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Analysis

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Global greenhouse gas emissions mitigation potential of existing and planned hydrogen projects

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Hydrogen will play a critical role in decarbonizing diverse economic sectors. However, given limited sustainable resources and the energy-intensive nature of its production, prioritizing its applications will be essential. Here, we analyse approximately 2,000 (low-carbon) hydrogen projects worldwide, encompassing operational and planned initiatives until 2043, quantifying their greenhouse gas (GHG) emissions and mitigation potential from a life cycle perspective. Our results demonstrate the variability in GHG emissions of hydrogen applications, depending on the geographical location and hydrogen source used. The most climate-effective hydrogen applications include steel-making, biofuels and ammonia, while hydrogen use for road transport, power generation and domestic heating should be discouraged as more favourable alternatives exist. Planned low-carbon hydrogen projects could generate 110 $MtH_2\ yr^{-1}$, emit approximately 0.4 $GtCO_2e\ yr^{-1}$, and potentially reduce net life cycle GHG emissions by 0.2–1.1 $GtCO_2e\ yr^{-1}$ by 2043, depending on the substituted product or service. Addressing the current hydrogen implementation gap and prioritizing climate-effective applications are crucial for meeting decarbonization goals.

Stringent climate mitigation scenarios show substantial hydrogen requirements to achieve full decarbonization throughout all energy sectors[1–5]. Currently, most hydrogen is generated from fossil resources, such as steam methane reforming of natural gas and coal gasification[6]. Hydrogen production can be decarbonized using low-carbon energy sources, such as renewable electricity for water electrolysis[5], by biomass gasification[7] or by capturing and permanently storing CO_2 from fossil-based processes[8,9]. However, even very low-carbon hydrogen causes life cycle greenhouse gas (GHG) emissions and environmental burdens. These need to be quantified to better understand the real emission reduction potential of hydrogen production and applications[5,10].

Hydrogen-based applications have been assessed from an environmental perspective in existing studies, focusing, for example, on aviation[11] and e-fuels in general[12], but substantial gaps remain. A comprehensive and systematic comparison of the GHG emission reduction potential associated with hydrogen applications across sectors is lacking. Hydrogen can play a crucial role as an intermediate chemical for producing hydrogen-based products such as jet fuel (that is, synfuels), methanol and ammonia, which can replace products and services relying on fossil resources in many sectors, such as aviation[11,13], chemicals manufacture[14] and agriculture[15]. Furthermore, hydrogen can directly help decarbonize hard-to-abate sectors[16], such as applications where battery electric propulsion systems may be less economically or technically feasible, or in energy-intensive industries, to produce low-carbon steel[17]. However, low-carbon hydrogen is expected to remain a scarce resource in the foreseeable future[18]. Hence, hydrogen applications

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Table 1 | Overview of the (considered) hydrogen applications

Application	Description, derived from the IEA	Boundaries in this Analysis	Unit	Transport & storage of H_2
Refining	Use of hydrogen in the refining of oil products.	Production of fossil fuel (combustion excluded).	kilogram	No
Ammonia	Use of hydrogen in ammonia production (includes ammonia as a chemical feedstock or as a fuel).	Ammonia production, including transport of ammonia.	kilogram	Transport
Methanol	Use of hydrogen in methanol production (includes methanol as a chemical feedstock or as a fuel).	Methanol production, including combustion.	kilogram	No
Iron & steel	Use of hydrogen in steel-making (direct reduced iron, injection in blast furnaces, hot finishing and other high-temperature processes).	Low-alloy steel production (direct reduced iron, processed in an electric arc furnace), including transport and storage of H_2.	kilogram	Yes[a]
High-*T* heat	Use of hydrogen for high-temperature heat (excluding oil refining, ammonia production, methanol production and steel-making).	Heat production in a furnace, including storage of H_2.	megajoule	Storage
Mobility	Use of hydrogen in vehicles (road, off-road, rail, maritime or aviation).	Freight transport with a 32-t fuel cell truck.	ton-kilometre	No
Power	Use of hydrogen in the supply of electricity to the electricity grid with gas turbines, reciprocating engines or fuel cells.	Power production using gas turbines, including storage of H_2.	kilowatt-hour	Storage
Grid injection	Injection of hydrogen in the natural gas grid.	Hydrogen production.	kilogram	No
CHP	Hydrogen used in CHP plants, such as fuel cells or turbines.	Heat and electricity production in a CHP plant, including transport and storage of H_2.	megajoule	Yes[a]
Domestic heat	Direct use of hydrogen in buildings for water and space heating.	Residential and commercial heat production in a hydrogen boiler, including transport and storage of H_2.	megajoule	Yes[a]
Biofuels	Use of hydrogen in second-generation biofuel production.	Second-generation biofuel Neste NEXBTL production, including combustion.	kilogram	No
Synfuels	Production of synthetic liquid fuels (excluding methanol).	Kerosene production using the Fischer–Tropsch process, including combustion.	kilogram	No
CH_4 grid injection	Injection of synthetic methane in the natural gas grid.	Methane production using the Sabatier process, including combustion.	kilogram	No
CH_4 mobility	Use of synthetic methane in vehicles.	Methane production via the Sabatier process and combustion in a passenger vehicle.	kilometre	No
H_2	Hydrogen production, application unknown.	Hydrogen production.	kilogram	No

[a]The hydrogen is distributed by pipeline over 250 km to the regional storage (geological cavity) and then transported another 250 km to the consumer. Transmission loss (% output): 7.125×10^{-4}%. Regional storage loss (% output): 0.69. Arrives at 30 bar of pressure[22].

should be prioritized according to their GHG mitigation potential. A recent study[19] provided a comprehensive analysis of hydrogen production projects worldwide, but only partly addressed the use of hydrogen and hydrogen-based products and excluded future prospective changes in the global economy. Focusing solely on hydrogen production and transport, without considering a larger set of hydrogen applications, the work provides an incomplete picture of the overall emission reduction potential, as exploiting hydrogen in applications adds GHG emissions and environmental burdens.

In this work, we provide a comprehensive comparative assessment of the climate mitigation potential of various hydrogen applications. Our research goals are twofold: quantifying the GHG emissions and emission reduction potential of recently announced projects for hydrogen-based applications and their use globally up to the year 2043[20]; and identifying amongst these projects the most climate-effective applications of hydrogen and derived products. Note that, from this point onward, we use the terms 'emission reduction potential' and 'emission mitigation potential' interchangeably. We focus solely on climate change impacts and the effectiveness of hydrogen applications, thus an important limitation of our analysis is the exclusion of economic criteria.

Here, we comprehensively show that the climate effectiveness and usefulness of hydrogen applications strongly depend on the specific application of hydrogen and its derivatives[4]. Our main findings are the following: GHG emissions vary substantially among hydrogen-based applications, mainly depending on the hydrogen source and location-specific primary energy resource availability; production of second-generation biofuels, ammonia and steel-making represent the most climate-effective hydrogen applications, while the use of hydrogen in road transportation, power generation and domestic heating should be generally discouraged; planned projects would reach 110 MtH_2 production per year by 2043 and emit approximately 0.4 $GtCO_2e\ yr^{-1}$, achieving an emission reduction potential between 0.2 and 1.1 $GtCO_2\ yr^{-1}$—that is, approximately 0.5–3% of current global annual CO_2 emissions; quantifying only hydrogen-production-related GHG emissions would leave roughly half of the climate impacts of hydrogen applications unaccounted for; the countries with the highest overall emission reduction potential across hydrogen applications, considering planned initiatives, are the United States, Australia and Mauritania; finally, there is a substantial gap between announced projects and the necessary hydrogen capacity build-up in a decarbonized global economy[18,21].

