environmental analysis is essential to guide policy and investment in a hydrogen economy.

3.1. Life cycle assessment (LCA) of hydrogen production

The sustainability of hydrogen energy is influenced by substrate type, processing technology, energy source, and end-use. This sustainability is often assessed using tools like LCA and life cycle cost assessment (LCC) [97]. LCA evaluates the environmental impacts and resource usage throughout a product's lifecycle [98]. Its significance spans various aspects of hydrogen, from production and storage to applications, with a particular emphasis on fuel cell-based electric vehicles. This comprehensive view of environmental impacts enables stakeholders to make well-informed decisions [99]. Although hydrogen vehicles emit no pollutants during operation, their lifecycle emissions can exceed those of internal combustion vehicles, depending on the hydrogen production method, prompting extensive LCA research [100].

LCA offers detailed insights into how each stage of the hydrogen fuel cycle contributes to emissions [101]. The environmental impacts during hydrogen utilization largely depend on the application's efficiency and emissions. Identifying significant environmental impact stages allows LCA to develop strategies to mitigate these impacts, improve efficiency, and enhance hydrogen's overall sustainability as an energy source [102]. Furthermore, LCA can pinpoint key process steps where changes could significantly reduce environmental impacts [103]. This comprehensive approach prevents suboptimization by focusing on all processes, enabling the comparison of potential ecological impacts of different alternatives [104]. This information is crucial for creating strategies to enhance the sustainability of hydrogen as an energy source, ensuring it supports global efforts to combat climate change and reduce environmental degradation, particularly in its use in fuel cell-based vehicles.

To achieve timely decarbonization of the transport sector, evaluating the environmental performance of hydrogen-fuelled cell vehicles (HFCVs) through LCA is crucial. Candelaresi et al. [105] analysed the LCA profiles of hydrogen fuel cell electric vehicles (HFCEVs), hybrid electric vehicles, internal combustion engine cars, and vehicles using hydrogen mixed with natural gas or gasoline. Their results demonstrate that pure hydrogen vehicles are highly effective for achieving decarbonization. However, further development of more durable fuel cells, optimized engines, and improved hydrogen storage systems is necessary to enhance hydrogen vehicles' environmental and technical performance and support their broader adoption.

Wang et al. [106] observed that HFCEVs powered by hydrogen from coal gasification have slightly higher well-to-wheel (WTW) GHG emissions than gasoline internal combustion engine vehicles (ICEVs). Additionally, HFCEVs using grid electricity for on-site water electrolysis exhibit 2.3 times higher emissions than battery electric vehicles (BEVs) and 1.4 times higher than gasoline ICEVs. For gasoline internal combustion engine vehicles (ICEVs), the tank-to-wheel (TTW) phase is responsible for about 80 % of well-to-wheel (WTW) greenhouse gas emissions. In contrast, for hydrogen fuel cell electric vehicles (HFCEVs), 63–80 % of WTW GHG emissions are associated with the hydrogen production and transportation stages.

Nguyen et al. [107] compared the well-to-wheel (WTW) greenhouse gas (GHG) emissions of hydrogen fuel cell electric vehicles (HFCEVs), plug-in hybrid vehicles, battery electric vehicles (BEVs), and gasoline internal combustion engine vehicles (ICEVs). The found that wind energy-powered hydrogen fuel cell electric vehicles (HFCEVs) produced the lowest emissions, followed by those using biomass, natural gas, and those with carbon capture and storage (CCS). Wong et al. [108] determined that gasoline internal combustion engine vehicles (ICEVs) had 49.5 % lower well-to-tank (WTT) CO_2 emissions compared to hydrogen fuel cell electric vehicles (HFCEVs) using natural gas reforming. However, the WTT CO_2 emissions for gasoline ICEVs were 200 % higher than those for HFCEVs using renewable electricity for electrolysis. Well-to-wheel (WTW) CO_2 emissions for gasoline internal combustion engine vehicles (ICEVs) were found to be 3.37 to 20 times greater than those for hydrogen fuel cell electric vehicles (HFCEVs), depending on the specific hydrogen production method. A Chinese study found that HFCEVs using solar-powered electrolysis reduced CO_2 emissions by 76.4 % compared to steam reforming, while electrolysis with China's grid mix increased global warming potential by 158.3 % [109]. Liu et al. [110] discovered that heavy-duty trucks fuelled by hydrogen produced via renewable energy sources (such as solar and wind) and steam methane reforming had lower greenhouse gas emissions per kilometre than diesel trucks. In contrast, trucks running on hydrogen from grid electricity and coal gasification exhibited substantially higher emissions.

Elsewhere, Colella et al. [111] conducted an LCA to compare the greenhouse gas emissions and energy consumption of hydrogen fuel cell vehicles (FCVs) and gasoline-powered vehicles. The study considered hydrogen production via steam methane reforming, coal gasification, and water electrolysis. The results indicated that transitioning to a hydrogen FCV fleet would substantially reduce air pollutant emissions. The life cycle emissions of internal combustion engines, fuel cells, and electric vehicles in China were assessed by Yang et al. [112]. Their findings indicated that fuel cell vehicles using hydrogen from electrolysis powered by abandoned hydropower and coke oven gas outperformed other options in terms of greenhouse gas emissions and energy consumption, particularly beyond 75,000 km. This highlights the importance of selecting the appropriate vehicle and fuel scenario for optimal sustainability. Joseck et al. [113] examined the well-to-wheel (WTW) emissions of hydrogen fuel cell hybrid electric vehicles (HFCHEVs) utilizing hydrogen sourced from coke oven gas (COG) and compared them with HFCHEVs using hydrogen derived from natural gas with carbon capture and storage (CCS), as well as gasoline and diesel vehicles. Their analysis revealed that HFCHEVs powered by hydrogen from COG produced the lowest emissions at 0.08 gCO2/mi. This was followed by HFCHEVs using hydrogen from CCS at 12 gCO_2/mi, natural gas at 26 gCO_2/mi, diesel hybrids at 29 gCO_2/mi, gasoline hybrids at 34 gCO_2/mi, and gasoline vehicles at 47 gCO_2/mi. Table 2 shows the emission overview of hydrogen production and consumption in 2023, highlighting different aspects contributing to the emission.

3.1.1. Limitations and gaps in current LCA studies on hydrogen production

Despite the increasing number of research papers applying LCA to hydrogen production and utilization systems, there are still several methodological limitations and inconsistencies in the literature that can affect the comparability and reliability of the results of different studies. One of the most notable limitations is the lack of uniformity of system boundaries and functional units, which significantly affects the interpretation of results. For example, while some studies use a "well-to-wheel" (WTW) boundary that includes fuel production, distribution, and vehicle operation [106–108], other studies use a narrower scope (e.g., "well-to-tank" or "tank-to-wheel"), which limits holistic environmental comparisons across all fuel pathways [115].

The variability of the data is another major limitation. Many LCA models rely on regional or outdated data sets that may not accurately reflect current technologies or geographic conditions. For example, the carbon intensity of grid electricity used for hydrogen production by electrolysis varies significantly by country and even by region, leading to significant uncertainties in the results [101,116–118]. In addition, LCA inputs such as emission factors for hydrogen production, especially for new or site-specific technologies such as biomass gasification or solar-powered electrolysis, often have insufficient or inconsistent primary data, leading to high sensitivity of results [119,120]. Geographical and temporal inconsistencies also impair comparability. Most LCA studies are context-specific and reflect localized energy mixes, transport infrastructures, and policy scenarios. However, this context dependency makes generalization and benchmarking difficult. For example, while electrolysis using surplus hydropower in Canada shows excellent performance [101], similar plants may not be feasible in regions without abundant renewable energy, limiting the reproducibility of results worldwide [118,121]. In addition, the methodologies used to allocate by-products used in hydrogen production, especially in multi-output processes such as methane steam reforming (SMR) with carbon capture or biomass gasification, often vary between energy-based, mass-based, or economic allocation approaches, contributing to different LCA results [113,116]. This methodological heterogeneity limits the harmonisation of results from different studies and makes it difficult to conduct robust meta-analyses.

Another limitation is that some assessments do not consider infrastructure-related impacts. Several studies focus exclusively on operational emissions and disregard the life cycle impacts associated with the construction of hydrogen refuelling stations, pipelines, or electrolysis units, which can be significant, especially in the early stages of deployment [101,122]. Furthermore, temporal dynamics and technological learning curves are rarely considered in LCA models. Most assessments assume static efficiencies and emission factors, although hydrogen technologies, especially electrolysers, storage systems, and fuel cells, are developing rapidly. Ignoring these advances can lead to outdated or pessimistic estimates of environmental impacts [117,119,122]. Finally, water consumption and land use change, although recognized as critical sustainability metrics, are often under-reported or assessed only qualitatively. However, they are of crucial importance for the assessment of hydrogen production through water electrolysis or biomass-based pathways, especially in water-scarce or land-constrained regions [116,118].

Although life cycle assessment (LCA) is a powerful tool for assessing the environmental impacts of hydrogen production and use, these gaps highlight the need for standardized LCA frameworks, regionally adapted data inputs, and transparent methodological reporting to improve the robustness and policy relevance of LCA in hydrogen research. Addressing these limitations requires improved and harmonised data collection with transparent reporting of assumptions and uncertainties, the inclusion of regional specificities through adaptable LCA frameworks, the inclusion of new technologies and comprehensive system boundaries, and the development of standardized protocols for hydrogen LCA. Future work should also emphasise dynamic LCA modelling, integration with techno-economic assessments (TEA), and the inclusion of wider social and environmental indicators such as water stress, land use, and resource depletion to support informed decision making for large-scale hydrogen deployment. Such advances will improve the robustness and applicability of LCAs and thus support more informed decisions on the role of hydrogen in the sustainable energy transition.

