nature climate change

Article

https://doi.org/10.1038/s41558-026-02763-1

Prioritizing demand-side use of clean hydrogen for cost-effective mitigation

Received: 30 April 2026

Accepted: 3 September 2026

Published online: 15 October 2026

Check for updates

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Clean hydrogen can play a pivotal role in decarbonizing 'hard-to-abate' sectors. However, it cannot be universally adopted given energy-intensive production, high costs and limited near-term supply. It is therefore critical to prioritize clean hydrogen demands that deliver the most cost-effective emission reductions. Here we evaluate the decarbonization potential and economic costs of clean hydrogen in ten carbon-intensive sectors around 2035. Steelmaking, oil refining and ammonia production emerge as 'no-regret' sectors, offering the lowest levelized carbon mitigation costs, whereas hydrogen use in on-road and rail transport is economically unfavourable compared with direct electrification. Although policy support is needed to make clean hydrogen cost-competitive, production incentives are not an effective policy lever for prioritizing its use in 'no-regret' sectors. Uniform supply-side subsidies risk misallocating limited clean hydrogen supply and public funds. We conclude that sector-specific demand-side policies are required to align priorities and fully realize the decarbonization potential of clean hydrogen.

Clean hydrogen is expected to play a pivotal role in decarbonizing 'hard-to-abate' sectors that currently have no economically feasible technologies for deep decarbonization[1,2]. Hard-to-abate sectors include heavy industries that demand high-temperature heat (for example, cement production), use carbon-intensive feedstocks (for example, ammonia production) or require both (for example, steelmaking)[3]. Additionally, long-haul transportation modes, such as shipping and aviation, rely on energy-dense fuels and can be challenging to electrify[4]. These sectors collectively contribute over a quarter of global energy-related CO_2 emissions[2], posing a major challenge to worldwide climate change mitigation efforts.

Hydrogen has a wide array of potential applications, ranging from its traditional role as a chemical feedstock to its emerging use as a carbon-free energy carrier[5–7]. However, nearly all current hydrogen production (excluding by-product hydrogen) is reliant on natural gas (NG) or coal, making it both energy- and carbon-intensive. For hydrogen to contribute to deep decarbonization, the production of clean hydrogen—defined as hydrogen with life-cycle GHG emissions below specific thresholds (see Supplementary Table 9 for definitions across jurisdictions)—needs to scale up rapidly. In 2023, the USA introduced a production tax credit of up to US$3 kg^{-1} for clean hydrogen[8], although the availability of the credit was truncated by subsequent legislation in mid-2025[9]. Meanwhile, the European Union (EU), the UK, Australia, Canada, China, India and other nations are also implementing supply-side policies to boost clean hydrogen production[7].

Given its versatility, clean hydrogen is often described as the 'Swiss Army Knife of decarbonization'[10]. However, clean hydrogen production entails low energy efficiency, high costs and probably limited near-term supply[11,12]. In addition, hydrogen must compete with other low-carbon alternatives—such as electrification and carbon capture and sequestration (CCS)—in specific end-use sectors. Hydrogen is also a leak-prone gas, which indirectly warms the climate[13–16]. Given these challenges, strategically prioritizing the use of clean hydrogen in applications that deliver the greatest environmental and economic benefits is critical.

Despite the diversity of potential end-use applications, current government policies in major economies predominantly focus on

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supporting hydrogen production, while efforts to stimulate demand in 'no-regret' sectors lag behind. Although global clean hydrogen production targets by 2030 exceed 30 million metric tons per year (MMT yr^{-1}), demand targets remain below 10 MMT yr^{-1} (ref. 7). At the same time, much of the existing literature on clean hydrogen concentrates either on production technologies[17–19] or sector-specific applications[20–22], with limited academic studies[23,24] or industry reports[25,26] evaluating its broader role in decarbonization across several end-use sectors. These gaps underscore the need for a systematic cross-sectoral analysis that jointly evaluates the decarbonization potential and economic performance of clean hydrogen technologies, as well as the availability of alternative low-carbon pathways. Such analysis is essential for identifying priority applications, revealing limitations in current supply-side-focused policies and informing the design of effective demand-side measures.

In this study, we develop a systematic approach to evaluate the role of clean hydrogen in decarbonizing ten carbon-intensive sectors in the USA around 2035. We combine GHG emissions assessment with techno-economic analysis to quantify the GHG mitigation potential and economic costs of both hydrogen technologies and alternative low-carbon options—such as direct electrification and CCS—in each end-use sector. This approach enables both intrasectoral comparisons between clean hydrogen technologies and their alternatives within a specific sector and intersectoral comparisons of clean hydrogen applications across sectors. On the basis of these quantitative evaluations, we classify clean hydrogen applications into 'no-regret', 'maybe' and 'do-not-use' categories and identify their relative priorities for hydrogen allocation.

Using the US 45V clean hydrogen production tax credit (Supplementary Note 2) as an illustrative example, we show that uniform supply-side subsidies are not an effective policy lever for prioritizing clean hydrogen use in 'no-regret' sectors and can lead to inefficient allocation of limited clean hydrogen supplies and public funds. We conclude that sector-specific demand-side policies are crucial to maximize the environmental and economic benefits of clean hydrogen.

Hydrogen and alternative low-carbon technologies

We adopt two metrics to evaluate both hydrogen technologies and alternative low-carbon technologies in each sector: (1) decarbonization potential and (2) the levelized cost of carbon mitigation (LCCM). Decarbonization potential measures the effectiveness of a low-carbon technology in reducing GHG emissions by comparing its carbon intensity with that of the incumbent technology. LCCM quantifies the economic cost of mitigating one ton of CO_2-equivalent GHG emissions (US\$ tCO_2e^{-1}). See Methods for further details.

For each end-use sector, we evaluate hydrogen technologies alongside a range of alternative low-carbon technologies, such as direct electrification and CCS. We present results for hydrogen technologies and the best-performing alternatives in each sector in Figs. 1 and 2, with detailed sector-specific decarbonization contexts provided in Supplementary Notes 3–13.

Steelmaking

Blast furnace-basic oxygen furnace (BF-BOF) and direct reduced iron (DRI) are currently the two dominant routes for primary steel production worldwide. Our analysis shows that both routes require green hydrogen to achieve deep decarbonization. In the BF-BOF route, green H_2-DRI replaces the blast furnace—the most carbon-intensive process in steelmaking—reducing carbon emissions by 82% (Fig. 1). In existing NG-DRI facilities, green hydrogen can replace NG-derived reducing gases, reducing carbon emissions by 67%.

Although green H_2-DRI requires substantial capital expenditures to build new DRI reactors and melters when replacing BF-BOF and relies on relatively expensive green hydrogen as a reducing agent, its substantial emission reductions result in a comparatively low cost (~US\$120–230 tCO_2e^{-1}; Fig. 2). CCS is the best alternative decarbonization technology for steelmaking but reduces emissions by only ~50%. Thus, although CCS and H_2-DRI routes have comparable LCCMs, hydrogen-based routes deliver substantially greater overall emission reductions.

