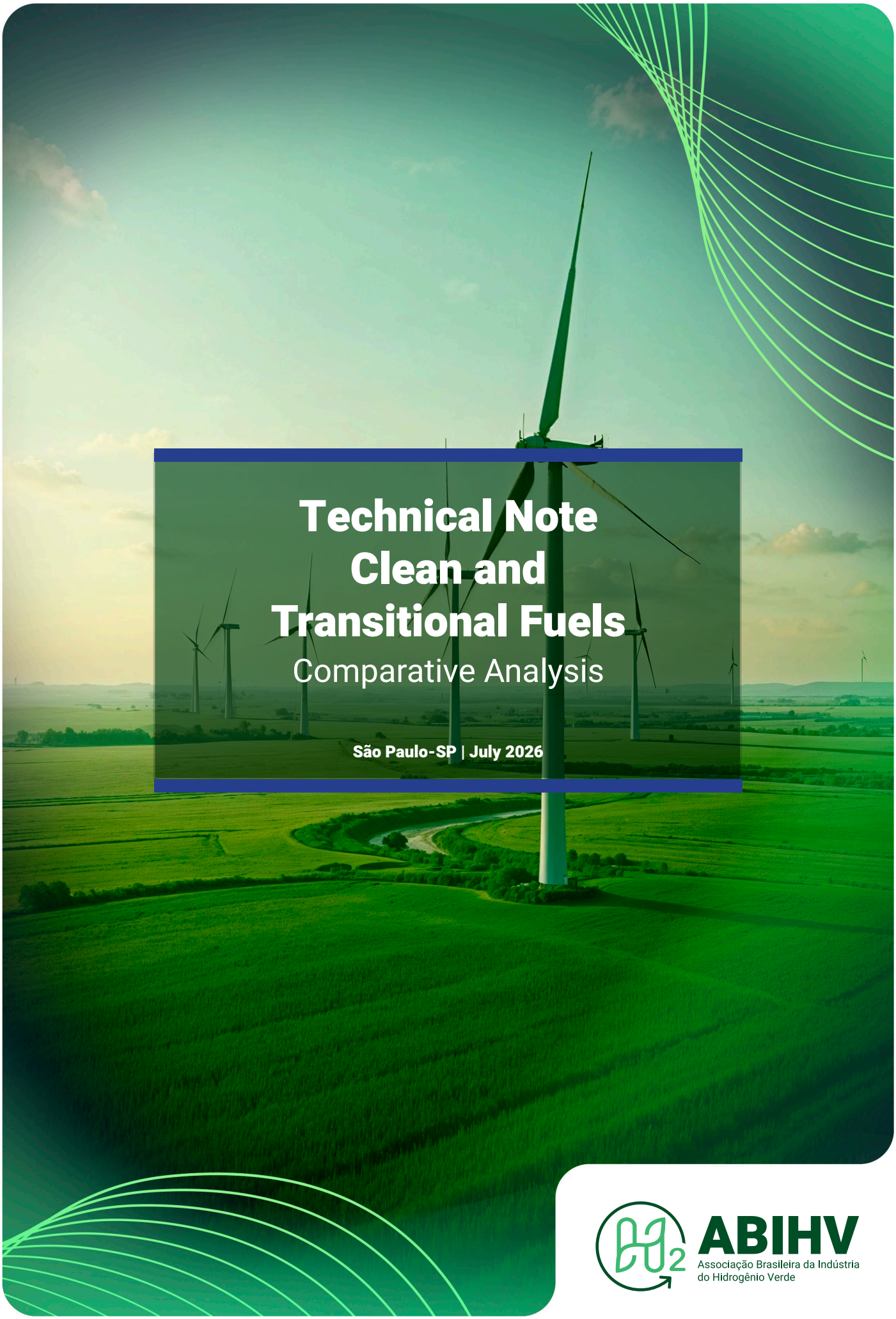


Technical Note Clean and Transitional Fuels

Comparative Analysis

São Paulo-SP | July 2026

ABIHV
Associação Brasileira da Indústria do Hidrogênio Verde

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Executive Summary

This Technical Note, prepared by ABIHV, analyzes the economic competitiveness of sustainable fuels compared to fossil fuels, focusing on the 2025 and 2030 time horizons. The study shows that the global energy transition is not only an environmental agenda, but also an opportunity for strategic reindustrialization in Brazil, with the potential to attract investments, create skilled jobs, and strengthen the national industry.

Key findings

- **Accelerating competitiveness (2025–2030).**
  Although fossil fuels still maintain a direct cost advantage in the short term, projections indicate a significant reduction in green hydrogen production costs by 2030. According to estimates by the IEA for regions with excellent wind and solar resources, the production cost of electrolytic hydrogen could fall to the range of US$ 1.5 to 2.2/kg by 2030 [14], mainly reflecting the reduction in electrolyzer CAPEX and the expansion of competitive renewable electricity supply.
  However, this is an indicative and conditional range, sensitive to factors such as energy costs, capacity factor, project scale, and cost of capital.