Table 2

Aspect	Details
Total Emissions (2023)	920 Mt CO_2 globally from hydrogen production
Production Sources	~ 66 % from unabated natural gas (10–12 kg CO_2-eq/kg H_2) ~ 20 % from unabated coal (22–26 kg CO_2-eq/kg H_2)
Emission Location	75–95 % of emissions occur at the point of production
Carbon Capture Potential	CCUS can reduce emissions at source Abatement costs (natural gas SMR): ↳ USD 60–85/t CO_2 (55–70 % capture) ↳ USD 85–110/t CO_2 (>90 % capture)
Electrolytic Hydrogen	- Emissions-free at production point - Depends on electricity emissions intensity: ↳ Must be < 200–240 g CO_2/kWh to be better than SMR ↳ Embedded emissions (construction, etc.): 0.4–2.7 kg CO_2-eq/kg H_2
Losses due to conversion to Transport carrier	- Energy loss: 45–70 % during carrier conversion - Emissions multiply by 2–3 times if grid electricity is used - Lowest emissions: Liquid hydrogen (efficiency >50 %)
Hydrogen-Derived Fuels	- CO_2 source should be biogenic or from air - Electricity intensity thresholds for lower emissions: ↳ Synthetic methanol: <160–190 g CO_2/kWh ↳ Synthetic methane/kerosene: <95–140 g CO_2/kWh
Accounting Considerations	- Emissions depend on how CO_2 is allocated across supply chain steps, especially in combustion

3.2. Environmental assessment of hydrogen utilization

Hydrogen's distinctive physical and chemical characteristics make it ideal for energy storage, transportation, and utilization, although its high flammability poses considerable fire and explosion risks [123]. Currently, hydrogen is mainly produced from fossil fuels through processes such as coal gasification and natural gas steam reforming [124]. However, future demand is expected to be met by low-carbon alternatives like water electrolysis powered by low-carbon electricity, biomass gasification, and fossil fuels combined with carbon capture and storage. Hydrogen finds applications in steel production, biofuel processing, oil sands enhancement, high-temperature processes, welding, hydrogenation, superconductivity, and rocket engines [102]. More recently, hydrogen is being utilized in fuel cells for electricity generation, in combustion engines for transportation, and as a feedstock in industrial processes [100]. The anticipated growth of fuel cell vehicles (FCVs) is expected to boost hydrogen demand and accelerate the industry's development.

However, the widespread adoption of hydrogen technologies necessitates a comprehensive environmental assessment to evaluate potential impacts on ecosystems, water resources, and air quality. Current assessments of conventional hydrogen technologies often fail to account for hydrogen emissions and their immediate warming effects, which occur because the atmospheric oxidation of hydrogen raises the levels of other short-lived greenhouse gases like methane, stratospheric water vapor, and tropospheric ozone [125]. While FCVs are promoted as a crucial solution for reducing pollutant emissions in road transport and energy consumption, their overall greenhouse gas (GHG) emissions can be higher than conventional vehicles if the hydrogen generation pathways are not sufficiently clean [116]. Major considerations encompass life cycle assessment (LCA), greenhouse gas emissions, impacts on air quality, water and land utilization, efficient use of energy, effects on biodiversity, and waste generation. By evaluating these factors, it is possible to identify the most sustainable production methods, optimize the environmental benefits of hydrogen, and mitigate potential negative impacts.

This holistic approach ensures that the transition to hydrogen energy contributes to broader environmental goals, such as reducing global warming, improving air quality, and conserving natural resources. Additionally, the ecological evaluation process guarantees that projects are environmentally viable by promoting comprehensive planning and design, enhancing environmental protection, improving government coordination and accountability, and easing the processes of permitting and regulatory approval.

Table 3 compares various hydrogen production methods for fuel cell electric vehicles (FCEVs), focusing on critical environmental metrics such as greenhouse gas (GHG) emissions, energy consumption, and water usage. The assessment is based on a Well-to-Wheel (WTW) analysis of both energy use and GHG emissions using the GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies), developed by Argonne National Laboratory. The GREET model is a widely recognized tool for modelling the full life cycle impacts of transportation fuels and technologies [126]. The analysis indicates that hydrogen produced through electrolysis using renewable energy sources has the lowest GHG emissions, making it the most environmentally friendly option. Conversely, hydrogen generation from non-renewable energy sources, whether through coal-powered electrolysis or steam methane reforming (SMR), is less sustainable due to higher emissions and energy consumption. Hydrogen consumption in vehicles results only in water vapor as a byproduct, enabling zero CO_2 emissions during driving. The entire lifecycle can achieve very low carbon emissions when hydrogen is entirely sourced from renewable energy like wind, solar, or biomass [127,128].

To better understand the trade-offs and synergies among key life cycle metrics for various hydrogen production pathways, a radar plot (Fig. 6) was developed using normalized data for greenhouse gas (GHG) emissions, energy intensity, and water consumption. This multi-metric visualization offers a clear comparative perspective across the eight hydrogen pathways presented in Table 3, standardizing values on a 0–5 scale relative to the highest observed value within each metric.

The radar plot reveals that electrolysis using coal-dominated grid electricity exhibits the widest environmental footprint, characterized by extremely high GHG emissions (normalized to 5.0), despite low water usage [116]. This finding reinforces concerns raised in prior literature regarding the environmental inefficiency of hydrogen derived from fossil-intensive electricity grids, where thermal power still dominates the energy mix [117]. Thus, deploying electrolysis without decarbonizing the electricity sector undermines the climate benefits of hydrogen. In contrast, methanol steam reforming and steam methane reforming (SMR) using pipeline methane display more compact profiles, suggesting a lower cumulative burden across all three impact categories [116]. Methanol reforming demonstrated the lowest energy intensity (0.23 MJ/MJ H_2) and GHG emissions (23.17 g CO_2-eq/MJ) among all evaluated pathways. However, its performance is highly dependent on the sustainability of upstream methanol feedstock, which must be sourced renewably to maintain these advantages.

Biomass gasification and biogas reforming offer favourable GHG profiles but incur higher energy consumption, with normalized values approaching or exceeding 3.0. This highlights the thermochemical complexity and lower conversion efficiencies typically associated with solid biomass feedstocks [118]. Notably, biogas reforming outperforms biomass gasification in both energy and water metrics, supporting its viability as a near-term renewable hydrogen source with fewer process penalties [118]. Catalytic ammonia decomposition, though increasingly recognized for its potential in long-distance hydrogen storage and transport, exhibits a distinct environmental trade-off: it ranks among the lowest in energy intensity but shows the highest water use (8.34 L/km), likely due to intensive process cooling and ammonia handling requirements [116]. This highlights the need to couple ammonia cracking with low-carbon ammonia synthesis and water-recycling strategies to mitigate its environmental load.

The radar plot emphasises the critical role of the electricity source in shaping the sustainability of hydrogen. Photovoltaic or hydropower-based electrolysis, though not explicitly separated in this dataset, has consistently shown in prior studies to offer substantially reduced GHG emissions when compared to fossil-based pathways [101,119]. From a system optimization perspective, pathways located closer to the centre of the radar plot represent more balanced environmental performance, while those extending along one or more axes indicate trade-offs that may require mitigation through policy, technology improvements, or supply chain decarbonization. Such visual tools are thus invaluable for informing multi-criteria decision-making in hydrogen strategy development, particularly as countries aim to align their hydrogen roadmaps with both climate and resource conservation goals.

3.3. Safety and environmental impact of hydrogen handling

The flammability and ignition properties of hydrogen pose a significant safety and environmental risk during storage, transport and use. Its exceptionally wide flammability range in air (4–75 by volume) and extremely low minimum ignition energy (~0.017 mJ) make it highly susceptible to ignition by static discharge or small electrical sparks [132,133]. In contrast to methane or petrol vapours, hydrogen flames emit only limited radiant heat (17–25 %) and are almost invisible in daylight, which makes fire detection considerably more difficult and increases the probability of undetected combustion (Table 4). The high flame speed (2.88 m/s) and high auto-ignition temperature (~585 °C) allow the flame to spread rapidly after ignition, especially in enclosed or poorly ventilated spaces, where the risk of deflagration and detonation is increased [133–135]. Compared to methane (5–17 vol% flammability range, 0.28 mJ ignition energy) and gasoline vapours (1.4–7.6 vol%, ~0.24 mJ), the ignition sensitivity and detonation potential of hydrogen (0.8 g tetryl equivalent) require enhanced engineering controls, including flame sensors, optical detection systems, antistatic protocols and advanced ventilation strategies to protect both personnel and surrounding ecosystems.

The dangers associated with storage add to the complexity of hydrogen. Compressed gaseous hydrogen (CGH_2) is typically stored at pressures of up to 700 bar, which requires reinforced containment vessels with multi-layered composite structures and active pressure relief systems [136]. If these containers are damaged, due to the low density of hydrogen (~0.0827 kg/m^3) and high sonic speed (~1294 m/s), large volumes of gas can be released with high jet impulse, leading to rapid volumetric dispersion and overpressure scenarios. Liquid hydrogen

Table 3
Comparison of Life Cycle Assessment (LCA) of hydrogen utilization in Fuel Cell Electric Vehicles (FCEVs).