Quantifying project-specific GHG emissions of hydrogen applications

In our work, we match currently planned global hydrogen production facilities with 14 associated applications. Next, we couple these projects to location-specific yields of energy sources for low-carbon hydrogen production and integrate (prospective) environmental life cycle assessment (LCA)[22] and energy system optimization. This allows the quantification of life cycle GHG emissions of 2,000 announced hydrogen projects and their GHG emission reduction potential compared with

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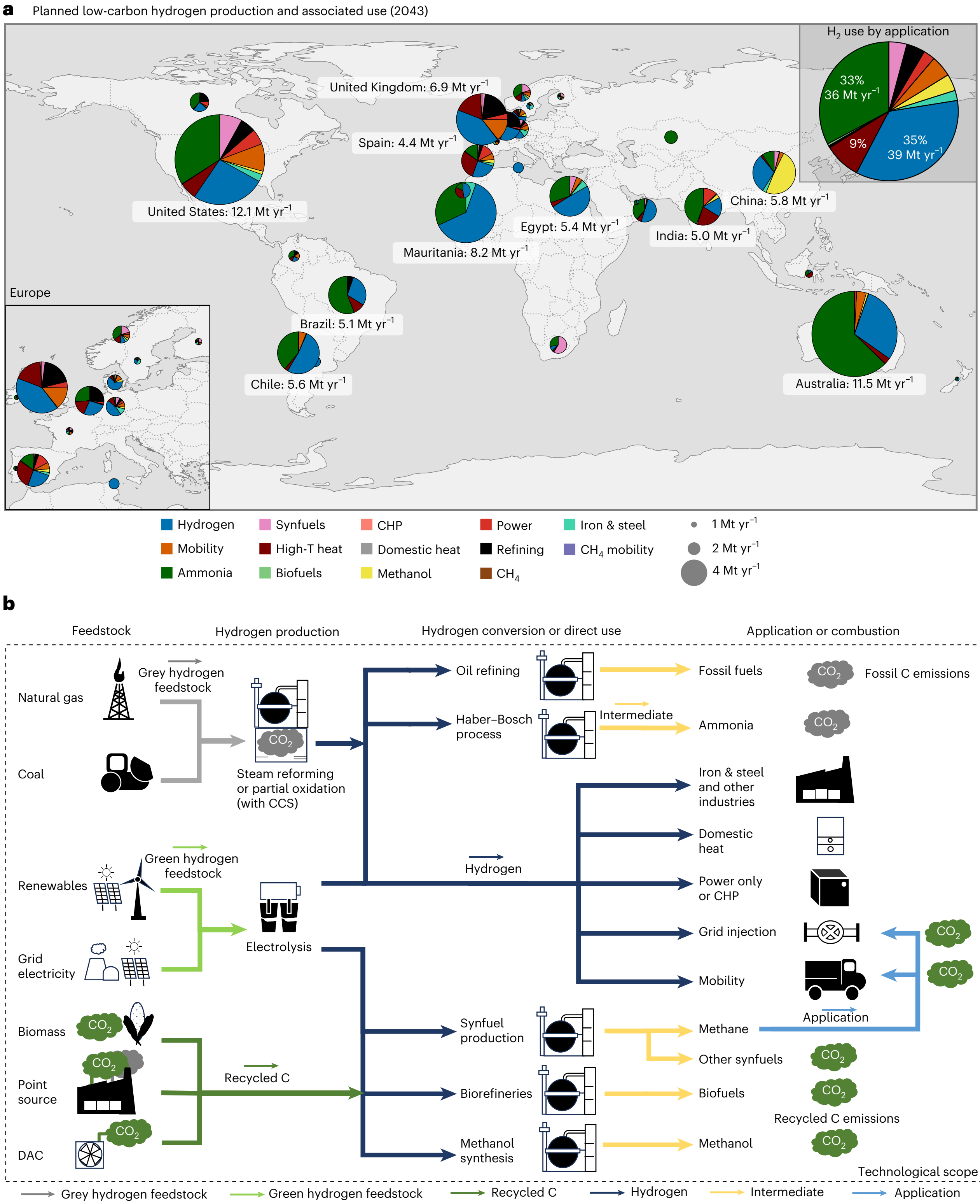

Fig. 1 | Annual hydrogen production (maximum in 2043 if all considered hydrogen facilities are deployed) and configuration flowchart of hydrogen applications. a, Annual hydrogen production of announced projects (MtH_2 yr^{-1}, in 2043) and corresponding applications; please refer to the Zenodo repository[49] for the data used. **b**, Flowchart of hydrogen production and applications considered. The pie chart in **a** to the top right provides the overall hydrogen production and mix of applications. 'Hydrogen' refers to unspecified hydrogen use/applications in the database, and 'Refining' refers to the refining of fossil fuels. DAC, direct air capture. 'Recycled C' refers to carbon sourced from biomass, waste materials or point-source CO_2 emissions, captured and repurposed to create chemicals. A zoom-in is provided for Europe in **a** to better visualize the initially overlapping pie charts for some countries. Basemap in **a** from Natural Earth (https://www.naturalearthdata.com/).

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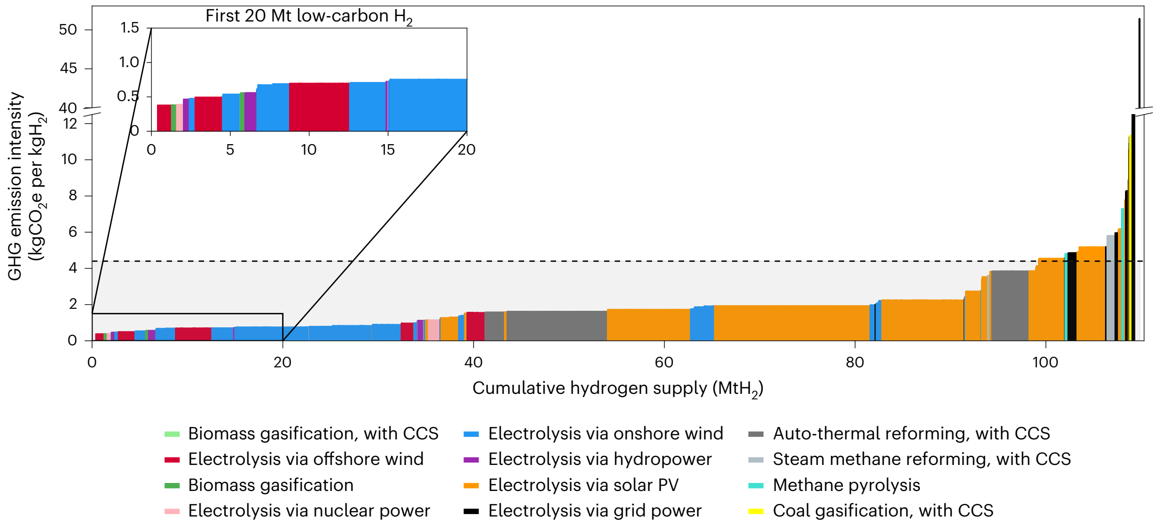

Fig. 2 | Hydrogen supply curve showing the range of underlying hydrogen sources used up to 2043. The horizontal dashed line illustrates the GHG emission intensity limit of green hydrogen defined by CertifHy[52]. Hydrogen production via biomass gasification with CCS—leading to negative emissions, assuming that CO_2 emissions from biomass combustion are equal to CO_2 uptake associated with biomass growth—is not illustrated due to the very small number of hydrogen facilities sourcing this type of hydrogen.

the energy carriers, products or services they replace, and the identification of the most climate-effective applications and the countries with the most considerable emission reduction potentials over the next 20 years. As this study focuses on hydrogen projects currently announced by the International Energy Agency (IEA)[20], which may not all materialize, it reflects the current intentions rather than a comprehensive analysis of future hydrogen deployment. While future hydrogen projects may change, the range of climate impacts will probably remain representative, considering the diverse number of projects available in the current database.