Oil refining and ammonia production

Green hydrogen can serve as a drop-in replacement for fossil-based hydrogen in both sectors[27,28]. In oil refineries, replacing fossil-based hydrogen feedstock with green hydrogen, together with carbon capture in fluid catalytic cracking units, reduces carbon intensity by 33% (Fig. 1) and yields a relatively low LCCM of US\$154 tCO_2e^{-1} (Fig. 2). Further deployment of high-temperature thermal energy storage (TES) for process heating increases the overall emission reduction to 94%. In conventional ammonia production, hydrogen production through NG-SMR accounts for more than 97% of total GHG emissions. Substituting green hydrogen for this grey hydrogen therefore reduces emissions to near zero, with a relatively low LCCM of US\$158 tCO_2e^{-1}. In contrast, blue hydrogen is insufficient for deep decarbonization in either oil refining or ammonia production, as it reduces emissions by only ~70%.

On-road transportation

For on-road vehicles, replacing internal combustion engine powertrains (ICEPs) with battery-electric powertrains (BEPs) can reduce carbon intensity by ~75–90% when powered by projected 2035 US grid electricity (Fig. 1), primarily driven by the considerably higher energy efficiency of BEPs. By contrast, fuel cell-electric powertrains (FCEPs) using grid hydrogen are estimated to have a carbon intensity 210–240% higher than that of BEPs. This difference reflects the lower overall efficiency of FCEPs[29,30] and considerable hydrogen leakage across the transportation hydrogen supply chain[31].

Although BEP trucks are expected to have purchase costs comparable to ICEPs by the 2030s, they offer considerably lower fuel and maintenance costs (Fig. 2). Consequently, their LCCM ranges from −US\$400 tCO_2e^{-1} to −US\$150 tCO_2e^{-1}, indicating simultaneous reductions in emissions and costs. In contrast, FCEPs exhibit higher LCCM than BEPs across all vehicle types, owing to the relatively low energy efficiency of fuel cells (~50%) (refs. 29,30), high hydrogen leakage rates (~13%) (ref. 31) and high hydrogen delivery and dispensing costs (~US\$5 kgH_2^{-1}) (refs. 32–34).

Freight rail

Most US freight trains are powered by diesel-electric locomotives (DELs)[35–37]. Replacing DELs with battery-electric locomotives (BELs) reduces GHG emissions by 78% when powered by projected 2035 US grid electricity (Fig. 1). Although this transition requires additional capital expenditures in battery tender cars and power-delivery wires[35], the resulting fuel and maintenance cost savings exceed these added costs, yielding a negative LCCM of −US\$30 tCO_2e^{-1} (Fig. 2). In contrast, fuel cell-electric locomotives (FCELs) using grid hydrogen have a carbon intensity 190% higher than that of BELs. FCELs also have a higher LCCM because of the high costs of hydrogen production and dispensing.

Fuels and synthetic chemicals/fuels

When green hydrogen is used as a carbon-free fuel in cement production or for firm electricity generation, the LCCM is relatively high (>US\$230 tCO_2e^{-1}; Supplementary Notes 6 and 7), primarily because of the replacement of low-cost fossil fuels. When used as a feedstock for synthetic chemical/fuel production, such as e-methanol for long-haul shipping and sustainable aviation fuel (SAF) for long-haul aviation, the LCCM is substantially higher (>US\$500 tCO_2e^{-1}, Fig. 2) because of the large demand of green hydrogen and the high cost of an additional key feedstock, namely carbon-neutral CO_2.

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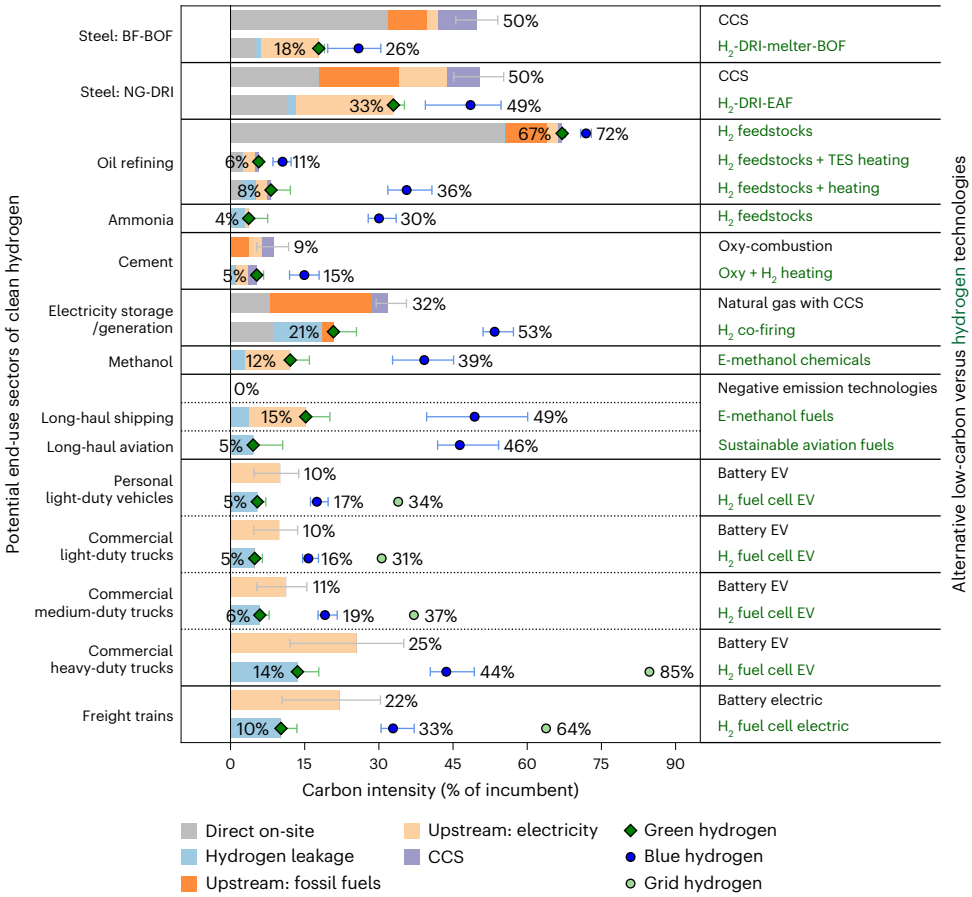


Fig. 1 | Carbon intensity of hydrogen and the best alternative low-carbon technologies in each end-use sector. Carbon intensity values are expressed as percentages relative to the corresponding incumbent technologies. Coloured bars decompose carbon intensity into direct on-site emissions, emissions associated with hydrogen leakage, upstream emissions of fossil fuel and electricity production and emissions associated with CCS. Hydrogen technologies are identified by green labels on the right. Results for hydrogen technologies are shown for both green and blue hydrogen. Grid hydrogen (produced via water electrolysis using grid electricity) is included for the transportation sector. Error bars indicate uncertainties in carbon intensity arising from variations in key assumptions (Supplementary Note 14). Detailed sectoral analyses are provided in Supplementary Notes 3–13. EV, electric vehicle.