Hydrogen Production Method	Energy Source	GHG Emissions	Energy Consumption	Water Usage	Key Findings	Ref
SMR	Natural Gas	52.91–81.77 g CO_2 e/MJ H_2 (15 %–45 % lower than gasoline ICEV)	0.87–1.24 MJ/MJ H_2 (5 %–33 % lower than gasoline ICEV)	–	• HFCEVs have lower WTW GHG emissions and fossil energy use than gasoline ICEVs, even when hydrogen is produced via fossil-based SMR. • Emissions from HFCEVs are influenced by the electricity source used for hydrogen compression or liquefaction, affecting overall environmental performance.	[129]
SMR	Natural Gas	48.10 g CO_2 e/MJ H_2 (50 % of ICEV)	0.65 MJ/MJ H_2 (50 % of ICEV)	–	• Coal-based electrolysis produces the highest GHG emissions and energy consumption among hydrogen production methods. • Electrolysis powered by nuclear energy and natural gas reforming have similar energy demands. • Nuclear-powered electrolysis results in significantly lower emissions compared to natural gas reforming. • Minimizing coal-based hydrogen production is essential for hydrogen to be a sustainable primary transport fuel	[117]
Electrolysis	Coal	144.30 g CO_2 e/MJ H_2 (50 % higher than ICEV)	1.55 MJ/MJ H_2 (19 % higher than ICEV)	–		
Electrolysis	Nuclear power	12.51 g CO_2 e/MJ H_2 (87 % lower than ICEV)	0.65 MJ/MJ H_2 (50 % lower than ICEV)	–		
SMR	Natural Gas	117.10 g CO_2 e/MJ H_2	20.10 MJ/km H_2 (~10.5 MJ/MJ H_2)	0.86 L/km	• Hydrogen from biomass gasification accounts for ~88 % of the total life cycle energy load. • Hydrogen from the steam reforming of maize silage biogas contributes ~83 % of the total energy load. • Both pathways highlight the energy-intensive nature of hydrogen production for bus applications. • Biogas reforming is approximately 32 % less energy demanding than solid biomass gasification among renewable hydrogen production methods.	[118]
Biomass Gasification	Biomass	43.90 g CO_2 e/MJ H_2	34.50 MJ/km H_2 (~17.9 MJ/MJ H_2)	4.50 L/km		
Water Electrolysis	Grid electricity, Argentina	201.90 g CO_2 e/MJ H_2	19.60 MJ/km H_2 (~10.2 MJ/MJ H_2)	1.04 L/km		
Biogas Reforming	Biogas	51.50 g CO_2 e/MJ H_2	23.50 MJ/km H_2 (~12.2 MJ/MJ H_2)	0.92 L/km		
Water Electrolysis	Grid electricity (comprises 88 % hydroelectric power, 11 % thermal power, and 1 % other renewable power plants)	26.94 g CO_2 e/MJ H_2 (72 % reduction compared to gasoline ICEV)	1.57 MJ/MJ H_2 (21 % higher than gasoline ICEV)	–	• 72 % reduction in total GHG emissions when switching from gasoline vehicles to HFCVs. • 21 % increase in life cycle energy use for HFCVs, mainly due to energy-intensive hydrogen production, distribution, dispensing, and vehicle material requirements.	[101]
Methanol Steam Reforming	Methanol	2780 kg CO_2-eq/1000 Nm^3 H_2 (~23.17 g CO_2-eq/MJ H_2)	27900 MJ/1000 Nm^3 H_2 (~0.2325 MJ/MJ H_2	30 tonnes/1000 Nm^3 H_2 (~3.34 L/km	• Electrolysis has the highest environmental impact among the four common hydrogen production methods in China. • Methanol steam reforming shows the lowest environmental impact, at only 2.24 % of that of electrolysis. • Electrolysis causes a significantly greater global warming impact, mainly due to China's coal-dominated power grid. • Even with a reduced thermal power share (from 71.6 % to 41.6 %), electrolysis still exhibits higher environmental burdens than other methods. • Electrolysis has the highest fossil energy consumption among the hydrogen production methods studied (44.4 times more than methanol steam reforming, 3.2 times more than steam methane reforming, and 3.5 times more than catalytic ammonia decomposition) • Without major breakthroughs in upstream energy sources or technology, electrolysis is unlikely to be a sustainable first choice for hydrogen production in China.	[116]
SMR	Methane	4580 kg CO_2-eq/1000 Nm^3 H_2 (~38.17 g CO_2-eq/MJ H_2)	385000 MJ/1000 Nm^3 H_2 (~3.21 MJ/MJ H_2)	28.67 tonnes/1000 Nm^3 H_2 (~3.19 L/km		
Electrolysis	Grid electricity (China coal-heavy grid)	124000 kg CO_2-eq/1000 Nm^3 H_2 (~1033.33 g CO_2-eq/MJ H_2)	1240000 MJ/1000 Nm^3 H_2 (~10.33 MJ/MJ H_2	820 kg/1000 Nm^3 H_2 (~0.091 L/km		
Catalytic Ammonia Decomposition	Ammonia	36600 kg CO_2-eq/1000 Nm^3 H_2 (~305 g CO_2-eq/MJ H_2)	352000 MJ/1000 Nm^3 H_2 (~2.93 MJ/MJ H_2)	75 tonnes/1000 Nm^3 H_2 (~8.34 L/km		
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Natural gas	132 kg CO_2/GJ (132 g CO_2-eq/MJ H_2)	770 MJ/GJ H_2 (0.77 MJ/MJ H_2)	–	• Hydrogen fuel cycle results in higher energy consumption and GHG emissions compared to the gasoline fuel cycle.	[122]

(continued on next page)

Table 3 (*continued*)

Hydrogen Production Method	Energy Source	GHG Emissions	Energy Consumption	Water Usage	Key Findings	Ref
Electrolysis	Hydropower and Nuclear power	61–130 g CO_2-eq/km (50.83–108.33 g CO_2-eq/MJ H_2)	0.48–0.94 MJ/MJ H_2	–	• During the vehicle operation phase, ICEVs have higher energy consumption and GHG emissions than PEMFC. • Hydropower- and nuclear-based hydrogen pathways show the lowest energy consumption, approximately 0.48–0.94 MJ/MJ H_2. • Natural gas, coal, and grid-based hydrogen pathways do not offer energy or emission advantages over direct fossil fuel use. • FCVs using grid power-based hydrogen exhibit 2–3 times higher life-cycle GHG emissions than ICEVs.	[121]
Electrolysis	Natural gas, Coal and Grid power	187–235 g CO_2-eq/km (155.83–195.83 g CO_2-eq/MJ H_2)	–	–		
SMR	Natural Gas	0.15 kg CO_2-eq/km (~125 g CO_2-eq/MJ H_2)	2.5 MJ/km (~2.08 MJ/MJ H_2)	–	• Hydrogen fuel from SMR plays a dominant role in overall environmental and energy impacts. • Renewable hydrogen (from biomass gasification and wind electrolysis) contributes less significantly to the system's footprint. • SMR-based hydrogen has the highest energy footprint among the options evaluated. • Renewable hydrogen sources demonstrate a lower energy and carbon footprint, highlighting their importance in sustainable energy systems. • Substituting SMR hydrogen with renewable hydrogen is crucial for achieving low-carbon, low-energy hydrogen systems.	[120]
Biomass Gasification	Biomass	0.06 kg CO_2-eq/km (~50 g CO_2-eq/MJ H_2)	1.1 MJ/km (~0.917 MJ/MJ H_2)	–		
Electrolysis	Wind Power	0.065 kg CO_2-eq/km (~54.17 g CO_2-eq/MJ H_2)	0.9 MJ/km (~0.75 MJ/MJ H_2)	–		
Steam Reforming	Natural Gas	15 kg CO_2-eq/kg H_2 (~125 g CO_2-eq/MJ H_2)	93 MJ/kg H_2 (~0.775 MJ/MJ H_2)	–	• Grid electricity-based water electrolysis for hydrogen production has the highest energy consumption and produces the largest GHG emissions among the three pathways. • PV electrolysis for hydrogen production has the lowest total energy consumption and generates the least GHG emissions.	[119]
Water Electrolysis	Grid Electricity	40 kg CO_2-eq/kg H_2 (~333 g CO_2-eq/MJ H_2)	359 MJ/kg H_2 (~2.99 MJ/MJ H_2)	–		
Water Electrolysis	Photovoltaic (PV) Electricity	0.2 kg CO_2-eq/kg H_2 (~1.67 g CO_2-eq/MJ H_2)	70 MJ/kg H_2 (~0.583 MJ/MJ H_2)	–		

WTW GHG Emission for gasoline = 96.2 g CO_2 e/MJ H_2 [126,130]; WTW energy use for gasoline = 1.3 MJ/MJ H_2 [130,131], (MJ/MJ H_2 ≈ 0.52*MJ/km H_2).

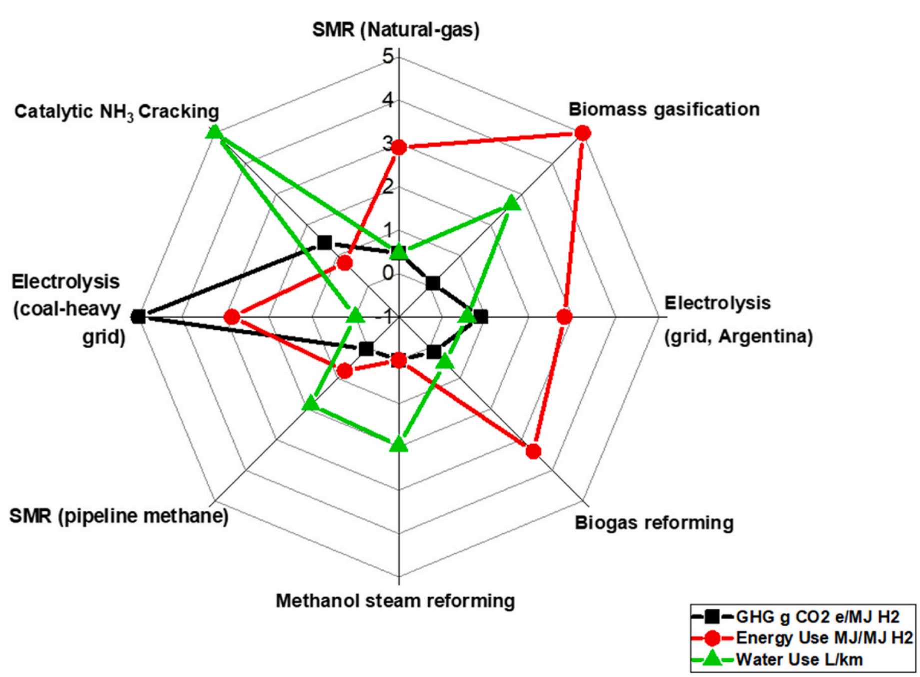

Fig. 6. Radar chart comparing the life cycle assessment (LCA) metrics of key hydrogen production pathways.

Table 4
Safety properties of hydrogen, methane, and gasoline: *a comparative analysis*

Properties	H_2	CH_4 (LNG)	Gasoline	Implications for Safety and Handling
Gas density at NTP (kg/m^3)	0.0827	0.659	~3.2	Hydrogen rises rapidly; gasoline vapours sink and pool, increasing fire risk near ground.
Flammability range (25 °C, 101.3 KPa) (vol%)	4–75	5–17	1.4–7.6	Hydrogen has an extremely wide flammability range, leaks are more easily ignitable.
Autoignition temperature (°C)	~585	~537	~280	Gasoline ignites easily near hot surfaces; hydrogen needs higher temperature but ignites more readily due to low energy threshold.
Amount of energy, heat of combustion (lower heating value, LHV) (kJ/g)	120	50	~44	Under identical conditions of pressure and nozzle size, hydrogen releases approximately 85 % of the discharge energy (per gram) compared to methane during high-pressure gas outflow.
Minimum ignition Energy (mJ)	~0.017	~0.28	~0.24	Hydrogen is extremely sensitive to sparks and static discharge compared to methane and gasoline
Boiling Point (°C)	−253	−161	38–204	Hydrogen demands cryogenic conditions, raising complexity and material risks; gasoline is volatile at ambient temperatures.
Maximum burning Velocity in NTP air (cm/s)	~265–325	~37–45	~35–45	Hydrogen's fast flame speed raises explosion severity in confined environments.
Adiabatic flame temperature (^{o}C)	2045	1875	2045K	Hydrogen flames can be hotter
Speed of sound at NTP (m/s)	1294	446	446	Hydrogen's low density and high sound speed increase leak volume but result in similar jet momentum to methane at equal pressure and nozzle size.
Laminar diffusion coefficient at NTP (cm^2/s)	0.16	0.16	0.05–0.2	Dispersion is mainly driven by turbulence; hydrogen's flow speed and low density are more critical, leading to extended momentum jets.
Detonability measured in minimum mass of tetryl (%)	0.8	16000	50	Hydrogen's easily denotable in confined mixtures demands stringent leak detection and ventilation controls.
Radiant heat from flame to surroundings (%)	17–25	23–33	35–40	Hydrogen fires may go unnoticed without proper sensors; gasoline flames radiate intensely.
Compressibility factor Z average 0 to 300 barg	0.1 Jan	0.9	–	Non-ideal gas effects slightly lower the hydrogen mass leak rate compared to ideal gas predictions, with the discrepancy increasing at higher pressures.
Joule-Thomson effect when pressure is relieved	Causes a small temperature increase	Causes a temperature decrease	Causes a temperature decrease	Hydrogen's minimal temperature rise during filling has little effect. However, heat buildup in compressed hydrogen (CH_2) tanks limits filling speed, especially during bunkering.