The database of the IEA[20] provides information on the hydrogen facility planned, country, year of installation, production capacity, and hydrogen production source and application. To account for facility-specific aspects, we consider a large set of (potential low-carbon) hydrogen sources: for example, electrolytic hydrogen using different power sources, such as solar photovoltaics (PV), wind, nuclear or hydropower, or fossil-based hydrogen via steam methane reforming or coal gasification with carbon capture and storage (CCS). The hydrogen applications include crude oil refining, ammonia production, methanol production, steel-making, high-temperature heat ('high-*T* heat') in industry (direct hydrogen combustion in a furnace), mobility (via fuel cell trucks), power generation (hydrogen turbines), combined heat and power (CHP) using a fuel cell, domestic (residential) heat using a hydrogen boiler, production of second-generation biofuels, production of Fischer–Tropsch synfuels or synthetic methane production for grid injection and mobility (passenger vehicles). These hydrogen applications are comprehensively described in Table 1 and illustrated in Fig. 1.

To quantify project-specific GHG emissions, including the application of hydrogen and derived products, we use environmental LCA[23,24]. Prospective LCA[22] is applied to quantify GHG emissions of future hydrogen projects using a 2-°C scenario from the integrated assessment model REMIND v.3.3[25,26] to modify the background ecoinvent LCA database[24]. We conduct a sensitivity analysis in Supplementary Note 7 using IMAGE's 2-°C scenario ('SSP2-RCP26')[27] to show the effect of using different integrated assessment models. The specific life cycle inventory (LCI) data used for the different hydrogen applications is given in Supplementary Notes 3 and 4. Our procedure matches the IEA facility-specific data with the LCI, including the hydrogen source and application, on the basis of location-specific boundary conditions such as the capacity factors of solar PV and wind installations. We then compare the GHG emission intensity of each hydrogen application from all planned facilities with alternatives providing the same service, considering two different reference cases: a 'business-as-usual' scenario (based on current practices mainly using fossil fuels) and a 'low-carbon' scenario. The low-carbon scenario describes a decarbonized global economy in which most production processes and services are either directly electrified, biomass based or equipped with CCS if relying on fossil resources. The system boundaries of our analysis include all supply chain activities, from producing the hydrogen up to the application of hydrogen. More explanation is provided in Methods. Note that throughout this Analysis climate impacts and GHG emissions refer to life cycle GHG emissions.

GHG emission intensities of hydrogen applications

Figure 2 is a hydrogen supply curve illustrating the range of life cycle GHG emissions of hydrogen production only (that is, without considering the climate impacts of their application). Figure 3 is a set of violin plots showing the range of life cycle GHG emissions of the 14 different hydrogen-based products and their specific applications. Further explanation of these applications is given in Table 1.

GHG emissions associated with one specific application of hydrogen or derived product can vary widely, mainly depending on the hydrogen source used (Fig. 2) and the location of the hydrogen production facility. As such, using fossil energy sources for hydrogen production—for example, natural gas in steam methane reforming or water electrolysis coupled to GHG-intensive power grids—results in substantially higher GHG emissions during production than using renewable electricity for water electrolysis. For most hydrogen applications, the climate impact can be more than ten times larger for fossil routes (that is, illustrated by the red dashed line as the business-as-usual scenario) than for low-carbon sources, as shown in Fig. 3. Net negative emission potentials are possible for several applications due to the sourcing of hydrogen produced via biomass gasification with CCS. Overall, GHG emissions from planned hydrogen production processes amount to 0.23 $GtCO_2e\ yr^{-1}$, reaching an average GHG emission intensity of 2.1 kg CO_2e per kg H_2 by 2043. In the following paragraphs, we show that including the hydrogen application increases GHG emissions substantially ('Overall GHG emissions and the emission reduction potential of hydrogen applications').

Generally, most hydrogen applications cause lower GHG emissions than do their fossil-fuel-based counterparts in the business-as-usual scenario. However, compared with the low-carbon scenario, in which we compare hydrogen and derived products with non-fossil alternatives,

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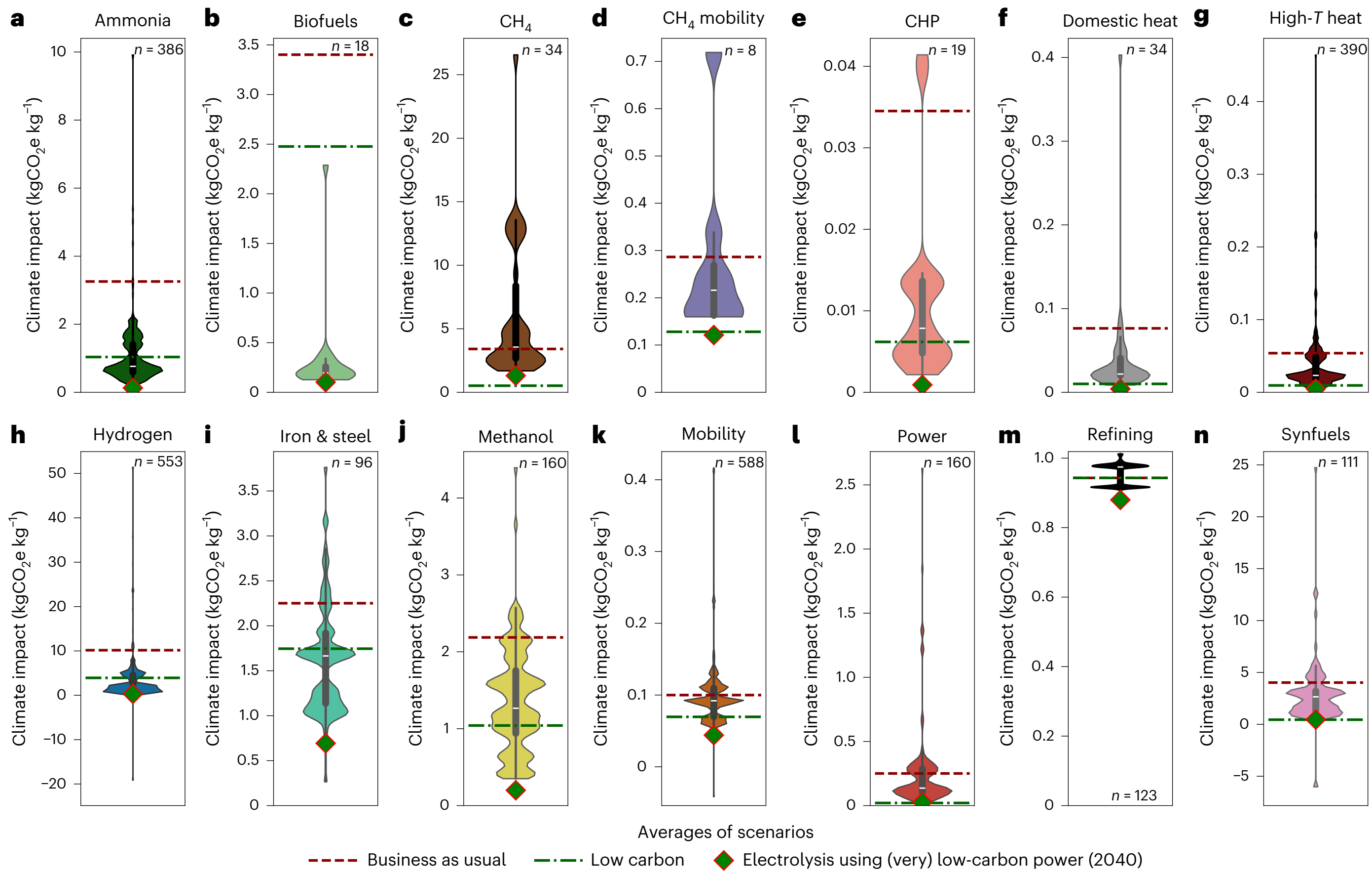