Relative competitiveness of green hydrogen

On the basis of the relative competitiveness of green hydrogen across potential end-use sectors, we classify them into three groups: 'no-regret', 'maybe' and 'do-not-use'. Relative competitiveness is evaluated using two metrics: whether a hydrogen technology achieves (1) a lower carbon intensity and (2) a lower LCCM than the best-performing alternative low-carbon technology. We present the relative competitiveness of hydrogen technologies across end-use sectors in Fig. 3, with detailed sector-by-sector comparisons provided in Supplementary Table 8.

We identify three 'no-regret' end-use applications of green hydrogen: steelmaking, oil refining and ammonia production, which have the lowest relative GHG emissions and LCCM. Green hydrogen can directly replace grey hydrogen currently used in oil refining and ammonia production, achieving a relatively low LCCM of ~US$150–160 tCO_2e^{-1}. In steelmaking, despite the high transitioning cost to green H_2-DRI, the large emission reductions yield a low LCCM of ~US$120–230 tCO_2e^{-1}. Alternative low-carbon options, such as CCS or blue hydrogen, cannot achieve comparable levels of deep decarbonization. Given that hydrogen technologies offer the most effective and cost-competitive decarbonization pathways, these applications should be prioritized for green hydrogen deployment.

Conversely, we classify on-road and rail transportation as 'do-not-use' applications. BEPs outperform hydrogen FCEPs in both GHG emissions and LCCM metrics, as a result of their higher overall energy efficiency and the high costs of hydrogen production and dispensing. Moreover, the necessary hydrogen infrastructure for transportation sectors—such as hydrogen liquefaction facilities and fuelling stations—is not yet in place and would take considerable time to build. Such widespread infrastructure would be expensive to construct and operate[32–34] and could result in high hydrogen leakage rates[31,38]. Given that direct electrification offers both lower emissions and lower costs, hydrogen use in on-road and rail transportation is not recommended.

We classify the remaining applications as 'maybe' applications, for which green hydrogen should be carefully evaluated against alternative decarbonization options before deployment. When green hydrogen is directly used as a fuel—such as for oil refining, cement production and electricity generation—hydrogen technologies typically have comparable or lower GHG emissions but higher LCCM than alternatives. Their relatively high LCCMs reflect both the higher cost of green hydrogen compared with fossil fuels and the smaller emission reductions achieved compared with 'no-regret' sectors. Green hydrogen should therefore be considered for these applications only where abundant, low-cost supply is available and demand from 'no-regret' applications has been fully met.

For synthetic chemicals and fuels that replace fossil-based counterparts—such as e-methanol production for replacing conventional methanol and fuelling long-haul shipping, as well as SAF production for long-haul aviation—the LCCM remains high because of the high costs of both green hydrogen and carbon-neutral CO_2 feedstock. These products must also compete with the continued use of fossil fuels offset by negative emission technologies (Supplementary Note 11), which may have LCCMs within a similar range (Fig. 2). These

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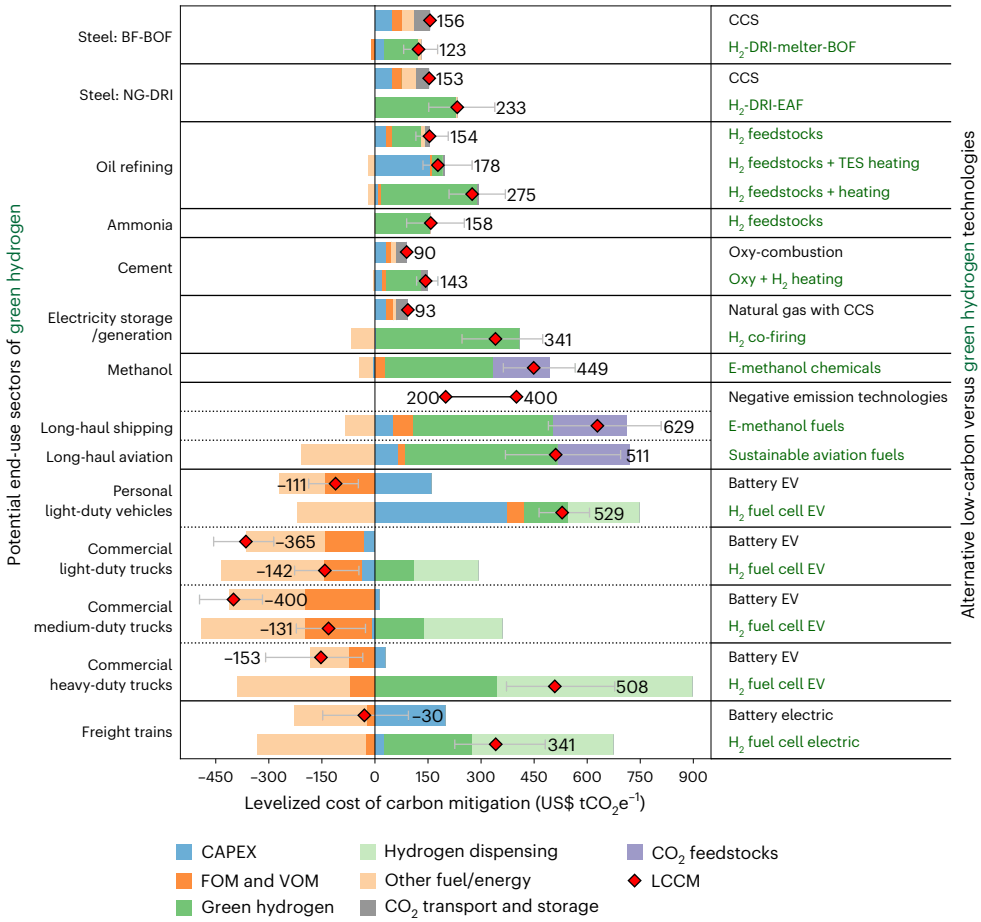


Fig. 2 | LCCM for green hydrogen and the best alternative low-carbon technologies in each end-use sector. LCCM represents the cost of abating 1 tCO_2e emissions by deploying a specific low-carbon technology. Coloured bars decompose LCCM into capital expenditures (CAPEX), fixed and variable operating and maintenance costs (FOM and VOM), hydrogen and dispensing costs, other fuel and energy costs (excluding hydrogen), CO_2 transport and storage costs and CO_2 feedstock costs. Error bars indicate uncertainties in LCCM arising from variations in key assumptions (Supplementary Note 14). Hydrogen technologies are identified by green labels on the right. All hydrogen technologies are assumed to use green hydrogen. Detailed sectoral analyses are provided in Supplementary Notes 3–13.

applications should therefore be pursued only when green hydrogen and carbon-neutral CO_2 become sufficiently inexpensive to achieve competitive LCCM.