Values for H_2 an CH_4: adapted from Ref. [135]. Gasoline values: adapted from Refs. [138–150] respectively.

(LH_2) held at cryogenic temperatures (−253 °C) has an extreme phase change expansion ratio of approximately 1:848, which poses a serious over-pressurisation risk in the event of boil-off events or venting errors [137],. Improper venting can lead to container rupture and the uncontrolled release of hydrogen clouds, which can displace ambient oxygen and cause asphyxiation hazards. Material degradation due to hydrogen embrittlement, particularly in metal storage systems, further increases the risk of leakage and structural failure, necessitating the use of hydrogen-compatible alloys and long-term integrity monitoring [133].

In contrast, methane and gasoline have different but similarly serious safety profiles. The higher ignition energy and narrower flammability range of methane reduce the risk of spontaneous combustion, but the spread of methane is heavier than air and increases the formation of pools near the ground and the persistence of flammable clouds. Gasoline vapours with high radiant heat output (33–42 %) and low auto-ignition temperature (~280 °C) are particularly susceptible to ignition near hot surfaces and open flames. These safety differences highlight the unique challenges of hydrogen and the need for specialised infrastructure, monitoring technologies and regulatory frameworks to effectively mitigate the risks.

3.4. Environmental impact assessment of hydrogen storage and transportation

Hydrogen storage technologies span physical, chemical and geological domains, each with different trade-offs in terms of performance,

Table 5
Environmental implications of different hydrogen storage methods.

Storage method	Key features	Application area	Technical/safety challenges	Environmental implications	Ref.
Compressed Gas (CGH_2)	Hydrogen stored at 350–700 bar in high-strength pressure vessels	Cylinders, mobile/stationary systems, aircraft, fuel cell vehicles	Low volumetric density, energy-intensive compression, safety risks (leaks/explosions)	Moderate lifecycle emissions due to energy use; recyclable vessel materials	[151,157]
Liquid Hydrogen (LH_2)	Stored at −253 °C in cryogenic tanks	Space propulsion, long-distance transport, aerospace	High energy demand for liquefaction, boil-off losses, complex insulation	Significant energy input; potential for GHG emissions if powered by non-renewables	[151,152]
Cryo-compressed (CcH_2)	Combines high pressure and cryogenic temperature	Heavy-duty vehicles, fuel cell buses, backup power, stationary storage	Thermal management during filling, boil-off, material integrity, denotation	Lower boil-off than LH_2; still energy-intensive	[151,158]
Metal Hydrides	Hydrogen absorbed into metal lattices (e.g., Mg-based alloys)	Submarines, rail/marine transport, portable devices, home energy systems	Heavy system weight, slow kinetics, degradation over cycles	Safer storage, mining and disposal of metals pose environmental concerns	[151,159]
Chemical Carriers	Hydrogen stored in compounds (e.g., ammonia borane, LOHCs)	Long-range shipping, ammonia-based fuel systems, LOHCs for stationary/mobile use	Irreversible reactions, regeneration complexity, catalyst needs	Potential toxicity, handling risks, and recycling challenges	[151,160]
Solid-State H_2 Storage (SSHS)	Hydrogen adsorbed on nanomaterials (e.g., MOFs, graphene)	Small-scale transport, FCVs, portable electronics, stationary systems	Low uptake at ambient conditions, costly synthesis, energy intensive, immature technology, high temp.	Low emissions, material production may involve hazardous chemicals	[151,155]
Underground Storage (UGS)	Hydrogen stored in salt caverns or porous formations	Seasonal grid storage, large-scale energy buffering	Geological integrity, microbial conversion, leakage risks, site selection	Minimal surface footprint; potential subsurface contamination	[151,156]

safety and environmental impact (Table 5). Compressed gas systems offer ease of operation and rapid refuelling but are limited by low volumetric energy density and high energy requirements for pressurisation. Liquid hydrogen (LH_2) achieves a higher storage density and is well suited for aerospace and long-range applications. However, its dependence on cryogenic infrastructure and susceptibility to boil-off losses limit its feasibility for decentralised energy systems. Cryo-compressed hydrogen represents a bridge between these approaches and seeks to combine high pressure and low temperatures to increase density [151,152]. In contrast, metal hydrides and chemical carriers offer compact and inherently safer alternatives, especially for stationary applications [151,153,154]. However, their benefits are offset by issues such as the large mass of the system, slow kinetics and the challenges of material regeneration and reversibility. Emerging solid-state adsorption methods including those based on organometallic frameworks and nanostructured materials offer high gravimetric densities and pressureless storage with favourable safety profiles, but require breakthroughs in ambient temperature uptake and cost-effective synthesis for scalability [151,152,155].

Underground hydrogen storage (UHS) in salt caverns or porous geological formations promises a large and seasonal capacity with minimal above-ground space requirements. However, long-term success depends on overcoming the challenges associated with geological integrity, hydrogen loss through microbial transformation and geochemical interactions that can compromise containment [151,152,156]. From an environmental perspective, the life cycle emissions and resource requirements of each method are primarily determined by the energy source used for compression, liquefaction or chemical conversion. Material-based options may entail risks associated with mining, processing and end-of-life disposal, while underground storage requires rigorous geotechnical assessment to prevent subsurface contamination. The choice of an optimal hydrogen storage strategy therefore depends on balancing energy performance, safety criteria, infrastructure compatibility and environmental responsibility.

3.4.1. LCA of hydrogen storage and transportation

The hydrogen produced is subsequently stored and distributed to various end-use sites, including industrial facilities, fuelling stations, and other demand centres. Various hydrogen storage and transportation methods have been investigated, with LCA typically concentrating on the most widely adopted pathways. These include.

- storage and pipeline transport of compressed hydrogen gas,
- storage and over-the-road transport of gaseous hydrogen using tube trailers,
- road transport of liquid hydrogen via cryogenic tankers, and
- rail transport of liquid hydrogen.

To conduct the LCA, several key assumptions were made concerning the storage and transport of hydrogen in its gaseous and liquid forms [161]. For gaseous hydrogen storage, it was assumed that the hydrogen is stored in subterranean salt caverns, involving only compression and drying stages. In the case of gaseous hydrogen transport via pipelines, it was assumed that additional compression is required to achieve a delivery pressure of 100 bar. Specifically, electricity consumption for compressing hydrogen from 30 to 100 bar is estimated at 1.05 kWh/kg H_2 [162], or 0.48 kWh/kg H_2 when compressing from 50 to 100 bar [163], based on pipeline distances of 100 km. For extended pipeline transport, recompression is necessary at defined intervals to maintain pressure. If recompression is performed every 250 km, the energy consumption increases to 0.6 kWh/kg H_2 [164]; for recompression every 100 km, the requirement is reduced to approximately 0.02 kWh/kg H_2 [165]. In the case of tube trailer transport, hydrogen must be compressed to pressures ranging between 200 and 500 bar, with an associated energy consumption of approximately 1.36 kWh/kg H_2 [162]. Trailers are assumed to transport up to 1100 kg of hydrogen and are powered by EUR6 diesel-fuelled trucks with a total carrying capacity of 32 tonnes [164]. For the distribution of liquid hydrogen, transport by both road and rail was considered. Hydrogen is first compressed and then liquefied to −253 °C. Liquefaction requirements for both transport methods were assumed to be equivalent, with rail transport consuming 1.1 kWh/km [166]. Cryogenic tanks are employed, with road tankers capable of carrying 4200 kg of liquid hydrogen and rail wagons up to 8000 kg [137]. Across all four scenarios (Table 6), a uniform hydrogen loss rate of 4 % was incorporated to reflect typical operational losses [167].

The transportation and storage calculations were conducted using a functional unit of 1 tonne of hydrogen transported over 100 km. In the analysis, the COP26 and EU27 electricity scenarios [168,169], were selected, representing the lowest and highest environmental impacts respectively. The storage and transport options were assessed based on their greenhouse gas emissions, energy consumption and impacts in terms of acidification, eutrophication and human toxicity. Each storage and transport pathway were evaluated against a comprehensive set of environmental impact indicators, including greenhouse gas (GHG) emissions, cumulative energy demand, acidification potential, eutrophication potential, and human toxicity potential. The key outcomes of this assessment are summarized in Table 6 (adapted and modified from Ref. [161]), offering a comparative insight into the environmental implications of different hydrogen logistics configurations under varying energy supply conditions.

The findings reveal that the pipeline-based transportation of gaseous hydrogen presents the lowest environmental burden among the assessed storage and transport pathways, particularly when the COP26 electricity mix is applied. This outcome aligns with prior studies such as that by Akhtar et al. [164], which identified pipeline transport as having the lowest greenhouse gas (GHG) emissions and environmental impact potentials. Similarly, Wang et al. [170] reported emission and cost advantages of pipeline transport, exceeding 50 % reduction compared to rail and barge - albeit in the context of oil logistics. However, under the EU27 electricity scenario, the environmental impacts rise markedly due to the mix's reliance on fossil fuels for electricity generation. Electricity-intensive processes, notably hydrogen compression and liquefaction, significantly contribute to the environmental footprint. Transporting hydrogen via pipelines (compressed to 100 bar), high-pressure storage tanks (up to 500 bar), or in liquefied form (at 700 bar) all require considerable energy input, with environmental burdens escalating with increasing compression levels. Liquefied hydrogen transport demonstrates the highest environmental impact due to the substantial energy demand of the liquefaction process. Among liquid hydrogen delivery options, road transport has a slightly greater impact than rail, attributed to diesel-fuelled trucks versus electrically powered trains, which offer greater energy efficiency per unit of transport. Rail thus emerges as a more sustainable option, even over relatively short distances such as 100 km. Future research should prioritize optimizing hydrogen logistics through energy-efficient transport solutions, supported by advanced modelling tools, to address the sector's significant contribution to climate change as highlighted by Lee et al. [171].