Fig. 3 | Climate impacts of hydrogen applications compared with two scenarios: business as usual and low carbon. **a**, Ammonia. **b**, Biofuels. **c**, Methane. **d**, Methane mobility. **e**, CHP. **f**, Domestic heat. **g**, High-temperature industrial heat. **h**, Hydrogen. **i**, Iron and steel. **j**, Methanol. **k**, Mobility. **l**, Power. **m**, Refining. **n**, Synfuels. Violin plots show the full distribution of results (kernel density estimation). The width of each violin represents the frequency of values; the white line marks the median, and the thicker bar the interquartile range (IQR). The thin line indicates the remainder of the distribution, defined as the range from Q1 − 1.5 IQR to Q3 + 1.5 IQR. Data points outside this range are considered outliers. Sample size (*n*), representing the number of times hydrogen is supplied in considered hydrogen projects, is shown for each distribution. The *y* axis in the violin plots shows the climate impact of the application of hydrogen for specific purposes per application-specific functional unit up to 2043, while the *x* axis illustrates the distribution of (non-weighted) results: the wider the area, the more facilities exhibit a specific amount of climate impacts. Red and green horizontal lines in each plot indicate the means of the business-as-usual scenario (fossil-fuel-based application) and a low-carbon scenario regarding climate impacts of reference processes. The diamond markers in the violin plots illustrate the climate impact if very low-carbon hydrogen is sourced from water electrolysis using nuclear power within a decarbonized global economy in 2040.

hydrogen options often cause higher emissions. For example, this is the case for power generation, domestic heat supply, methane applications and to a lesser extent mobility. This implies that these applications are less meaningful for emission reduction with hydrogen.

Emission reduction potential of hydrogen applications

Figure 4 illustrates the emission reduction potential of each hydrogen application compared with the two reference scenarios. In this context, it is key to distinguish between the type of service or product that the hydrogen application can replace, as indicated in the subplot to the top right for each application. For example, low-carbon processes directly using electricity are easier to implement than those using constrained resources such as biomass or, to a lesser extent, geological CO_2 storage. Note that we focus on the specific hydrogen use in each application to identify which one could deliver the highest climate benefits per tonne of hydrogen used, given the current scarcity of low-carbon hydrogen and the need to prioritize its use.

Figure 4 shows that biofuels, steel-making and ammonia are the most promising hydrogen applications for effective decarbonization due to insufficient alternatives with low-carbon impacts. In this case, biofuels (Fig. 4b) refers to second-generation biofuels via hydrotreated vegetable oil produced from used cooking oil, a waste-derived feedstock, which offers substantial emission reduction potential. In contrast, hydrogen use for road transport, power generation, methane applications and domestic heat should be (generally) discouraged since there are other scalable low-carbon alternatives with higher emission reduction potential based on direct electrification. For power production and domestic heating (low-carbon electricity fed into a heat pump) in particular, electrified alternatives reach (much) higher emission reduction potential and overall supply chain efficiency, which aligns with recent research[28,29].

Overall, the emission reduction potential can be substantial compared with the business-as-usual fossil-fuel-based scenario. This potential may disappear compared with the low-carbon scenario. However, it is essential to note that low-carbon alternatives based on biomass and CCS face substantial challenges in upscaling—biomass, especially by-products and residues, is a limited resource, and the infrastructure for CCS has yet to be developed.

Still, using hydrogen for less climate-effective applications may advance the integration of hydrogen technologies, in general. This is the case if there is no power (or grid network) available or if there is a

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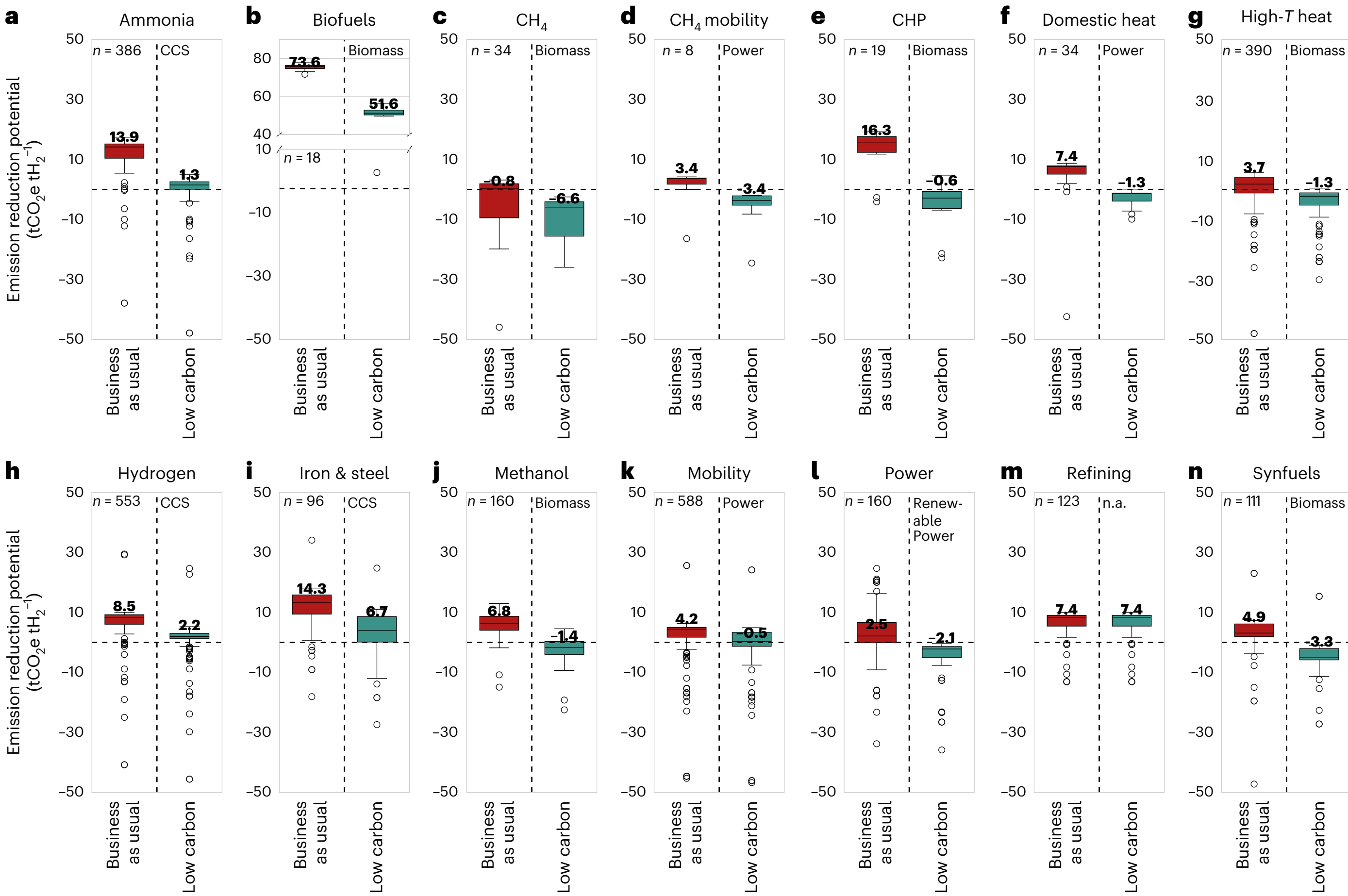