Misaligned emission reduction and private sector priorities

Our analysis reveals a notable misalignment between emission reduction priorities, which aim to maximize GHG abatement and the objectives of private sector actors, who seek to maximize profits. From an emission reduction perspective, the limited supply of clean hydrogen should be allocated to sectors that deliver the greatest emission reductions at the lowest cost. Accordingly, we rank hydrogen end-use applications by their LCCM within each of the 'no-regret', 'maybe' and 'do-not-use' categories (Fig. 4a). Meanwhile, to capture the perspective of private sector actors, we calculate the break-even hydrogen cost (BH_2C) of end-use applications (Fig. 4b), representing the hydrogen price at which hydrogen technologies reach cost parity with incumbent technologies. See Methods for further details.

As the cost of green hydrogen declines—either through technological progress or supply-side subsidies—sectors with higher BH_2C are more likely to adopt hydrogen technologies earlier. If emission reduction and private sector priorities were aligned, BH_2C would decrease as LCCM increases. However, this pattern is not observed in Fig. 4 (panel a versus panel b), revealing a clear misalignment between emission reduction goals and private sector incentives for hydrogen adoption. This misalignment reflects a heterogeneous transition gap across sectors.

The 'no-regret' end-use applications of green hydrogen—including steelmaking, oil refining using hydrogen as feedstock and ammonia production—exhibit the lowest LCCM across sectors when excluding 'do-not-use' applications. Among them, oil refining and ammonia production have relatively high BH_2C values of US$1.4 kgH_2^{-1} because of the minimal fixed cost of transition. These sectors are therefore likely to adopt green hydrogen under a US$3 kgH_2^{-1} subsidy (equivalent to the full 45V value). In contrast, the transition from BF-BOF to H_2-DRI-melter-BOF in steelmaking has a negative BH_2C of −US$0.9 kgH_2^{-1}, due to the high capital expenditures required and the low cost of incumbent BF-BOF technologies. As a results, this transition would require a subsidy level as high as US$6 kgH_2^{-1}.

Conversely, certain 'do-not-use' transportation applications—such as commercial light- and medium-duty trucks—show very high BH_2C. These applications may adopt green hydrogen ahead of 'no-regret' applications, even though direct electrification provides a more cost-effective pathway to achieve deep decarbonization. Similarly, all 'maybe' applications exhibit higher BH_2C than the H_2-DRI-melter-BOF route and could therefore compete with steelmaking for limited green hydrogen supplies. Yet hydrogen use in these applications has a relatively high LCCM and uncertain competitiveness relative to alternative low-carbon technologies.

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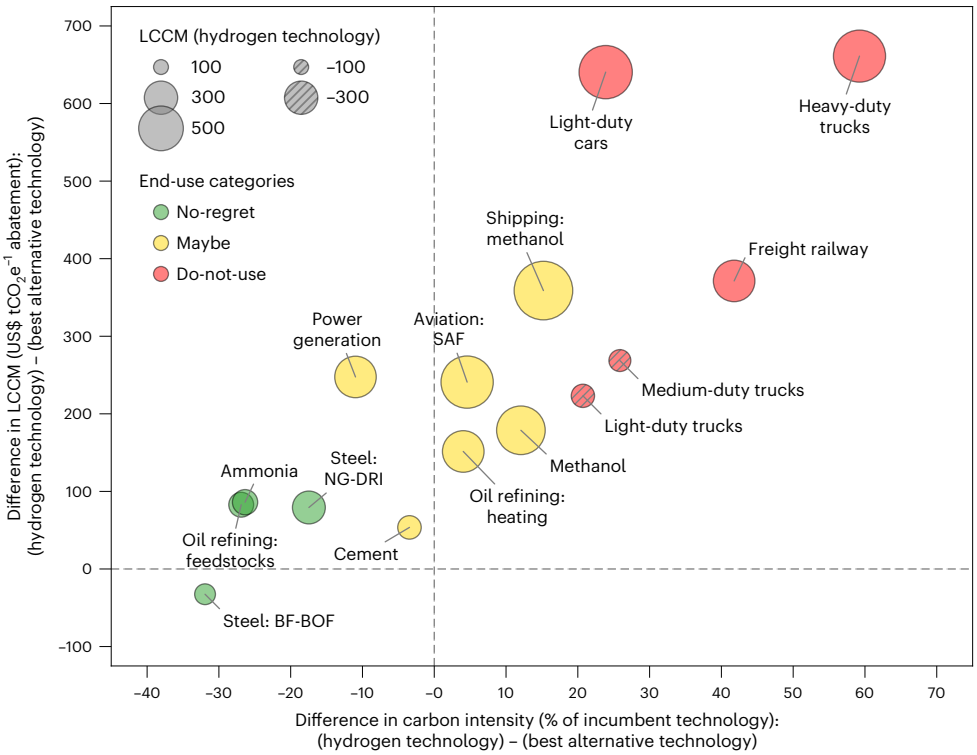


Fig. 3 | Relative competitiveness of green hydrogen in end-use applications. Carbon intensity (*x* axis) and LCCM (*y* axis) of hydrogen technologies are compared with those of the best alternative low-carbon technologies. On the basis of these comparisons, end-use applications are categorized into 'no-regret' (green circles), 'maybe' (yellow circles) and 'do-not-use' (red circles) groups. Circle size represents the absolute LCCM of hydrogen technologies. Detailed sector-by-sector comparisons are provided in Supplementary Table 8.

Ineffectiveness of supply-side subsidies

Uniform supply-side subsidies for clean hydrogen exert heterogeneous impacts across end-use applications and are ineffective in resolving the misalignment between emission reduction and private sector priorities. To quantify these effects, we calculate the levelized subsidy for carbon mitigation (LSCM) under various supply-side subsidy levels. LSCM is defined as the implied end-use subsidy per ton of CO_2-equivalent emission reductions (Fig. 5a). We also estimate the required hydrogen subsidy for cost parity, defined as the subsidy level needed for hydrogen technologies to achieve cost parity with incumbent technologies (Fig. 5b).

Despite being a 'no-regret' sector, steelmaking receives the lowest LSCM among sectors when excluding 'do-not-use' applications. Under a subsidy equivalent to the full 45V value (US$3 kgH_2^{-1}), the green H_2-DRI-melter-BOF route receives an LSCM of only US$64 tCO_2e^{-1}, as it requires relatively little hydrogen (57 kgH_2 t^{-1} of steel) while delivering substantial emission reductions (1.9 tCO_2e t^{-1} of steel). The green H_2-DRI-EAF (EAF, electric arc furnace) route similarly receives a low LSCM of US$151 tCO_2e^{-1}. However, when supply-side subsidies are used as the sole policy lever, subsidy levels would need to reach US$5–6 kgH_2^{-1} to incentivize hydrogen adoptions in steelmaking applications. This high required subsidy level indicates that supply-side subsidies alone are not an effective policy instrument for supporting hydrogen adoption in the steel sector.