3.4.2. Comparative analysis of the environmental impacts of hydrogen production, storage, and transport

To assess the effect of electricity gen1eeeration sources on the environmental performance of different hydrogen production processes, the analysis considered several electricity supply options, each characterised by different environmental trade-offs [161]. Four electricity supply scenarios were analysed: the average Slovenian electricity mix, the average EU27 electricity mix [168], the Slovenian electricity mix aligned with the Glasgow COP26 guidelines in 2021 [169] and a scenario using 100 % biomass-based electricity. The biomass scenario, which includes only renewable fuels, was considered due to the extensive forest coverage in countries such as Finland (73.7 %), Sweden (68.7 %), Japan (68.4 %) and South Korea (64.5 %) [172]. However, recent

Table 6
Footprint and potential environmental results for the storage and transportation alternatives. Adapted and modified from Ref. [119].

	Liquid-rail	Liquid-road	Gas-road	Gas-pipeline	Unit
Energy footprint	3931	25,547	6221	3931	$\frac{MJ}{t\,H_2}$ *100 km
Human toxicity	83–138	556–923	112–184	83–138	Kg 1,4 $\frac{-DBDeq.}{t\,H_2}$ *100 km
Eutrophication	0.11–0.53	0.72–3.52	0.14–0.68	0.11–0.53	Kg PO_4 $\frac{MJ}{t\,H_2}$ *100 km
Acidification	0.20–0.75	1.32–4.89	0.27–0.97	0.20–0.75	Kg SO_2 $\frac{eq.}{t\,H_2}$ *100 km
GHG footprint	50–500	336–3332	83–665	50–500	Kg CO_2 $\frac{eq.}{t\,H_2}$ *100 km

political developments may have changed some of these figures.

The comparative analysis of the GHG footprints of hydrogen-producing technologies shows that T8 (water electrolysis) has the highest emissions when fuelled by the EU27 electricity mix, which relies heavily on fossil fuels (43.6 %) (Fig. 7). However, when applying the COP26 electricity scenario, which is characterised by a cleaner energy mix, the GHG footprint of T8 decreases significantly, underlining the crucial influence of the electricity source on electrolysis-based hydrogen. Also, T11 (iron-based chemical looping) and T9 (aluminium process) show increased GHG emissions due to their high electricity demand for feedstock preparation, pyrolysis and separation processes. In contrast, T1 (methane steam reforming) and T7 (conversion of acid gas to synthesis gas, AG2S) are less electricity-intensive but still have high GHG footprints, primarily due to steam generation, which accounts for 44 % and 85 % of the respective emissions. For T1, natural gas combustion accounts for an additional 27 % of the footprint. These results are consistent with previous studies by Bauer et al. [173] and Cetinkaya et al. [25] that reported comparable or higher emissions from SMR, especially when infrastructure and non-renewable energy sources are considered.

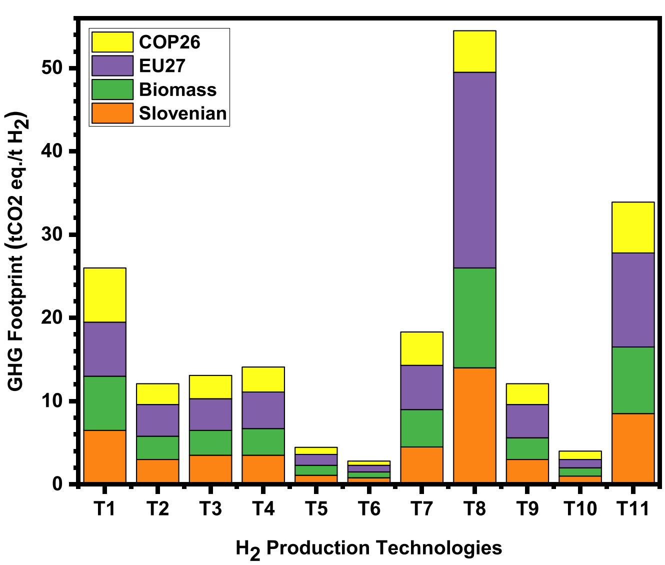

Fig. 7. Greenhouse gas footprint of hydrogen-producing technologies (modified and reproduced from Ref. [161] with permission from Elsevier, copright 2023).
T1 to T11 represent different hydrogen producing technologies: **T1** - Steam Methane Reforming (SMR), **T2** - Biomass Gasification, **T3** - Steam Reforming of Biogas, **T4** - Autothermal Reforming of Biogas, **T5** - Steam reforming of alcoholic waste, **T6** - Glycerol Steam Reforming, **T7** - AG2S process, **T8** - water electrolysis, **T9** - Aluminium Process, **T10** - Dark Fermentation Process, **T11** - iron-based chemical looping.

Biomass-based technologies such as T2 (residual hardwood gasification), T3 (steam reforming of biogas) and T4 (autothermal reforming of biogas) also have significant GHG footprints due to upstream resource handling transport, fertilisation and silage processing. While T3 consumes more electricity, T4 demands greater biomass input, reflecting a trade-off in resource intensity. The lowest GHG footprints were observed for T5 (steam reforming of alcoholic waste), T6 (glycerol steam reforming) and T10 (dark fermentation). In T5 and T6, steam production remains the dominant emission source, while the footprint of T10 is primarily due to enzyme preparation.

A comparative analysis was conducted to evaluate the primary contributors to the greenhouse gas (GHG) footprint across the hydrogen value chain [161]. This assessment encompassed four storage and transportation alternatives, in conjunction with the hydrogen production technology exhibiting the lowest GHG emissions - namely, T6 (glycerol steam reforming), as previously illustrated in Fig. 7. For consistency, the T6 production method was applied across all scenarios. The storage and transport options analysed include: (a) gaseous hydrogen delivery via pipeline, (b) gaseous hydrogen delivery via road transport, (c) liquid hydrogen delivery via road transport, and (d) liquid hydrogen delivery via rail transport (Fig. 8). Each alternative provides insight into the relative environmental burdens associated with the different stages of the hydrogen supply chain.

The analysis reveals that hydrogen production accounts for the most significant portion of the GHG footprint, particularly when the hydrogen is transported via pipeline, contributing up to 92.1 % of total emissions. In contrast, for the remaining transport alternatives, storage plays a more dominant role in GHG contributions, primarily due to the high electricity demand associated with compressing hydrogen to the requisite pressures. Specifically, compression to 100 bars for pipeline delivery results in a 2.2 % contribution, while compression to 500 bars for road transport increases this value to 9.3 %. The liquefaction process, which is considerably more energy-intensive, contributes approximately 34.9 % to the overall GHG emissions in both road and rail transport scenarios [161].

Hydrogen holds substantial promise as a low-emission energy carrier, particularly for decarbonising sectors that are challenging to electrify, such as heavy industry and long-haul transport and for balancing the intermittency of renewable energy sources [174]. Nevertheless, a comprehensive assessment of the hydrogen supply chain highlights several persistent challenges, including the absence of mature value chains for clean hydrogen, high costs associated with production, storage, and transportation, a lack of internationally harmonised standards, and underdeveloped infrastructure for storage and distribution [175].

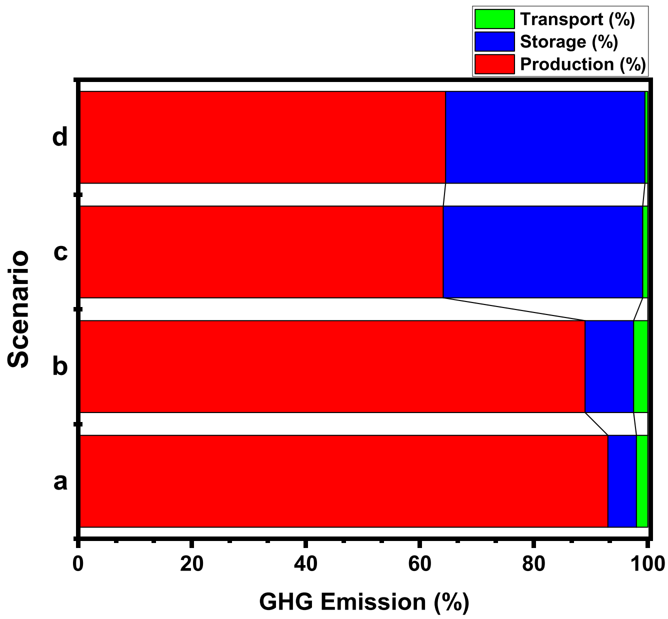

Fig. 8. GHG footprint breakdown for the production of 1 tonne of hydrogen via glycerol steam reforming (T6), coupled with various storage and transportation options over 100 km: (a) gaseous storage with pipeline transport, (b) gaseous storage with road transport, (c) liquid storage with road transport, and (d) liquid storage with rail transport. Modified and reproduced from Ref. [161] with permission from Elsevier, copyright 2023.

Additional concerns include investment risks, low efficiency in medium-to large-scale applications [28], significant power requirements, and safety considerations. A comparative environmental impact analysis of hydrogen pathways is therefore critical for identifying environmental hotspots and informing the sustainable development of hydrogen infrastructure. Such assessments support emissions reductions and the provision of cleaner, more affordable energy, contributing meaningfully to the achievement of Sustainable Development Goals (SDGs) [176] and environmental, social, and governance (ESG) targets [177].

4. Public perception of hydrogen deployment: a social challenge

Public acceptance is a crucial factor for the successful deployment of hydrogen infrastructure, especially in residential areas and cities where perceptions of safety and sensitivity to land use are particularly high. Despite hydrogen's potential to decarbonise mobility and industry, its flammability, association with high-pressure systems and relative unfamiliarity can cause significant public fears. These concerns are exacerbated by NIMBYism (Not In My Backyard), perceived risks to property values and limited trust in regulatory oversight. Transparent communication, participatory site selection processes and the visible implementation of robust safety protocols are needed to counteract these dynamics [178–180].

4.1. Lessons learnt from different regions: the role of risk perception and trust

Empirical data from South Korea provides an illustrative example: according to a recent study, 48 % of respondents were in favour of building hydrogen refuelling stations near their homes, while 23 % were against and 29 % were neutral indicating a significant acceptance gap [179]. Safety concerns and proximity to residential areas were cited as the main reasons for opposition. Reportedly, 70–80 % of proposed station sites were cancelled due to community opposition. However, acceptance increased when clean (green or blue) hydrogen was used and when safety protocols were clearly communicated [179]. These findings emphasise the need for integrated public engagement strategies tailored to the local context, where acceptance depends not only on technical assurances but also on perceived fairness and environmental legitimacy.