Fig. 4 | Boxplots showing the potential emission reductions for all hydrogen projects associated with the specific application, compared with business-as-usual and low-carbon scenarios. **a**, Ammonia. **b**, Biofuels (note the broken *y* axis). **c**, Methane. **d**, Methane mobility. **e**, CHP. **f**, Domestic heat. **g**, High-temperature industrial heat. **h**, Hydrogen. **i**, Iron and steel. **j**, Methanol. **k**, Mobility. **l**, Power. **m**, Refining. **n**, Synfuels. In the boxplots, the horizontal line inside the box represents the median. The box itself spans the IQR, capturing the central 50% of the data, with its lower and upper edges corresponding to the first (25th percentile) and third quartiles (75th percentile). The whiskers extend up to 1.5 times the IQR from these quartiles. The black circles represent outliers, that is, individual hydrogen projects with substantially lower or higher emission reduction potential. Sample size (*n*), representing the number of times hydrogen is supplied in considered hydrogen projects, is shown for each distribution. The subplots have shared primary *y* axes (except for the different *y*-axis scale for biofuels). The *y* axis illustrates the emission reduction potential per specific amount of hydrogen used in the application. The *x* axis illustrates the results based on two reference scenarios. The mean values of the emission reduction potentials for both reference scenarios are provided in each panel; positive values represent emission reduction potential per specific amount of hydrogen used, while negative values represent GHG emissions higher than the reference. n.a., not applicable.

need to improve flexibility. It is, however, important to ensure that this does not result in a lock-in effect for specific hydrogen applications. For example, entire transport supply chains may rely solely on hydrogen, while electrified alternatives are likely to perform better in the future.

Similar considerations apply to synfuels and methanol. Replacing conventional fossil-fuel-based kerosene with hydrogen-based kerosene (using atmospheric CO_2 from direct air capture) could have substantial emission reduction potential per unit of hydrogen used. This climate mitigation potential disappears when compared with (very) low-carbon kerosene production via biomass gasification pathways (using wood chips). Solely relying on biomass feedstock for all applications (of the facilities in the IEA database) within the low-carbon alternatives would require 6% of the 67-EJ current annual biomass supply[30]. However, if all future kerosene needs are to be met by low-carbon biomass-based kerosene (that is, synfuels using hydrogen via gasification of wood chips), this figure may increase to 35%. Hydrogen-based synthetic fuels are expected to play a pivotal role in the future of aviation and shipping, offering substantial emission reduction potential compared with fossil fuels. This is particularly true when considering aspects beyond GHG emission mitigation, since direct electrification alternatives for long-haul flights and ships are unlikely to be available in the next two decades and the scalability of biomass is limited.

Overall GHG emissions and the emission reduction potential of hydrogen applications

Figure 5 shows the annual (cumulative) GHG emissions and emission reduction potential of hydrogen applications up to 2043 compared with the two reference scenarios. Refining is excluded here as oil and gas products must be limited in a future low-carbon energy system. Figure 5 shows the following key findings.

First, the overall decarbonization strongly depends on the product or service the hydrogen application might replace. Second, overall GHG emissions of the analysed hydrogen applications will reach approximately 0.4 $GtCO_2e\ yr^{-1}$ by 2043; specific GHG emissions of hydrogen applications will decrease due to the expected decarbonization of the global economy, which we anticipate by modifying the background LCA database using a 2-°C scenario. Third, the use of hydrogen and derived products exacerbates the climate impact of hydrogen economies from around 0.23 $GtCO_2e\ yr^{-1}$ (dashed red line in Fig. 5a) to more than 0.4 $GtCO_2e\ yr^{-1}$, that is, leaving around half of the GHG emissions

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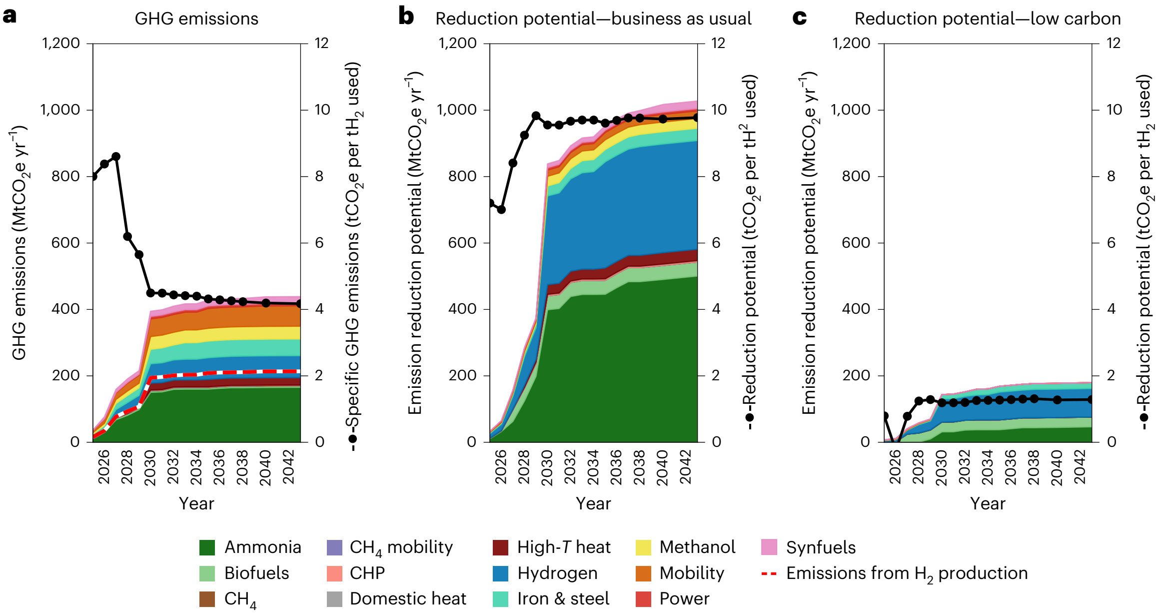

Fig. 5 | Total GHG emissions and emission reduction potentials of all hydrogen projects. a, Overall and specific life cycle GHG emissions of hydrogen applications. **b**, Overall and specific GHG emission reduction potential compared with the business-as-usual scenario. **c**, Overall and specific GHG emission reduction potential compared with the low-carbon scenario. The different colours indicate the contributions of the different applications regarding overall life cycle GHG emissions and emission reduction potential. The secondary *y* axes (black lines) show the average specific annual GHG emissions (**a**) and average emission reduction potential per specific use of hydrogen (**b**,**c**). The dashed red line in **a** provides the summed total GHG emissions from hydrogen production only. Only positive emission reduction potentials are illustrated.

unaccounted for if the hydrogen application is excluded from the quantification. Most of these overall GHG emissions are emitted by hydrogen used for ammonia production, mobility, unspecified use and steel-making.

Fourth, the highest overall emission reduction potential is derived from ammonia and hydrogen (unspecified application) in the GHG-intensive business-as-usual scenario. At the same time, all other applications have a minor contribution. The overall emission reduction potential is around 0.2–1.1 $GtCO_2e\ yr^{-1}$ by 2043, depending on the reference scenario. Fifth, the emission reduction potential is more than 80% lower in the low-carbon scenario than in the business-as-usual scenario.

Country-specific emission reduction potential

Figure 6 shows potential country-specific emission reduction potentials with breakdowns per application on the basis of the location of the hydrogen production facilities. It is worth noting that these results are to some extent hypothetical, as some of the underlying hydrogen projects may not materialize. Also, it is important to note that hydrogen production and application are most likely decoupled, and the trade of these products to different world regions might shift GHG emissions and emission reduction potential to other countries. The countries with the highest potential in the business-as-usual scenario are Australia (133 $MtCO_2\ yr^{-1}$), the United States (103 $MtCO_2\ yr^{-1}$) and Mauritania (97 $MtCO_2\ yr^{-1}$), representing almost a third of the global GHG emission reduction potential in the business-as-usual scenario. Most global emission reduction potential from announced projects is derived from ammonia production and hydrogen (application unspecified). The United States (almost all applications and derived products) and the United Kingdom (including high-temperature heat, refining and mobility) have a more varied set of hydrogen applications.