In contrast, some 'maybe' applications—such as e-methanol and SAF production—consume large amounts of hydrogen and therefore receive the highest LSCMs under 45V (~US$200–300 tCO_2e^{-1}). The 45Q tax credit for carbon capture provides additional support for these applications under the US policy framework, further increasing the concentration of public subsidies in these relatively high-cost mitigation pathways.

Supply-side subsidies for green hydrogen may also extend to 'do-not-use' application in on-road and rail transportation. By lowering the overall cost of hydrogen FCEPs, these subsidies could inadvertently encourage hydrogen adoption in applications for which more cost-effective low-carbon alternatives are available.

In summary, uniform supply-side subsidies for clean hydrogen—such as the 45V production tax credits—disproportionately benefit applications that consume large amounts of hydrogen. They are excessively generous for 'maybe' and 'do-not-use' sectors while falling short for key 'no-regret' applications such as steelmaking. As a result, supply-side subsidies alone fail to align the priorities of private sector actors with the priorities of emission reduction.

Discussion

The global clean hydrogen industry has expanded substantially over the past decade, supported by ambitious policy targets and growing private investment. However, it continues to face investment volatility and policy uncertainty[39], contributing to a persistent gap between announced and realized projects[12]. In the USA, the policy landscape shifted dramatically in 2025. The One Big Beautiful Bill Act of 2025[9] cut the window of eligibility for the 45V tax credit established under the Inflation Reduction Act of 2022[8] by 5 years, terminating it for projects starting construction after 2027 (Supplementary Note 2). Likewise, the Bipartisan Infrastructure Law[40] of 2021 allocated US$8 billion to establish seven regional clean hydrogen hubs[41] across the country; however, in October 2025, the current administration cancelled federal funding for two hubs[42,43] and the remaining five also face substantial funding uncertainty. These changes are likely to constrain clean hydrogen supply in the USA for the foreseeable future, further underscoring the importance of allocating limited supplies to applications that deliver the greatest climate benefits.

Amid ongoing policy uncertainty at the federal level, state-level initiatives are becoming increasingly important in the USA. Yet existing state hydrogen policies are not designed to direct clean hydrogen towards 'no-regret' sectors and often remain focused on 'do-not-use'

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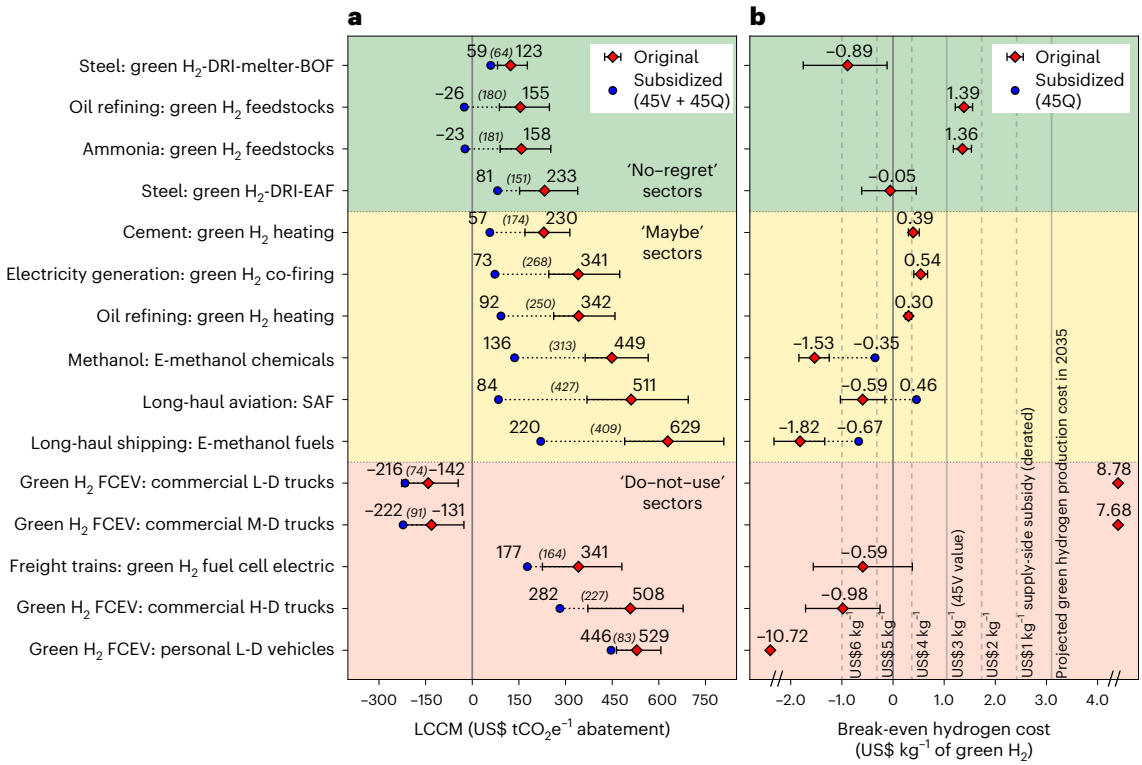


Fig. 4 | Misaligned emission reduction and private sector priorities. **a**, End-use applications are ranked by LCCM within each category, reflecting emission reduction priorities aimed at maximizing GHG mitigation under limited resources. The values in italics indicate the differences between the original and subsidized LCCM. **b**, BH_2C reflects private sector priorities, with higher BH_2C indicating stronger economic incentives to adopt hydrogen technologies at a given hydrogen cost. Subsidized LCCM incorporates a US$3 kg^{-1} of green hydrogen subsidy (equivalent to the full 45V value) and the 45Q credit for CCS, whereas subsidized BH_2C reflects the impacts of the 45Q credit. All nominal subsidy values are derated to account for project lifetimes exceeding policy durations (Supplementary Note 2). Error bars indicate uncertainties in LCCM and BH_2C arising from variations in key assumptions (Supplementary Note 14). All hydrogen technologies are assumed to use green hydrogen with zero production emissions. H-D, heavy-duty; L-D, light-duty; M-D, medium-duty.

transportation applications, as exemplified by several initiatives in California[44–46]. Targeted demand-side support is also insufficient in other major economies. Although jurisdictions such as the EU[47] and China[48] have introduced strategic clean hydrogen plans, these initiatives continue to emphasize electrolyser deployment and clean hydrogen production targets. Systematic demand-side strategies that prioritize high-value uses of clean hydrogen remain largely absent. See Supplementary Note 15 for a detailed discussion of current clean hydrogen policies in US states, the EU and China.

Taken together, these examples highlight a common global pattern: policy frameworks remain heavily skewed towards scaling clean hydrogen supply, while mechanisms to guide efficient demand allocation are underdeveloped. To realize the full decarbonization potential of limited near-term supply of clean hydrogen and promote efficient use of public funds, we put forward three policy recommendations.