The Japanese study represents a pioneering attempt to investigate public acceptance of hydrogen refuelling stations in terms of risk perception. According to Ono and Tsunemi [180], the result of a nationwide online survey show that 66 % of respondents were in favour of building a hydrogen refuelling station at their nearest refuelling station, with acceptance among male respondents being higher than among female respondents, regardless of age. The study demonstrates that most important factors influencing acceptance include demographic factors (gender, education), personal mobility habits, knowledge about hydrogen and perceived refuelling station risks [180].

Complementary findings from Germany deepen our understanding of the socio-psychological dimensions of hydrogen acceptance. A study by Hildebrand et al. [178] examined how hydrogen infrastructure is linked to society's perception of risk. When asked about environmental hazards associated with hydrogen technologies, 38 % of respondents said they perceived no risk and only 15 % expressed concern. Interestingly, only 26 % responded 'don't know', which is significantly lower than other risk categories, suggesting that environmental issues are more tangible or understandable to the public (Fig. 9). In addition, perceived risks associated with living near hydrogen-using industrial sites produced ambiguous responses: 26 % disagreed that there was a risk, 20 % agreed, and 35 % were not sure. Of particular interest is the finding that systemic risks such as energy cost volatility and supply insecurity were seen as more significant than accidental risks such as explosions or leaks. However, potential health effects showed the strongest correlation with public resistance, suggesting that personal safety and physical risk are central to risk perception and resistance [178].

A key finding from the German case is that public acceptance improved after infrastructure deployment, particularly among residents living within 500 m of hydrogen refuelling stations [178]. These individuals reported lower perceived risk and a more favourable risk-benefit assessment following direct exposure, suggesting that transparency of operations and familiarity with operations can recalibrate public perception over time. Hildebrand et al. [178] emphasises that the public's perception of risk is deeply subjective, driven by emotion and particularly influential in the early stages of adoption. Scepticism is often exacerbated when the source of technological risk is poorly understood or abstract. Consequently, scientific and governmental communication should cover the entire life cycle of hydrogen from production and storage to distribution and end use. Narrowly focusing communication on consumer-facing technologies (e.g. hydrogen cars) misses the broader societal concerns and limits the impact of engagement efforts.

5. Addressing challenges in the hydrogen economy and future work considerations

As hydrogen garners increasing global recognition as a clean energy carrier, addressing key limitations related to storage, safety, environmental sustainability and public perception is essential for enabling widespread deployment. Rather than being viewed solely as barriers, these areas present actionable opportunities for technological innovation, infrastructure development, and international collaboration.

5.1. Enhancing hydrogen storage solutions

The optimization of hydrogen storage systems must prioritize energy efficiency, system durability, and cost-effectiveness. Hydrogen's low volumetric energy density necessitates advanced storage solutions. To address the energy-intensive nature of traditional methods like high-pressure compression and cryogenic liquefaction, researchers are

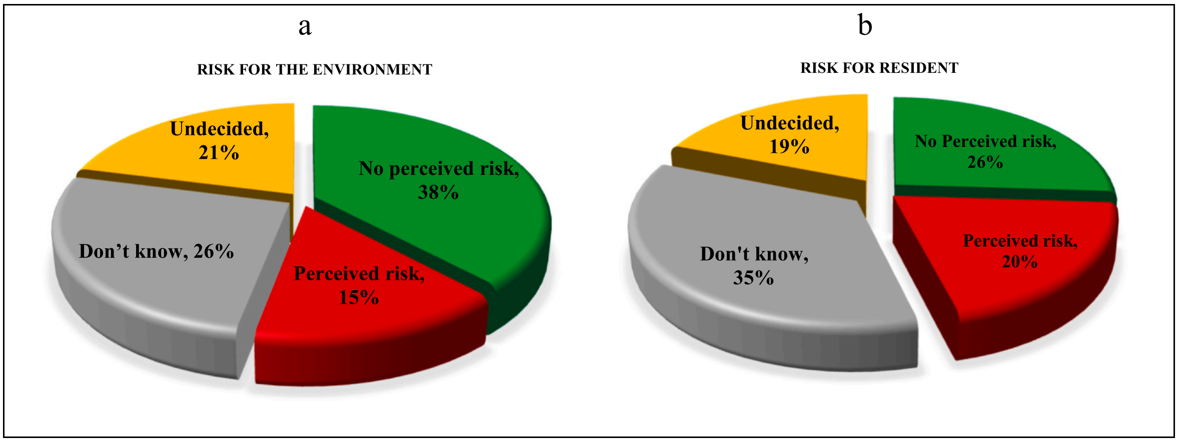

Fig. 9. Public perception of (a) environmental hazards and (b) Residential proximity risks associated with hydrogen technologies. Modified and reproduced from Ref. [178] with permission from John Wiley and Sons, copyright 2024. This summarizes survey responses on perceived environmental hazards of hydrogen technologies and perceived risks of living near hydrogen-utilizing industrial sites, indicating a mix of acceptance, concern, and uncertainty among the public.

advancing solid-state storage technologies [181–183]. Solid-state carriers such as metal hydrides, chemical hydrogen storage, and liquid organic hydrogen carriers (LOHCs) allow for storage at lower pressures and ambient temperatures, significantly improving safety and energy efficiency [184]. Metal-organic frameworks (MOFs), complex hydrides and nanostructured alloys offer promising alternatives due to their high gravimetric capacities, reversibility and safety profile. For example, MOF-808-Hf has shown hydrogen uptake of 7.5 wt% under moderate conditions, exceeding the US Department of Energy's minimum uptake capacity of 5.5 wt% [185–187]. Zhang et al. [188] reported 6.7 wt% H_2 storage capacity at 30 °C with magnesium-based hydrides (MgH_2). These hydrides, enhanced by nano-refinement and catalytic doping have demonstrated improved kinetics and thermodynamic stability with reversible absorption/desorption cycles suitable for mobile and stationary applications [188–190]. Despite these advances, challenges in cost, scalability and material degradation remain, necessitating further research and development on hybrid composites, entropy-stabilised alloys and machine learning-guided material discovery [191].

Underground storage in geological formations, like salt caverns, presents a viable option for large-scale, long-term hydrogen storage, facilitating seasonal energy balancing [192]. These materials also reduce the risk of leakage and flammability compared to compressed gas or liquid hydrogen systems. Moreover, next-generation composite pressure vessels with advanced polymer liners and carbon fibre reinforcements are being developed to withstand higher pressure ratings while minimizing weight and cost. These innovations enhance both mobile and stationary hydrogen storage, supporting use cases in transport and renewable energy integration [184]. In addition, modular underground hydrogen storage in depleted gas fields and salt caverns offers large-scale, long-term options for seasonal energy balancing, especially when coupled with intermittent renewables. To scale these solutions, pilot projects demonstrating reliable and cost-efficient storage are needed. Investments in simulation tools, materials testing, and LCA of storage technologies will ensure performance is evaluated across technical, economic, and environmental dimensions.

Notable hydrogen storage initiatives in different regions include HyStock (CH_2G, Netherlands) [193]; NASA Hydrogen and HyMARC (LHS and SSHS, USA) [194,195]; HySTRA (LHS, Japan) [196]; RAG Storage (UGS, Austria) [197]; and HyCavMobil (UGS, Germany) [198]. These projects span multiple storage modalities including compressed hydrogen, liquefied storage, and underground geological solutions and reflect growing international investment in scalable hydrogen infrastructure.

5.2. Improving safety through innovation and standardization

Safety concerns surrounding hydrogen's flammability and leak potential require robust detection, containment, and mitigation strategies. One essential step is the deployment of real-time hydrogen sensors with high sensitivity and low false-positive rates. These sensors can be integrated with automated shutdown systems in vehicles, pipelines, and storage facilities to prevent ignition incidents. Advancements in nanostructured sensing materials, such as palladium-alloy coatings and metal oxide films, are driving improvements in responsiveness and reliability of detection systems [199]. Innovations in fire-retardant materials, flame arrestors, and explosion-proof enclosures also enhance infrastructure resilience. Additionally, implementing redundant safety layers, including pressure relief valves, containment zones, and safety vent stacks, is critical for preventing catastrophic failure in hydrogen refuelling stations and production plants [200].

Recent developments include fibre-optic sensors with palladium-coated Bragg gratings that can detect hydrogen concentrations below 4 % at cryogenic temperatures [201]. Electrochemical and metal oxide sensors while cost-effective, face challenges in cross-sensitivity and response time, necessitating integration with AI-based predictive systems for real-time monitoring [202]. MEMS-based ultrasonic and photoacoustic sensors are also being trialled for pipeline and tank applications and offer high precision and durability [203,204]. These innovations are critical for industrial zones, transport corridors and airborne systems where undetected leaks pose a significant safety and reputational risk.

At the policy level, the development of internationally harmonised safety standards is vital to streamline hydrogen deployment across borders. Agencies such as the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO), and regional regulators are increasingly cooperating to define codes for hydrogen handling, transport, and fuelling infrastructure [205,206]. Incorporating these standards into national regulations will build trust among stakeholders and facilitate global trade of hydrogen and hydrogen-based fuels [207]. Public safety awareness campaigns, community engagement, and workforce training will further support safe hydrogen adoption. Transparent communication and emergency preparedness planning should accompany new infrastructure rollouts to cultivate public confidence and reduce resistance to hydrogen projects.

5.3. Reducing environmental impact through sustainable integration

Hydrogen itself as a clean-burning fuel, the environmental profile of its lifecycle varies based on production, transport, and storage methods.

The path forward involves scaling green hydrogen production using renewable energy sources such as solar, wind, or hydropower to drive water electrolysis [31]. Investments in next-generation electrolysers, including proton exchange membrane (PEM) and solid oxide electrolysers (SOEC), are reducing energy losses and capital costs, making green hydrogen increasingly competitive [32,208–211]. To mitigate these environmental impacts, hydrogen production should incorporate low-carbon feedstocks and renewable energy sources [212]. In addition to natural gas-based steam reforming, other renewable and waste-derived feedstocks can be utilized, including biogas, glycerol, and alcohol-based waste. Alternative production pathways include autothermal reforming (ATR) of biogas, lignocellulosic biomass gasification, and the acid gas to syngas (AG2S) process, a modified Claus process that repurposes acid gas as a feedstock [213].