However, the overall emission reduction potential is most probably (much) lower due to more suitable low-carbon alternatives, mostly the ones based on direct use of low-carbon electricity, application of CCS and use of biomass as feedstock (Fig. 6b). As such, the overall net emission reduction potential may be reduced to less than 0.2 $GtCO_2\ yr^{-1}$ by 2043, mainly driven by hydrogen (unspecified application), ammonia, refining, biofuels and steel-making, while other applications have minor or even negative GHG mitigation contributions (that is, they emit more GHG emissions compared to the counterfactual scenario). Countries with the highest emission reduction potential in the low-carbon scenario are Mauritania (26 $MtCO_2\ yr^{-1}$), Panama (21 $MtCO_2\ yr^{-1}$, mainly due to the climate benefits of biofuels even if compared with the low-carbon alternative) and the United Kingdom (14 $MtCO_2\ yr^{-1}$).

These scenarios highlight two key insights. First, hydrogen deployment may be most climate effective for ammonia, biofuels and steel-making, as these offer the most substantial emission reduction potential regarding specific hydrogen utilization. This implies that countries could strategically prioritize these applications over others. Second, estimates regarding the overall contribution of hydrogen to the emission reduction potential of the global economy may be too optimistic if based on a comparison with current conventional processes and technologies relying on fossil fuels, as these can be expected to be phased out in a world of stringent climate policies, which a massive scale-up of hydrogen production and use would require.

Discussion

The IEA database allows a detailed assessment of the climate effectiveness of currently announced hydrogen projects, covering global hydrogen production and application. Our results imply that current hydrogen supply from announced projects (that is, 110 $MtH_2\ yr^{-1}$ by 2043) is insufficient to meet projected global demand (110–610 $MtH_2\ yr^{-1}$ by mid-century[5,31]), particularly when aiming at net-zero emissions targets and considering the fact that only a fraction of the announced projects will be implemented[32]. This aligns with recent implementation gaps identified by UN reports[21]. Due to this implementation gap and the non-negligible life cycle GHG emissions associated with hydrogen production, the emission reduction potential we

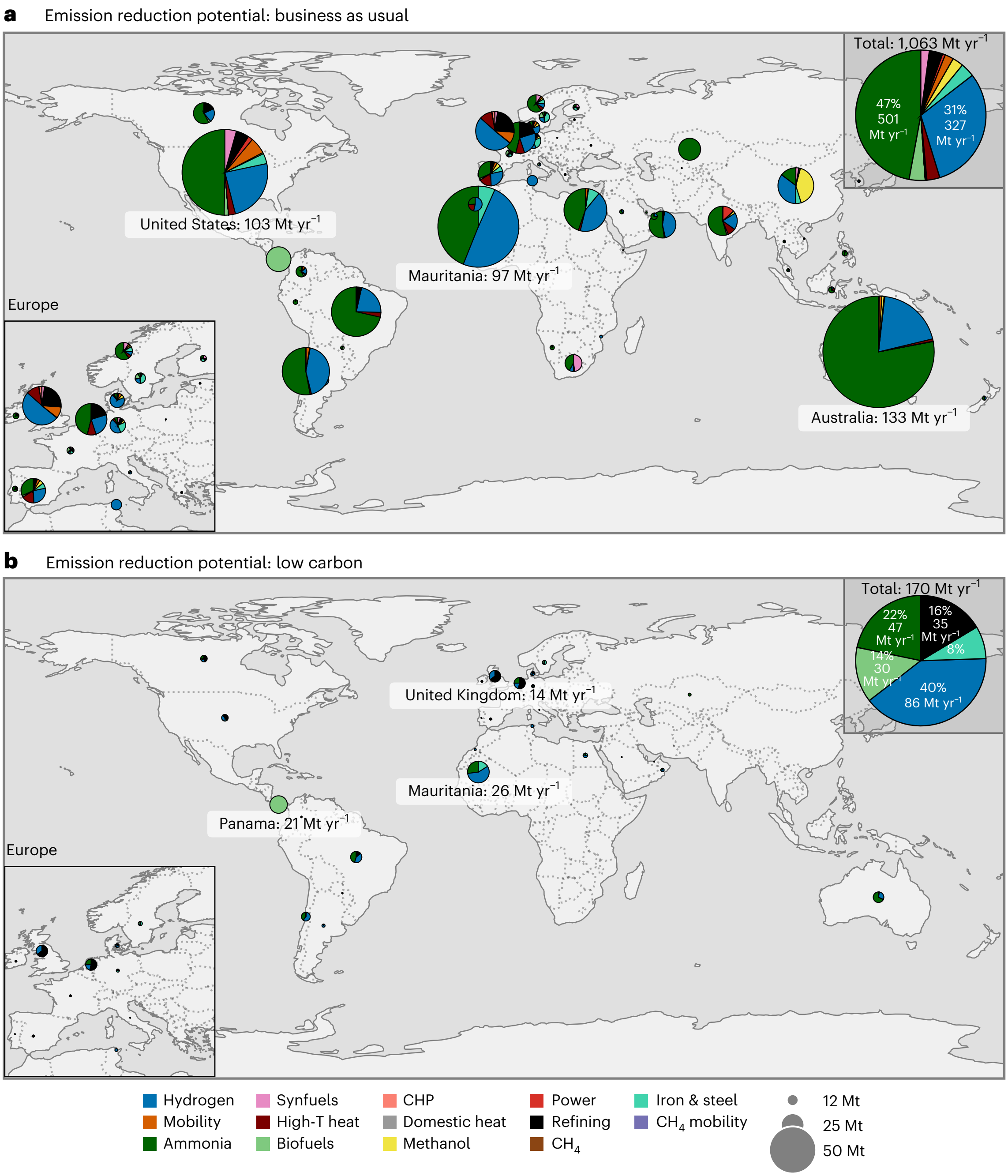

Fig. 6 | Annual country-specific net emission reduction potentials of planned hydrogen projects in 2043 compared with two reference scenarios. a, The business-as-usual scenario. **b**, The low-carbon scenario. The potential of each country is shown as a pie chart with its specific share of hydrogen applications. The size of the pie chart corresponds to the amount of emission reduction potential. The larger pie chart to the top right of each panel (not in proportion) illustrates the overall net global emission reduction potential. Note that the sum of GHG-mitigating hydrogen projects (in the larger pie chart) can exceed the "Total" value shown above the chart (that is, visible in the Total on the top right of **b**), as this total represents the net emission reduction potential, which also includes hydrogen projects that emit more GHG emissions compared to the reference scenario (resulting in a negative contribution). A zoom-in is provided for Europe to better visualize the initially overlapping pie charts for some countries. Basemaps from Natural Earth (https://www.naturalearthdata.com/).

quantify on the basis of currently announced projects is rather small, between 0.2 and 1.1 $GtCO_2e\ yr^{-1}$ (0.5–3% of global annual CO_2 emissions).

This broad range in GHG emission reduction potential and the variation in project- and application-specific GHG emission reduction is mainly driven by differences in hydrogen sources and the potential for each application to replace carbon-intensive alternatives. These findings remain consistent when using a different 2-°C scenario for modelling decarbonization efforts in the global economy (Supplementary Note 7 and Supplementary Figs. 8–10). Further analysis shows that, for most applications, the emission mitigation potential is primarily explained by integrating future changes that pertain to the decarbonization of the power sector. This is, of course, true especially when the hydrogen is produced from grid electricity, but not only then (Supplementary Note 7 and Supplementary Fig. 12). Additionally, the graph traversal analyses show that, generally, infrastructure-related emissions are relatively small compared with the supply and processing of the feedstock. However, exceptions exist. For example, the fuel cell stack and high-pressure tanks that equip a hydrogen-powered

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truck cause about as much GHG emissions as the hydrogen supply on a vehicle-kilometre basis (Supplementary Note 7 and Supplementary Fig. 11).