First, supply-side subsidy levels should be carefully designed and dynamically adjusted over time. Such subsidies are particularly effective in encouraging existing fossil-based hydrogen users to switch to clean hydrogen. However, subsidy levels should be calibrated to achieve cost parity between clean hydrogen and fossil-based hydrogen and progressively reduced as clean hydrogen costs decline. This approach would minimize public expenditure and limit the 'leakage' of subsidized hydrogen into 'maybe' or 'do-not-use' applications.

Second, targeted demand-side support is essential for mobilizing capital- and innovation-intensive sectors that cannot be effectively supported by supply-side measures alone. Potential policy instruments may include (1) direct government funds for commercial demonstration and deployment[3], (2) government-led investment and financing for project construction[49] and (3) green public procurement policies[50] and offtake agreements with downstream users[51]. These measures can reduce upfront investment risks and increase market certainty, thereby accelerating clean hydrogen adoption.

Third, policy-makers should refrain from introducing additional demand-side incentives for 'do-not-use' transportation applications. These applications rely on hydrogen distribution and fuelling infrastructure that is either minimal or nonexistent and costly to build and operate[34,45]. Without careful planning, such infrastructure risks becoming stranded assets or lock the transportation sector into a more costly decarbonization pathway. Policy-makers should therefore exercise caution when supporting these applications and their associated infrastructure, particularly when more cost-effective alternatives are available.

Our analyses have several limitations and uncertainties. First, projected green hydrogen costs in the 2030s are highly sensitive to certain underlying assumptions. We conduct comprehensive sensitivity analyses and find that our main conclusions remain robust (Supplementary Note 14). Second, our analysis relies on currently available evidence and projected 2035 technology cost and emission assumptions, without explicitly modelling dynamic technology evolution or market feedback. Future work could extend this framework by incorporating endogenous learning, deployment spillovers, infrastructure constraints and multiperiod policy design. Third, we do not explicitly capture all transition barriers, especially non-economic ones[52,53]. Although some may be indirectly reflected in our sensitivity analyses, they extend beyond the scope of this study and merit further investigation. Fourth, our analysis is primarily based on a US-specific context. Therefore, the quantitative results should not be interpreted as directly transferable to other regions. Instead,

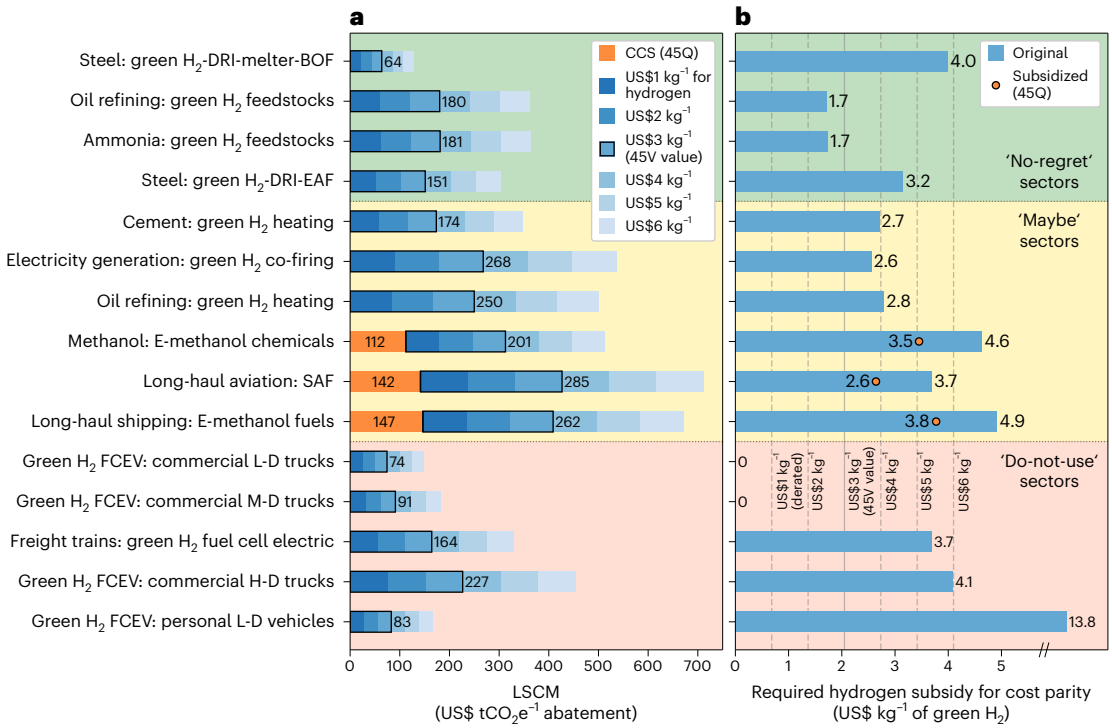


Fig. 5 | Ineffectiveness of uniform supply-side subsidies. a, LSCM. **b**, Required hydrogen subsidy for cost parity. End-use applications are ranked from lowest to highest LCCM within each category (Fig. 4a). Subsidized values (orange circles) in **b** reflect the impacts of the 45Q carbon capture subsidies. All nominal subsidy values are derated to account for project lifetimes exceeding policy durations (Supplementary Note 2). All hydrogen technologies are assumed to use green hydrogen with zero production emissions.

the analytical framework developed in this study provides a general approach and can be adapted to other contexts using region-specific data, assumptions and policy conditions.

In summary, strategic sector-specific demand-side policies, in conjunction with appropriate levels of supply-side subsidies, are essential to align private sector adoption of clean hydrogen with broader emission reduction goals. Such alignment is critical to ensure the optimal allocation of clean hydrogen across end-use applications and to maximize the environmental and economic benefits of clean hydrogen.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-026-02763-1.

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Methods

Decarbonization potential of low-carbon technologies

In this study, we evaluate the decarbonization potential of hydrogen technologies and alternative low-carbon technologies across sectors by comparing their GHG emissions with those of the corresponding incumbent technologies (Fig. 1). Our GHG emissions assessment includes scope 1 direct on-site emissions, scope 2 indirect emissions from purchased energy and key scope 3 upstream emissions associated with fuel and feedstock production and transport, methane leakage and hydrogen leakage. Other scope 3 emissions, including those associated with equipment manufacturing, infrastructure construction, maintenance and decommissioning, are excluded. Detailed GHG emission estimates for each technological route, along with comprehensive uncertainty analyses, are provided in Supplementary Notes 3–13. Uncertainties in key assumptions affecting GHG emission estimates are outlined in Supplementary Note 1 and their impacts are discussed in Supplementary Note 14.