Additionally, photocatalysis has been explored for converting hydrogen sulfide (H_2S)-rich acid gas into hydrogen [214]. Iron-based chemical looping [215] and dark fermentation [216] present alternative methods for converting agricultural residues into hydrogen without requiring syngas as an intermediate. While certain feedstocks, such as biomass, necessitate energy-intensive pretreatment processes, others, like aluminium, can directly generate hydrogen through combustion [217] or water electrolysis. Recent technological advancements have also improved the efficiency of water electrolysis, with innovations such as next-generation electrolyser membranes and increased integration of renewable energy sources for electricity generation [218]. Moreover, improving the efficiency of compression and liquefaction systems used in hydrogen logistics will reduce indirect emissions. For instance, incorporating renewable electricity into liquefaction and high-pressure compression processes can dramatically cut lifecycle greenhouse gas emissions [219,220]. Research also suggests that optimizing logistics such as using pipelines over road or rail transport where feasible can significantly reduce energy consumption and emissions [221–224].

Environmental oversight must extend beyond carbon emissions to include potential impacts of production and infrastructure. For instance, the manufacture and disposal of solar panels and wind turbines used in hydrogen generation must be managed sustainably. Technologies should be assessed using comprehensive LCA frameworks to identify environmental hotspots and prioritize eco-design approaches across the hydrogen value chain. To prevent unintended ecological consequences, monitoring of hydrogen leakage is essential. Although hydrogen is non-toxic, atmospheric leakage can extend methane lifetime and affect ozone chemistry, indirectly influencing global warming. Integrating atmospheric models into environmental monitoring systems will be crucial for managing hydrogen's broader environmental footprint [225,226].

5.3.1. Optimizing hydrogen logistics and infrastructure deployment

Efficient hydrogen logistics requires integrated modelling of production, storage, transport and end-use systems. Multi-objective optimization systems such as those proposed by Riera et al. [227] evaluate trade-offs in cost, emissions and reliability under uncertainty and guide infrastructure investments in different regions. Metaheuristic algorithms have been applied to simulate boil-off losses, permeation rates and routing efficiency for truck, rail and barge transport, as demonstrated by Fraunhofer CML's H2-Logistics platform [228,229]. Projects such as HyTROS in the Netherlands integrate offshore hydrogen transport with underground storage and regulatory modelling and provide a blueprint for scalable deployment [230]. These models are critical for adapting infrastructure to market dynamics, especially in emerging hydrogen economies with fragmented supply chains.

5.4. Advancing **public acceptance of hydrogen energy: strategic enabler in hydrogen deployment**

Recent findings emphasise the need for a multi-layered approach that integrates transparent communication, participatory governance and contextual engagement strategies to effectively drive the deployment of hydrogen infrastructure [178–180]. Public acceptance depends not only on technical assurances, but also on perceived risks, trust in public authorities and the societal relevance of hydrogen technologies. Governments and developers need to prioritize open and accessible communication that addresses safety, environmental and health aspects ideally supported by published lifecycle emissions data, failure probabilities and emergency response protocols. Engagement must go beyond abstract messaging: community co-design in siting decisions, culturally adaptive outreach and operationally transparent pilot projects play an important role in building trust and shifting perceptions from scepticism to informed evaluation [178–180].

As Hildebrand et al. [178] argue, scientific communication should cover the entire hydrogen value chain from production, transport and storage to end use, rather than focusing on individual applications. Understanding regional sensitivities, such as Japan's seismic risk and high pressure H_2 pipeline [231,232] or Germany's industrial legacy [233,234], further underlines the value of localised outreach. Long-term and cross-cultural research will be essential to monitor how public opinion evolves and how social norms, procedural justice and environmental justice influence acceptance in different countries. As the hydrogen economy globalises, embedding these integrative principles into international policy will be central to ensuring both social legitimacy and sustainable energy transitions. As hydrogen economies globalize, embedding these inclusive principles into international policy frameworks will be central to achieving both societal legitimacy and sustainable energy transitions.

5.5. Improvement in hydrogen policy frameworks and ongoing developments

Hydrogen policy is entering a pivotal phase, transitioning from vision-setting to concrete action. Governments worldwide are introducing frameworks and policies to support production, distribution, storage, demand, and infrastructure development. This evolving policy landscape reflects growing recognition of hydrogen's role in decarbonization and addressing energy security. Coordination, standardisation, certification, transparency and targeted funding are becoming central themes to prevent hydrogen market integration. Addressing this requires significant technological breakthroughs and strong policy to support hydrogen large-scale implementation.

Global policy support for hydrogen is rapidly evolving, with governments moving from strategy development to practical implementation with nearly USD 100 billion in public funding announced, activated, or allocated to projects over the past year [114]. However, nearly two-thirds of this funding remains at the announcement stage and therefore uncertain. Notably, 95 % of these funds originate from advanced economies, which generally have more mature hydrogen strategies. Supply-side funding continues to outpace demand-side support, with a ratio of 1.5 to 1. In the past 12 months, 19 new national hydrogen strategies were introduced, raising the global total to 60. These strategies now span countries responsible for over 84 % of global energy-related CO_2 emissions. Most of the recent strategies and production targets were introduced by emerging markets and developing economies (EMDEs), although they largely remain non-binding and lack specific implementation mechanisms [114].

Demand-side funding reached USD 40 billion in 2023. Of this, about 20 % targets existing hydrogen applications, while approximately 60 % supports new uses. Current policies in force could drive demand for up to 6 million tonnes of hydrogen per year (Mtpa) by 2030. However, this is only half of what is targeted by announced demand goals, 15–20 % of the projected production, and under 10 % of the levels required to meet the Net Zero Emissions by 2050 Scenario [114]. Germany accounts for about two-thirds of this demand-side funding, primarily through initiatives supporting industrial decarbonization and power generation. Policy instruments vary by region as developed economies tend to use direct subsidies, whereas tax incentives are more common in EMDEs.

Competitive bidding processes have gained traction globally, with auctions launched in Egypt, India, Oman, and several European countries to foster market formation, improve price discovery, and encourage competition. Nine countries introduced incentives for electrolyser and fuel cell manufacturing, but only six have implemented them through active policies.

International collaboration is also advancing. At COP 28, 37 countries agreed to pursue mutual recognition of hydrogen certification schemes based on shared design principles. In Latin America, 14 countries formed the "CertHiLAC" initiative, supported by Multilateral Development Banks, to establish regional certification standards [114]. Additionally, the International Organization for Standardization (ISO) released a Technical Specification in December 2023, laying the foundation for a formal ISO standard on greenhouse gas emissions accounting for hydrogen production, conditioning, and transport expected to be finalized by 2025–2026 [34]. Table 7 provides a comparative overview of both operational and developing regional certification systems for hydrogen and its derivatives. It outlines key policy frameworks defining acceptable GHG emissions thresholds, system boundaries, production pathways, and emissions intensity serving as a reference for understanding both global alignment and divergence in hydrogen certification [114].

In addition to development of certifications schemes to reduce GHG emission, robust policy frameworks are essential to reduce the risk of hydrogen investments and ensure safe and equitable deployment. Initiatives such as HyTROS and IEC 80079 are developing harmonised safety standards covering leak detection, material compatibility and pressure thresholds [235]. Green hydrogen certification schemes based on lifecycle emissions and source traceability are gaining traction to promote cross-border trade and investor confidence [236,237]. Public–private partnerships such as the SoCalGas–NREL pilot projects show how targeted incentives can accelerate the introduction of solid-state storage and grid integration [238]. In addition, policy instruments need to address regional disparities, infrastructure bottlenecks and barriers to social acceptance through stakeholder engagement and adaptive governance [239].

5.5.1. Regional-based policy and certification frameworks for hydrogen deployment

Hydrogen's environmental potential as a zero-emission energy carrier is increasingly embedded in national decarbonization strategies. However, its integration into global energy systems is hindered by fragmented policy frameworks, inconsistent certification standards, and uneven monitoring, reporting, and verification (MRV) mechanisms. While over 60 countries have launched hydrogen strategies, many remain broad and lack enforceable, region-specific implementation pathways, undermining hydrogen's climate credibility and risking market fragmentation [240,241].

As shown in Table 7, there is a progressive development of policy and certification frameworks globally. Europe, as the leading region in hydrogen certification, have a harmonised regulatory framework classifying green hydrogen pathways with the lowest emissions (<2.26 $kgCO_2$ e/kgH_2) [242]. Emerging instruments such as the EU Green Deal [243], US Inflation Reduction Act (IRA, Section 45V) [244], Canada Clean Hydrogen Investment Tax Credit [245] and UK low Carbon Hydrogen Standard [246] link hydrogen to broader industrial decarbonization goals. These frameworks incentivize low-carbon hydrogen production through tax credits, subsidies, and emissions thresholds. However, their effectiveness is constrained by divergent MRV protocols and the absence of harmonised LCA methodologies particularly in accounting for upstream emissions and grid electricity attribution [240, 241]. This inconsistency fosters uncertainty and opens the door to "greenwashing," where hydrogen is labelled clean despite embedded fossil-based emissions, eroding stakeholder trust [247].

Emissions thresholds for hydrogen certification vary significantly across jurisdictions (Table 7). While frameworks in regions such as the EU and Canada adopt comparatively stringent limits, others remain lenient permitting fossil-derived hydrogen under offset-based accounting schemes that risk undermining environmental integrity. These disparities threaten the development of a unified global hydrogen market. For example, exporters in Africa may face higher verification costs and stricter tariff requirements than producers in Europe or Asia, despite comparable production methods [244]. South Africa, rich in renewable

Table 7
Comparative evaluation of different existing and planned regional hydrogen certification and policy schemes [114].