By addressing hydrogen production and its use, we can quantify project-specific GHG emission reduction potential and distinguish between effective and ineffective hydrogen applications and projects. As such, we identify steel-making, ammonia and (second-generation) biofuel production as the most promising hydrogen applications from a climate-benefit perspective. Further, considering the likely competition regarding limited sustainable biomass resources and the substantial future demand for sustainable aviation fuels (and methanol), we recommend considering synthetic hydrogen-based kerosene production as a climate-effective application. In contrast, due to higher process efficiency, electrified low-carbon alternatives—such as direct power generation, battery trucks and residential heat pumps—outperform competing hydrogen-based applications (that is, hydrogen use in power production, fuel cell trucks and domestic heating). Our analysis, however, provides a snapshot of current hydrogen project announcements on the basis of the IEA database, implying substantial uncertainty since many of these may not be implemented. Future hydrogen projects may differ, although the range of climate impacts will probably remain representative given the diversity of projects in the current database. Prospective energy systems modelling[5] could support future analysis to explore optimal hydrogen production locations.

Our findings represent a first comparative assessment of the climate mitigation potential of hydrogen applications. We include current feasibility studies and concepts for hydrogen projects, while the actual implementation of such projects is highly uncertain due to regulations and investment risks[33]. Failing implementation would reduce the overall estimated emission reduction potential. One key limitation of our analysis is the exclusion of economic criteria. A broader evaluation is needed for prioritizing certain applications. Applications with lower climate benefits in our analysis may still be attractive on the basis of strategic, economic or policy considerations[4,8]. Future research should integrate such socio-economic aspects, considering market behaviour and technological learning, potentially driving efficiency improvements and associated costs as well as climate impacts of hydrogen applications. These cost developments, potentially influenced by carbon pricing, are needed to understand the future adoption and performance of hydrogen applications and provide a more comprehensive assessment for informed decision-making[4,34]. To analyse this, our modular open-source framework may be (continuously) updated to assess the cost and environmental impacts of 14 hydrogen applications and thousands of hydrogen projects.

Finally, we provide the following recommendations for decision-makers. First, hydrogen development should be accelerated with supportive policy measures to enable a quick scale-up of climate-effective projects. Second, environmental LCA is needed to evaluate the climate benefits and mitigate other environmental burdens of hydrogen projects. Including the hydrogen application and derived products is decisive in such evaluations. Third, policies should be designed to prioritize hydrogen applications with the highest GHG emission reduction potential. Finally, the implementation gap between planned and required hydrogen projects should be seen not only as a challenge but also as an opportunity to guide future developments. By directing decision-makers and investors toward the most climate-effective hydrogen applications, future hydrogen projects can contribute to net-zero emissions targets in meaningful ways.

Methods

Our work quantifies the life cycle GHG emissions and emission reduction potential of roughly 2,000 announced hydrogen production facilities from the current year up to 2043, as provided by the IEA[20], and associated envisioned hydrogen and derived final product use, from a life cycle perspective.

IEA database

The IEA database[20] provides data on, among other things, the facility planned, the country, the year of installation, the hydrogen production capacity, the application of the hydrogen and the technology used to produce the hydrogen—which can be, for example, electrolytic hydrogen using different renewable power sources, such as solar PV, or nuclear or fossil-based hydrogen via steam methane reforming or coal gasification with CCS.

The IEA database[20] is used to generate LCIs for each hydrogen production facility, considering the hydrogen production technology, the derived product and the application of the hydrogen or the derived final products specified. As such, for most hydrogen production facilities, multiple hydrogen applications are given. To account for this, we evenly distribute the amount of hydrogen over the different end uses for each specific facility. We also exclude hydrogen production facilities with very low capacities (less than 10 $tH_2\,yr^{-1}$) and facilities installed before 2019 but still not operational. Additionally, we exclude decommissioned facilities from the database to consider only facilities that are or might be generating hydrogen in the future. Nonetheless, we include 99.9% of hydrogen production capacity represented in the IEA database.

Evaluation framework

Environmental LCA[24] is used to quantify GHG emissions of current and planned hydrogen production facilities up to 2043, including all relevant steps of the hydrogen value chains. The LCA database ecoinvent 3.10[24] with the "allocation, cut-off by classification" system model is used as the basic background LCI to calculate LCA results. The impact assessment method Environmental Footprint v.3.1 EN15804 global warming potential[35] is used to calculate life cycle GHG emissions (representing impacts on climate change), with an additional characterization factor of 11 kg CO_2e per kg H_2 to account for the indirect warming impact of emissions of hydrogen to the air (leakage)[36].

We aim to compare the hydrogen-based applications with alternatives providing the same service or derived product against two different reference cases: a business-as-usual scenario and a low-carbon scenario considering a decarbonized global economy in which most production processes and services are directly electrified, biomass based or, if relying on fossil resources, equipped with CCS. The system boundaries of our analysis include all supply chain activities from producing the hydrogen, the facility, up to the application of the hydrogen; these hydrogen uses and applications include producing oil products (refining), ammonia production, methanol production, steel production, high-temperature heat, using hydrogen for transportation/mobility, electrical power generation, CHP generation, residential heat supply, biofuels and synfuels. Refining of fossil fuels has been excluded as an application in the decarbonization analysis of Fig. 5 since sourcing the current amount of hydrogen for refining would lead to tremendous GHG emissions, and fossil fuels need to be phased out in a low-carbon future global economy. A suitable functional unit is defined if the technology differs from the reference process. A complete overview is given in Supplementary Note 3.

We focus on hydrogen use in second-generation biofuels, namely hydrotreated vegetable oil produced from used cooking oil, which is considered waste otherwise. Hydrotreated vegetable oil production requires hydrogen for upgrading, which makes it relevant to our analysis of hydrogen demand in biofuels.

The open-source Python package premise (v.2.2.7)[22] updates the LCA background data and integrates additional inventories associated with hydrogen production, use and derived products. Since the focus is on current and future hydrogen production facilities up to 2043, we produce different prospective background LCA databases using premise[22], considering a 5-yr interval. For this purpose, we use a scenario from the REMIND v.3.3 model[25,26]. This scenario leads to less than 2 °C of mean surface temperature increase relative to pre-industrial levels, following the shared socio-economic pathway SSP2[37], with a remaining carbon budget of 1,150 GtC between 2018 and 2100, called 'SSP2-PkBudg1150'. This scenario aligns with a potential hydrogen economy, which will probably only be implemented if a transformation to a low-carbon global economy materializes[5]. We link the hydrogen production facility with its start of operation date according to the IEA database to the LCIs corresponding to the 'nearest' 5-yr interval. To assess the results' sensitivity to the background scenario, the workflow is run with a scenario with a similar climate mitigation target, but from another model, IMAGE v.3.4 SSP2-RCP26[27]. This additional analysis reveals that the differences between the REMIND and IMAGE scenarios remain relatively marginal since the focus is on climate change impacts. In general, the emission reduction potential based on the IMAGE scenario is slightly lower, as it relies on CO_2 removal (mainly via bioenergy with CCS) to a larger extent than does the REMIND model. This CO_2 removal is not associated with specific hydrogen applications though. Including other impact categories could have amplified the differences between scenarios, but this is beyond the scope of our current analysis. If we had considered additional environmental impact categories beyond climate change, the differences between scenarios would probably be much more pronounced[22]. This offers a potential avenue for further research to ensure an optimal integration of hydrogen applications across a broader spectrum of sustainability indicators.

Additional LCIs

We generate additional LCIs for hydrogen production considering polymer electrolyte membrane, alkaline and solid oxide electrolysers. Solid oxide and alkaline electrolysers produce hydrogen at lower pressure levels (1 and 20 bar, respectively) than do polymer electrolyte membrane electrolysers (30 bar). We account for additional compression electricity required to compress hydrogen to 30 bar using the equations provided in the work of ref. 38.