Direct on-site emissions are determined by well-established stoichiometric and energy-balance relationships, with emission factors obtained from the literature. For upstream emissions, we apply consistent emission parameters across all sectors analysed, which primarily reflect emissions associated with electricity generation; the production, processing and distribution of fossil fuels; and hydrogen leakage across the supply chain. Specifically, we calculate the CO_2-equivalent GHG emissions for each technological route, incorporating the warming effects of both CO_2 and non-CO_2 GHGs. We use the global warming potential (GWP) as a metric to compare the impact of different GHGs on a common scale[54]. GWP measures the cumulative amount of heat a GHG traps in the atmosphere relative to carbon dioxide over a specific time frame, typically 20 yr (GWP-20), 100 yr (GWP-100) or 500 yr (GWP-500)[55]. Unless otherwise specified, all results reported in the main text and figures are based on GWP-100. We also present results based on GWP-20 in Supplementary Notes 3–13.

The upstream GHG emission factors are 0.72(0.62–0.90) kg CO_2e kg^{-1} for NG and 0.32(0.21–0.48) $kgCO_2e\ kg^{-1}$ for coal, which are calculated on the basis of a methane leakage rate of 1.6(1.3–2.1)% for NG[56] and 6.6(3.3–11.1) $gCH_4\ kg^{-1}$ for coal[57]. See Supplementary Table 2 for further details. In addition, we apply full-supply-chain hydrogen leakage rates of 2.2–3.1% for industrial sectors, 7.8–8.7% for hydrogen storage for power generation and 12.0–12.9% for transportation sectors[31]. Hydrogen is an indirect GHG with a GWP-20 of ~33 and a GWP-100 of ~11 (ref. 13). These hydrogen leakage rates correspond to GHG emissions of 0.36, 1.04 and 1.63 $kgCO_2e\ kg^{-1}$ of green H_2 delivered for industry, power generation and transportation, respectively. See Supplementary data available via Zenodo[58] for further details.

To compare the decarbonization potential of low-carbon technologies across sectors, we calculate the relative emission intensity of each technology by normalizing its carbon intensity to that of the corresponding incumbent technology. Results are expressed as percentages of incumbent carbon intensity. Key findings are summarized in Fig. 1, with detailed analyses provided in the Supplementary data via Zenodo[58].

LCCM

We calculate the LCCM for each technological route to enable comparisons both within a sector and across different sectors (Fig. 2). LCCM is a comprehensive metric that accounts for all-in economic costs (from the techno-economic analysis) and changes in GHG emissions (from the GHG emissions assessment) during the transition from an incumbent technology to a low-carbon alternative[59,60]. This metric helps policy-makers to identify sectors and technologies that can achieve emission reductions at the lowest mitigation cost, thereby informing public policies to support cost-effective deployment of clean technologies[61].

Equation (1) outlines the general approach used to calculate LCCM for a specific technological route.

$$\mathrm{LCCM}\left(\frac{\mathrm{US\$}}{\mathrm{tCO_2}}\right)=\frac{\mathrm{LCOX_{clean\ tech}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)-\mathrm{LCOX_{incumbent\ tech}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)}{\mathrm{GHG_{incumbent\ tech}}\left(\frac{\mathrm{tCO_2}}{\mathrm{unit\ X}}\right)-\mathrm{GHG_{clean\ tech}}\left(\frac{\mathrm{tCO_2}}{\mathrm{unit\ X}}\right)}\quad(1)$$

In equation (1), LCCM represents the costs of mitigating a unit of CO_2-equivalent emissions. LOCX represents the levelized cost of a specific technological route to produce (provide) a unit of X product (energy service), which is derived from the techno-economic analysis. $GHG_{clean\ tech}$ and $GHG_{incumbent\ tech}$ represent the carbon intensity of the low-carbon technology and the incumbent technology, respectively, derived from the GHG emissions assessment. The LCCM is calculated by dividing the difference between $LCOX_{clean\ tech}$ and $LOCX_{incumbent\ tech}$ (that is, the change in levelized cost) by the difference between $GHG_{clean\ tech}$ and $GHG_{incumbent\ tech}$ (that is, the change in GHG emissions). The unit for LCCM is US dollars per metric ton of CO_2-equivalent mitigation, denoted as US$ tCO_2e^{-1}. Further details on the LCCM calculation can be found in the Supplementary data via Zenodo[58].

We calculate the LCCM for hydrogen technologies and select alternative low-carbon technologies for each sector. The results for hydrogen technologies and the best alternative low-carbon technologies are summarized in Fig. 2. LCCM values for other technological routes, along with comprehensive uncertainty analyses, are detailed in Supplementary Notes 3–13. Uncertainties in key assumptions are outlined in Supplementary Note 1, while Supplementary Note 14 discusses their impacts.

BH_2C

We assess the BH_2C for each end-use sector to identify the hydrogen price at which private sector actors would have an economic incentive to adopt hydrogen technologies (Fig. 4b). When the levelized cost of a new technology exceeds that of the incumbent technology, private sector actors have little economic motivation to switch without additional policy support or regulatory constraints. Conversely, when the levelized cost of a new technology falls below that of the incumbent, private sector actors are more likely to adopt it voluntarily. As shown in Fig. 2, hydrogen costs constitute the largest component of LCCM for most hydrogen technologies, indicating that reductions in clean hydrogen costs are a key driver of hydrogen technology adoption.

Equations (2) and (3) show the general equation to calculate the BH_2C for an end-use sector of hydrogen.

$$\mathrm{BH_2C}\left(\frac{\mathrm{US\$}}{\mathrm{kgH_2}}\right)\times\mathrm{H_2\ intensity}\left(\frac{\mathrm{kgH_2}}{\mathrm{unit\ X}}\right)+\mathrm{LCOX_{H_2tech,excluding\ H_2cost}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)=\mathrm{LCOX_{incumbent\ tech}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)\quad(2)$$

$$\mathrm{BH_2C}\left(\frac{\mathrm{US\$}}{\mathrm{kgH_2}}\right)=\frac{\mathrm{LCOX_{incumbent\ tech}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)-\mathrm{LCOX_{H_2tech,excluding\ H_2cost}}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)}{\mathrm{H_2\ intensity}\left(\frac{\mathrm{kgH_2}}{\mathrm{unit\ X}}\right)}\quad(3)$$

In equations (2) and (3), LOCX represents the levelized cost of a specific technological route to produce (provide) a unit of X product (energy service). Importantly, $LCOX_{H_2\ tech\ excluding\ H_2\ cost}$ is identical to $LCOX_{H_2\ tech}$—the levelized cost of a specific hydrogen technology to produce (provide) a unit of X product (energy service)—except that the hydrogen cost itself is not included. H_2 intensity indicates the amount of hydrogen required by a specific hydrogen technology to produce (provide) a unit of X product (energy service). BH_2C denotes the BH_2C, expressed in US$ kgH_2^{-1}. The term $BH_2C \times H_2$ intensity represents the total cost of hydrogen to produce (provide) a unit of X product (energy service). Therefore, the left side of equation (2) represents the total levelized cost of a specific hydrogen technology. Equation (3) is a transformation of equation (2). We report the BH_2C for each hydrogen technology in Fig. 4b.