- **Effect of carbon pricing.**
  The introduction of carbon market mechanisms structurally alters the relative competitiveness between fossil-based and clean alternative molecules. With carbon pricing around US$ 100/tCO_2 [35] — a value adopted here as an analytical benchmark and consistent with the commonly cited international reference range of US$ 50 to 100/tCO_2 for 2030—green hydrogen tends to reach economic parity with gray hydrogen in various scenarios, significantly reducing, and in some cases nearly eliminating, the "green premium." This creates room for large-scale adoption of green hydrogen, ammonia, and methanol across industrial and transport sectors.

- **Logistics and global market.**
  The analysis indicates that, within the current cost and technology landscape, the most promising pathways for international trade in low-carbon hydrogen are those based on denser and more logistically established derivatives, particularly green ammonia. As a transoceanic transport vector, ammonia benefits from existing transport infrastructure, higher volumetric energy density, and more competitive supply chain costs, positioning it as the leading candidate for long-distance maritime flows.
  Pure hydrogen, in turn, is expected to play a primary role in regional markets, being consumed close to production hubs and distributed via pipelines or dedicated networks, where its use in gaseous form is more efficient than liquefaction and transport by ship.

- **Window of opportunity for Brazil.**
  Brazil has unique conditions—such as a predominantly renewable electricity matrix, abundant natural resources, and strategic port infrastructure—to lead relevant segments of the green hydrogen/green ammonia economy.

The definitive phase of the CBAM* entered into force in the European Union on January 1, 2026, and is expected to accelerate demand for low-emission products, creating a window of opportunity for Brazilian exporters to position themselves as preferred suppliers in decarbonized global value chains.

- **ABIHV recommendations.**
  To turn comparative advantages into effective competitiveness, ABIHV recommends:
  - Reducing the cost of capital for projects through policies that mitigate regulatory and exchange rate risks;
  - Advancing the implementation of a regulated carbon market that prices emissions and rewards low carbon intensity;
  - Promoting integrated industrial hubs for hydrogen and its derivatives, connecting renewable generation, molecule production, and end-use demand at scale.

This Technical Note provides objective inputs for policymakers, public-sector stakeholders, investors, and companies seeking to guide their decisions in light of the energy transition and the new demands of international competitiveness.



CBAM (Carbon Border Adjustment Mechanism) – The European Union's carbon border adjustment mechanism, which applies a carbon price to imports of emissions-intensive goods, aligning them with the carbon cost applied in the European market (EU ETS).

Current Overview (2026)

The energy landscape in 2026 highlights the coexistence of well-established fossil fuels and expanding low-carbon alternatives. A comparison on an energy basis (US$/MJ) allows for a more accurate analysis of the relative cost of each energy carrier, considering its lower heating value (LHV).

The data presented in **Table 1** were obtained from recognized sources, including the U.S. Energy Information Administration (EIA) [12,42], the World Bank's Commodity Markets Outlook: April 2025 [38], the IEA reports The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector [14] and The Role of E-Fuels in Decarbonising Transport [30], BloombergNEF publications [15,33,34], and CEPEA/ESALQ ethanol indicators [9,41].

All values were converted to **US$/kg** and **US$/MJ**, based on the average LHV of each fuel, according to international references.

Fossil fuels continue to dominate the global energy mix, driven by established infrastructure and historically low costs. **Natural gas** remains a transitional fuel, with an **energy cost of US$ 0.0033/MJ**, reflecting broad global supply and limited volatility. **Thermal coal**, although the cheapest on an energy basis, has the highest carbon intensity and is likely to lose competitiveness as carbon markets consolidate.

Among biofuels, **Brazilian sugarcane ethanol** demonstrates price stability and good energy density, establishing itself as a competitive low-carbon option in the short term.

Green fuels—such **as green hydrogen**, **green ammonia**, and **green methanol**—currently present higher energy costs, but are expected to see significant reductions by 2030, with hydrogen costs falling from **US$ 3.97/kg** to **US$ 1.85/kg**, according to IEA and BloombergNEF projections [14,33,34]. This trend is driven by the decline in electrolysis CAPEX from approximately US$ 1,000/kW to US$ 400–600/kW and the reduction in renewable electricity costs, which currently account for up to 70% of the total cost of the molecule.

In summary, the 2026 outlook confirms a gradual transition from a low-cost but carbon-intensive energy mix to an emerging scenario in **which clean molecules gain competitiveness**, driven by technological advances, climate regulation, and the expansion of carbon markets.

Qualitative Comparison of Fuels: Operational and Technological Aspects

The comparison between fossil fuels, biofuels, and e-fuels must go beyond direct energy costs, incorporating attributes such as biomass availability, net lifecycle emissions, technological maturity, and infrastructure and logistics requirements.

This distinction is central to this Technical Note, as it reinforces the rationale that molecules derived from green hydrogen have greater potential to assume a dominant role in medium- and long-term international markets, especially when combined with carbon pricing mechanisms and sectoral decarbonization policies (such as in aviation, shipping, and steelmaking).