Electrolytic hydrogen is produced at multiple sites using solar PV or wind power. While the IEA reports electrolyser capacity factors of 0.3 (solar PV), 0.4 (onshore wind) and 0.55 (offshore wind), we account for regional variability by generating LCIs across a range of capacity factors—incremented by 0.025 for solar PV and 0.05 for onshore wind—since recent work[5] revealed substantial differences in GHG emission factors of electrolytic hydrogen production when applying location-specific capacity factors of renewables[39–42]. Hence, when available, the facility's location provided by the database is matched with location-specific capacity factors. If this information is unavailable, country-specific average capacity factors are used for solar PV and onshore wind[39,41]. Average country-specific capacity factors from the Global Solar Atlas[41] (for solar PV) and Global Wind Atlas[39] (for onshore and offshore wind) are coupled with the generated (and most suitable) LCIs for electrolytic hydrogen production using these power sources. For onshore wind, the shapefile of the World Bank[43] is used for country boundaries to generate average country-specific onshore wind capacity factors. Cartopy[44] has been used to generate the global geospatial maps, which are made with Natural Earth.

One crucial addition to these LCIs is the consideration of the required oversizing of renewable generation capacities and the potential integration of batteries for stand-alone electrolysers powered by dedicated renewables without a grid connection. For example, if the electrolyser has a load factor of 0.3 in the case of solar PV-based hydrogen production facilities, either solar PV systems need to be oversized (and excess power curtailed) or batteries are required to achieve the load factor of the electrolyser, since a capacity factor of 0.3 for solar PV can be reached only with difficulty. To account for oversizing (and curtailment) and potential battery deployment to increase the capacity factor (and flexibility), an optimization problem is formulated to determine the optimal renewable energy capacity, curtailment and installed battery capacity. As in ref. 5, we use nonlinear curve fittings after applying the model to 120 case studies worldwide (960 optimizations) to determine the amount of curtailment needed and battery deployment using a cost optimization of hydrogen production systems. The cost parameters of the optimization problem are adjusted according to the technology and the year of manufacture and are given in Supplementary Note 5. Finally, the corresponding LCIs are adapted to the optimization problem solution. For offshore wind-based electrolytic hydrogen production, we assume the same capacity factor of the electrolyser (0.55) as for its wind power generation. The complete procedure, including the optimization problem, is explained in Supplementary Note 1.

In addition, we generate LCIs for nuclear- (~1% of facilities), hydropower- (~2% of facilities) and grid-power- (~9% of facilities) based hydrogen production by coupling them with a country-specific electricity source. Generating these additional LCIs enables a detailed linkage of the specific hydrogen production technology within a hydrogen application of a facility. Previous literature[45–48] has been used to generate the LCIs for hydrogen use in oil refining, iron and steel, and biofuel production. For hydrogen consumption by oil refining processing, we have neglected about half of the demand typically produced on site as a by-product of refining operations[46]. These LCIs can be found in the Zenodo repository[49]. Supplementary Note 3 includes the additional LCI data used to model hydrogen applications.

We generate a new LCI for each hydrogen production facility in the IEA database on the basis of the specified hydrogen applications, production methods and technologies (Supplementary Note 4). If multiple applications are specified, a separate LCI is created for each. Each facility–application pair is then linked and regionalized to the most appropriate hydrogen production source and inventory exchanges using the wurst Python package[23] (Supplementary Note 4). If no direct match is found, due to typographical errors or missing data, we use the rapidfuzz package to identify the closest match. We assign location- or country-specific hydrogen production sources for renewables (solar PV and onshore wind), nuclear, hydropower and grid electricity wherever possible.

Finally, life cycle GHG emissions are calculated for each hydrogen production facility, including the associated applications of hydrogen and derived products. These emissions are compared with two reference cases to assess reduction potentials: (1) a business-as-usual scenario using current fossil-based technologies and (2) a low-carbon scenario relying on alternatives such as biomass, low-carbon electricity or CCS. For instance, hydrogen-powered trucks are compared with diesel trucks (Euro VI) in the business-as-usual case, and with battery electric trucks in the low-carbon scenario, sourcing low-carbon power. Reference technologies for all cases are given in Supplementary Note 3. For transparency purposes, we show the contribution of each sectoral transformation applied by premise (v.2.2.7)[22] for all hydrogen applications. In addition, Supplementary Note 7 (and the Zenodo repository[49]) includes interactive Sankey diagrams that illustrate embodied GHG emissions along the hydrogen supply chain for the current and future (2040, on the basis of the REMIND scenario) contexts. A comprehensive table of alternative counterfactuals is provided in Supplementary Note 8.

Limitations

Our analysis provides decision support for specific hydrogen products and applications in different geographical regions. However, concerns remain regarding the overall feasibility of such a hydrogen economy. For example, low-carbon hydrogen production exhibits environmental trade-offs. It is energy intensive[5,50,51], thus requiring a tremendous expansion of renewable energy sources and large capacities of geological CO_2 storage volumes when relying on natural gas reforming with CO_2 capture. Future work should extend this analysis to costs, social aspects and broader sustainability indicators, such as land, water and material utilization.

The method exhibits other limitations. First, we considered one alternative for each application of hydrogen (or derived products), which may overlook differences in end-use efficiencies (for example, fuel cells versus combustion engines versus industrial processes), potentially affecting the estimated emissions reduction. A comprehensive discussion, in the form of a table, on alternative counterfactuals for the low-carbon scenario is provided in Supplementary Note 8. Some hydrogen production facilities might have been excluded from the IEA database (such as those provided by the Bloomberg database, https://about.bnef.com/), and limited information for some others may lead to slight deviations in calculated emissions, especially when no matching LCI is found—potentially misrepresenting the actual capacity factor (see "Life cycle inventories" in Supplementary Note 3). Second, the IEA database defines the capacity factor of electrolytic hydrogen production, which we used in our energy system optimization to quantify the oversizing of renewables, curtailment and potential battery deployment, statically. Designing hydrogen production configurations optimally—including the capacity factor of the electrolyser—could further reduce costs and environmental burdens[50]. Finally, the analysis only partially addresses hydrogen storage and transport challenges, especially for steel-making, heat and power generation. These involve energy losses and infrastructure requirements, further affecting the feasibility of hydrogen-based applications and their environmental impact, and increasing the burden shifts between regions.

Data availability

The data generated in this study can be found in a Zenodo repository: https://zenodo.org/records/16941997 (ref. 49). For hydrogen facility-specific information on location, project size, electrolyser technology and hydrogen application, we used the IEA Hydrogen Production and Infrastructure Projects Database (v.2024), accessible via https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database (ref. 20). For location-specific solar PV capacity factors, needed to build location-specific hydrogen production inventories, we used the Global Solar Atlas 2.0, a free, web-based application developed and operated by Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information see https://globalsolaratlas.info (ref. 42). For location-specific wind capacity factors, we used the Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by ESMAP. For additional information, see https://globalwindatlas.info (refs. 39,40). LCI files used in this study are sourced from the ecoinvent database (v.3.10)[24] and premise[22]. The LCIs for (low-carbon) steel production were confidential at the time of manuscript preparation, but are now publicly available through the work of Harpprecht et al.[48] in the following repository: https://zenodo.org/records/14968094.

Code availability

The code generated in this study can be found in a Zenodo repository: https://zenodo.org/records/16941997 (ref. 49).

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Author contributions

C.B. suggested the initial research question, which T.T. extended. T.T., C.M. and C.H. collected environmental data, while T.T. collected all other data. T.T. performed the analyses. T.T. and C.M. created the figures. All authors interpreted the results. T.T. wrote the paper with contributions from all authors.

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Competing interests

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