LSCM

We calculate the LSCM to quantify the heterogeneous impacts of uniform supply-side subsidies for clean hydrogen on different end-use sectors (Fig. 5a). We use the Section 45V Tax Credit for Clean Hydrogen Production (45V) under the Inflation Reduction Act (IRA) of 2022[8] as an illustrative example of such subsidies. We also consider the Section 45Q Tax Credit for Carbon Oxide Sequestration (45Q) when applicable. Detailed information on the 45V and 45Q tax credits is provided in Supplementary Note 2.

The LSCM represents the sum of the implied subsidies divided by the carbon mitigation achieved by adopting hydrogen technologies[21]. Equation (4) shows the general formula for calculating LSCM for a specific end-use application of clean hydrogen.

$$\mathrm{LSCM}\left(\frac{\mathrm{US\$}}{\mathrm{tCO_2}}\right)=\frac{45\mathrm{V\ credits}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)+45\mathrm{Q\ credits}\left(\frac{\mathrm{US\$}}{\mathrm{unit\ X}}\right)}{\mathrm{GHG_{incumbent\ tech}}\left(\frac{\mathrm{tCO_2}}{\mathrm{unit\ X}}\right)-\mathrm{GHG_{hydrogen\ tech}}\left(\frac{\mathrm{tCO_2}}{\mathrm{unit\ X}}\right)} \quad (4)$$

In equation (4), the LSCM represents the amount of implied IRA credits corresponding to 1 t of CO_2-equivalent emission reductions. The terms 45V credits and 45Q credits indicate the implied IRA credits for an end-use application of clean hydrogen to produce a unit of X product (energy service). $GHG_{hydrogen\ tech}$ and $GHG_{incumbent\ tech}$ represent the carbon intensity of the hydrogen technology and the incumbent technology, respectively. We divide the total implied IRA credits by the change in GHG emissions to get the LSCM. The unit of LSCM is US dollars per metric ton of CO_2-equivalent mitigation (US$ tCO_2e^{-1}). We report the LSCM for various hydrogen technologies in Fig. 5a.

Grey, blue, green and grid hydrogen

Currently, nearly all hydrogen production (excluding by-product hydrogen) in the USA relies on the steam methane reforming (SMR) process using NG[62]. The carbon intensity of NG-based hydrogen, known as grey hydrogen, can be as high as 11.6(11.3–12.2) $kgCO_2e\ kg^{-1}$ (Supplementary Table 1). Therefore, for hydrogen to contribute to deep decarbonization, the production process needs to be decarbonized first. In this study, we define 'clean hydrogen' as hydrogen produced either from SMR equipped with CCS—known as blue hydrogen—or from water electrolysis using zero-carbon electricity—known as green hydrogen. Both blue and green hydrogen have opportunities to qualify for partial or full 45V credits (Supplementary Note 2). We also define 'grid hydrogen' as hydrogen produced from water electrolysis using grid electricity, which is considered an alternative source of hydrogen for the transportation sector[34].

Blue hydrogen and green hydrogen differ substantially in their GHG emissions and production costs. Our analysis indicates that blue hydrogen has a carbon intensity of 3.3(3.0–3.9) $kgCO_2e\ kg^{-1}$ (Supplementary Table 1). The production cost of blue hydrogen is estimated at US$1.95(1.81–2.10) kg^{-1} (Supplementary Table 3), which can be reduced to US$1.47(1.32–1.62) kg^{-1} with 45V subsidies. By comparison, grey hydrogen cost is estimated at US$1.36(1.19–1.52) kg^{-1}. The higher cost of blue hydrogen is mainly because of the additional capital expenditures and CO_2 transport and storage costs required for CCS. See Supplementary Note 1 for further details.

Green hydrogen, produced from water electrolysis powered by zero-carbon electricity, is considered to have zero production emissions in this study. We also consider that the carbon intensity of green hydrogen has an upper limit of 0.45 $CO_2e\ kgH_2^{-1}$, which corresponds to the threshold required to qualify for full 45V subsidies under the IRA (Supplementary Table 6). We project that the production cost of green hydrogen will decrease to US$3.10(2.50–4.00) kg^{-1} by 2035 and 45V subsidies will further reduce the green hydrogen cost down to US$1.05(0.45–1.95) kg^{-1} (before distribution and fueling costs, if applicable). We also conduct comprehensive uncertainty analyses on key assumptions affecting green hydrogen cost. See Supplementary Note 14 and Supplementary data available on Zenodo[58] for further details.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data used and generated in this study are available in Supplementary Information and via Zenodo at https://doi.org/10.5281/zenodo.22214258 (ref. 58). Source data are provided with this paper.

Code availability

The code used in this study is available via Zenodo at https://doi.org/10.5281/zenodo.22214258 (ref. 58).

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Acknowledgements

Y.W. acknowledges graduate fellowship support from the Princeton School of Public and International Affairs at Princeton University.

Author contributions

Y.W., D.L.M. and J.D.J. conceptualized the research idea and designed the research procedures. Y.W. performed the research and produced the figures. M.A., F.C., Q.L. and A.T.D.P. contributed materials and data. Y.W. drafted, revised and finalized the paper. D.L.M. and J.D.J. advised on the analysis and reviewed and revised the paper.

Funding

This work was supported in part by Princeton University Zero-Carbon Technology Consortium, which is funded by gifts from Breakthrough Energy, Google and an anonymous foundation (M.A., F.C., Q.L. and A.T.D.P.).

Competing interests

J.D.J. is co-founder and CTO of Firma Power and serves as chief scientific advisor to Resilient, a technical advisor to Energy Impact Partners and MUUS Climate Partners and on the advisory boards of Eavor Technologies, Rondo Energy, Dig Energy, Karman Industries and Emerald AI. The other authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-026-02763-1.

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Peer review information *Nature Climate Change* thanks Michel Noussan, Natalie D. Popovich and Rui Shan for their contribution to the peer review of this work.

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Software and code

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Data collection	The data used in this study, along with its corresponding references, are available in the Supplementary Information and Supplementary Data files.
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Study description	In this study, we develop a systematic approach to evaluate the role of clean hydrogen in decarbonizing ten carbon-intensive sectors in the US circa 2035. We combine GHG emissions assessment with techno-economic analysis to quantify the GHG mitigation potential and economic costs of both hydrogen technologies and alternative low-carbon options—such as direct electrification and CCS—in each end-use sector. This approach enables both intra-sectoral comparisons between clean hydrogen technologies and their alternatives within a specific sector, and inter-sectoral comparisons of clean hydrogen applications across sectors.
Research sample	Ten carbon-intensive sectors.
Sampling strategy	n/a
Data collection	Source data and detailed references are included in the Supplementary Information and Supplementary Data files. The data are recorded by the authors.
Timing and spatial scale	We evaluate the decarbonization potential of clean hydrogen across ten carbon-intensive sectors circa 2035.
Data exclusions	n/a
Reproducibility	All source data, code, and generated data are included in the Supplementary Information and Supplementary Data files.
Randomization	n/a
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