Jurisdiction/Scheme	Purpose	Incentive Linked	System Boundary	Product	Production Pathway	Status	Chain of Custody	Emissions Intensity ($kg\ CO_2$-eq/unit)
GH_2 Green Hydrogen Standard (Global)	Voluntary certification	No	Well-to-gate	Hydrogen	Renewable electricity	Operational	Not specified	1 $kg\ CO_2$-eq/kg H_2
CertifHy (EU)	Voluntary certification	No	Well-to-gate	Hydrogen	Renewable, Nuclear, Fossil + CCUS	Operational	Book-and-claim	4.4 (low-carbon); 4.4 (renewable)
H_2Global (International)	Funding mechanism	Yes	Well-to-point of delivery	Ammonia, Methanol, SynKerosene	Renewable electricity	Operational	Mass balancing	3 $kg\ CO_2$-eq/kg
Clean Hydrogen Investment Tax Credit (Canada)	Tax incentive policy	Yes	Well-to-gate	Hydrogen, Ammonia	Electrolysis, Natural gas + CCUS	Operational	Not specified	<4 (ammonia); <0.75–4 (hydrogen, graded)
UK Low Carbon Hydrogen Standard (UK)	Regulatory standard	Yes	Well-to-gate	Hydrogen	Electrolysis, NG + CCUS, Biomass	Operational	In development	2.4 $kg\ CO_2$-eq/kg H_2
Clean Hydrogen Production Tax Credit (US)	Tax credit	Yes	Well-to-gate	Hydrogen	All	Under development	Not specified	<0.45–4 (tiered by emissions)
Hydrogen Production Tax Incentive (Australia)	Regulatory incentive	Yes	Well-to-gate	Hydrogen	Renewable electricity	Under development	Not specified	0.6 $kg\ CO_2$-eq/kg H_2
Green Hydrogen Standard (India)	Regulatory standard	Yes	Well-to-gate	Hydrogen	Renewable energy (incl. biomass)	Under development	Not specified	<2 $kg\ CO_2$-eq/kg H_2
Clean Hydrogen Certification Scheme (Korea)	Regulatory certification	Yes	Well-to-gate	Hydrogen	All	Operational	Mass balancing	Grade 1: 0–0.1; Grade 4: 2–4
Hydrogen Society Promotion Act (Japan)	National regulatory policy	Yes	Well-to-gate	Hydrogen, Ammonia, Synfuels	All pathways	Under development	Not specified	H_2: 3.4; NH_3: 0.87; Synfuels: ~40 g CO_2-e/MJ

energy (solar, wind) and mineral (platinum) resources, primarily used for electrolysers and fuel cells, in 2021, launched a Hydrogen Society Roadmap for 2030 [248]. However, the absence of robust monitoring, reporting and verification systems in Africa, along with the financial and technical capabilities of hydrogen, requires urgent attention. The lack of domestic certification infrastructure in Africa further compounds this, creating dependency on external verification and limiting equitable access to incentives [240,241].

Asia's hydrogen policy landscape is similarly fragmented. Japan and South Korea prioritize ammonia and blue hydrogen imports, while China is scaling green hydrogen via renewable-powered electrolysis [249]. However, the absence of enforceable carbon intensity thresholds across the region weakens certification credibility and complicates cross-border trade [240,241]. Without alignment, national schemes such as Japan's Hydrogen Society Promotion Act [249] or the U.S. IRA [244] risk becoming non-tariff barriers, impeding global hydrogen commerce.

To meet net-zero targets by 2050, global certification schemes must adopt stringent, lifecycle-based thresholds that reflect full emissions accounting and exclude fossil-dependent pathways. Establishing an international hydrogen certification body with interoperable standards and transparent MRV systems is imperative. Such a body would ensure equitable participation, reduce administrative burdens for resource-constrained regions, and safeguard environmental integrity. While policy momentum is growing, the current landscape remains fragmented and uneven. A harmonised global framework anchored in robust verification, ambitious thresholds, and inclusive governance is essential to unlock hydrogen's full decarbonization potential and support a just, sustainable energy transition [243,250].

5.6. Reflections on future work and recommendations

Looking ahead, targeted strategies are needed to address the persistent and unresolved environmental, storage and safety issues associated with hydrogen technologies and to enable hydrogen's role in a clean energy transition at scale.

- **Advanced materials and digital tools for safe and efficient storage:** Continued research and development of next-generation hydrogen storage materials such as metal–organic frameworks (MOFs), carbon nanotubes and boron nitride nanostructures can offer higher gravimetric and volumetric densities while operating at lower pressures, reducing both safety risks and strain on infrastructure. The integration of AI-powered sensor systems and digital twins can improve predictive maintenance, leak detection and fault modelling in real-world conditions critical for the safe handling and storage of hydrogen [239,251,252].
- **Supportive policies and harmonisation of safety standards:** Governments should create a favourable regulatory environment for green hydrogen through tax credits, carbon pricing and feed-in tariffs. Equally important is the harmonisation of safety and environmental regulations in different countries to avoid duplication, reduce barriers and ensure a consistent approach to hydrogen safety and emissions throughout the life cycle [253].
- **Infrastructure investments to improve distribution:** The development of dedicated hydrogen infrastructure including pipelines, electrolysers and refuelling stations will improve distribution efficiency and reduce reliance on high-pressure transportation, which poses a significant safety risk. Strategic aggregation of renewable energy sources with hydrogen hubs can minimise transmission losses and reduce the carbon footprint of hydrogen production [254].
- **International cooperation on certification and safety protocols:** The global adoption of hydrogen requires mutual recognition of certification schemes, especially for tracking the carbon intensity and safety performance of hydrogen products. Joint initiatives such as hydrogen corridors can standardise handling practises and promote consistent safety protocols across borders [255].
- **Engaging the public to address safety perceptions:** Information and education campaigns should address public concerns about the flammability and explosion risk of hydrogen. Transparent communication, supported by real-world case studies and community demonstrations, will be critical to gaining public trust and accelerating market adoption.
- **Integrating the circular economy to reduce environmental impact:** Integrating circular economy principles into the hydrogen value chain including the recyclability of fuel cell stacks and electrolysers and the reuse of waste heat and industrial by-products can significantly reduce the environmental impact and improve the sustainability of the system. Life cycle analyses (LCA) should guide technology development and policy decisions [256].

By focusing on scalable solutions in storage, safety, and environmental management, the hydrogen economy can evolve into a robust and sustainable pillar of the global energy transition. Ensuring that innovation is complemented by inclusive policy, rigorous safety governance, and public trust will be essential to realizing hydrogen's full potential. With strategic action across sectors, hydrogen is poised not just to complement, but to transform, the clean energy landscape. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis (Fig. 10) of hydrogen storage, safety, and environmental concerns reveals that, despite existing challenges, there are significant opportunities to advance and establish a viable hydrogen economy. The SWOT analysis emphasises that the realisation of a sustainable hydrogen economy requires an integrated approach that goes beyond technological progress and requires systemic integration in the areas of production, storage, safety and the environment. This shows that coordinated strategies that combine innovation with safety protocols, infrastructure design and stakeholder engagement are essential for a transition to a hydrogen economy that is not only technically sound, but also environmentally and socially robust.

6. Conclusion and outlook

The hydrogen economy offers immense potential as a cornerstone of global decarbonization strategies, but its realisation depends on addressing the intertwined challenges in the Techno-Enviro-Socio-Political (TESP) framework. This review provides a critical assessment of the key aspects of hydrogen deployment, including production technologies, storage modalities, safety considerations, environmental sustainability and the broader socio-political context: public perception and policy regulation, to provide an integrated perspective on the opportunities and barriers to large-scale adoption. Current global hydrogen production is still predominantly fossil-based, with ~90 % derived from grey and blue hydrogen routes, emitting an estimated 920 Mt CO_2, almost two-thirds of which is attributable to fossil fuel sources. This is also underpinned by LCA findings, which show that electrolysis fuelled by coal-dominated grids offers limited environmental benefits, producing up to 144 - 1033 g CO_2-eq/MJ and consuming 10.33 MJ/MJ H_2 of energy, reinforcing concerns about its environmental inefficiency. Without a simultaneous switch to low-carbon electricity, this route cannot deliver any significant climate benefits.

In contrast, methanol steam reforming had the lowest environmental footprint with GHG emissions of 23.17 g CO_2-eq/MJ and energy consumption of only 0.23 MJ/MJ, although its sustainability depends on renewable methanol feedstocks. Biogas reforming proved to be a practical short-term alternative, with moderate GHG emissions (51.5 g CO_2-eq/MJ) and favourable energy efficiency (12.2 MJ/MJ), outperforming biomass gasification (43.9 g CO_2-eq/MJ; 17.9 MJ/MJ) in terms of energy and water. Catalytic ammonia cracking, which is suitable for long-distance hydrogen transport, showed a promising energy demand (2.93 MJ/MJ) but imposed the highest water load (8.34 L/km), emphasising

Fig. 10. SWOT assessment of storage, safety, and environmental concern in the hydrogen economy.

the necessary trade-offs that need to be weighed against energy efficiency metrics. Apart from production, the thermophysical properties of hydrogen including low molecular weight, high diffusivity and low flammability lead to significant safety risks during storage and distribution. High-pressure and cryogenic systems require stringent containment strategies, while hydrogen's invisible flame, embrittlement potential and high jet impulse require advanced detection and mitigation protocols. Flame propagation behaviour and ignition sensitivity further complicate the environmental risk profile, especially in urban or closed environments.

A key finding of this study is the critical interaction between hydrogen production methods, storage limitations, safety risks, environmental impacts and socio-political factors. These interlinked challenges emphasise the need for a comprehensive, system-based strategy to fully exploit the potential of hydrogen as a clean and sustainable energy carrier. As emphasised in the SWOT analysis, the path to a sustainable hydrogen economy depends not only on technical innovation, but also on the integration of these areas through coordinated strategies. Stakeholders, from policy makers and industry leaders to infrastructure planners, need to balance decarbonised production with safe, scalable storage solutions that are reinforced by harmonised safety protocols and environmental protection measures. Public acceptance of hydrogen infrastructure depends on perceived safety risks, trust in governance, and familiarity with the technology. Transparent communication and community engagement are essential to overcome emotional and cognitive barriers, especially in the initial phase of deployment. Public relations tailored to the local context and proof of operational safety can significantly improve social support for hydrogen adoption.

These approaches must combine technological advances with robust policy frameworks, transparent certification schemes and proactive stakeholder engagement. Priorities include scaling up low-carbon production technologies (e.g. renewable-based electrolysis, biogenic reforming), strengthening safety policies and regulations, and promoting storage innovations that balance efficiency and environmental responsibility. These integrated strategies are essential to mitigate systemic risks, create confidence in investments and develop hydrogen systems that are both climate resilient and socially acceptable. Ultimately, the path to a sustainable hydrogen future will depend on aligning production, storage and end-use systems with climate targets, resource constraints and societal expectations. This review provides a basis for strategic investments, technical choices and governance tools that are essential for achieving a safe, scalable and environmentally friendly hydrogen economy.

CRediT authorship contribution statement

Ifeanyi Michael Smarte Anekwe: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sherif Ishola Mustapha:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Stephen Okiemute Akpasi:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Emmanuel Kweinor Tetteh:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Atuman Samaila Joel:** Writing – original draft, Validation. **Yusuf Makarfi Isa:** Writing – review & editing, Supervision.

Data availability

Data is available upon request

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Declaration of competing interest

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