In this context, beyond the quantitative comparison of energy costs, the assessment of competitiveness among fuels must consider qualitative factors such as efficiency, emissions, safety, infrastructure, technological maturity, and associated environmental and social externalities (for example, land use, local impacts, and accident risks). Diesel engines continue to exhibit high efficiency (up to 50%), which explains their predominance in heavy-duty transport, while natural gas can achieve similar performance in certain applications. Fuels such as ethanol, methanol, and ammonia have lower calorific value than diesel, resulting in lower thermal efficiency, although they offer relevant environmental advantages.

Figure 1 presents, in an integrated manner, how the **global supply of sustainable fuels** (biofuels, synthetic fuels/e-fuels, hydrogen, and derivatives) evolves and how this supply is absorbed by the **main demand sectors**—particularly aviation, shipping, heavy road transport, and industry—under an accelerated scenario through 2035. It highlights, over time, which energy carriers gain greater share in supply (for example, biofuels in the short term and e-fuels/hydrogen with stronger growth after 2030) and which sectors drive this expansion, indicating where market opportunities and challenges for sectoral decarbonization policies are concentrated.

Sustainable fuel supply by fuel type (left) and demand for sustainable fuels by sector (right) in the accelerated scenario, 2024–2035.

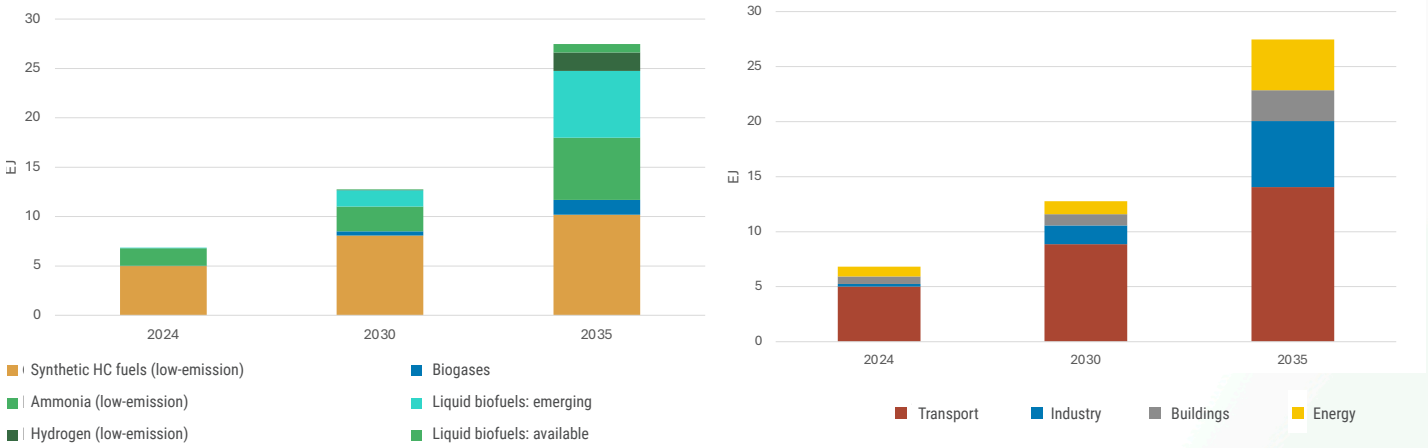


Figure 1. Sustainable fuel supply by fuel type and demand by sector in the accelerated scenario, 2024-2035. Source: Adapted from [4]
Notes: HC = hydrocarbon. "Liquid biofuels: available" refers to technology readiness level (TRL) 9, while "liquid biofuels: emerging" refers to TRL 7 or 8. "Industry" includes the on-site production of low-emission hydrogen, ammonia, and methanol, as well as the use of low-emission hydrogen in refineries. "Buildings" includes agriculture. "Energy" refers to electricity and heat generation in the energy sector.

From an emissions standpoint, diesel and natural gas remain associated with direct CO_2 emissions, while hydrogen and ammonia do not generate carbon emissions at the point of use, although they may produce nitrogen oxides (NOx) depending on combustion conditions, requiring proper control of these local pollutants.

Biofuels such as ethanol and methanol present lower—but not zero—carbon emissions, reinforcing the importance of the renewable origin of their feedstocks.

In terms of safety and operation, hydrogen presents higher flammability and requires high-pressure systems or cryogenic conditions, while ammonia, although less flammable, is toxic and demands stricter handling and emergency response protocols, especially in the event of leaks. Diesel and ethanol retain operational advantages due to their greater stability.

Existing infrastructure also favors fossil fuels and liquid biofuels, whereas hydrogen, ammonia, and methanol require substantial investments in storage, transport, and technological adaptations.

Technological Pathways

The set of technologies for producing sustainable fuels encompasses **biochemical** routes, **thermochemical** routes, and **hydrogen/electricity-based** processes, each with distinct requirements in terms of feedstock, infrastructure, and technological maturity. Biochemical routes (fermentation, enzymatic hydrolysis, among others) are well established for sugars and starches, while thermochemical routes (gasification + Fischer-Tropsch, hydrocracking, among others) are more suitable for lignocellulosic residues, wood, and municipal solid waste. Synthetic e-fuels, in turn, rely heavily on renewable hydrogen and captured CO_2, and still face relatively high costs. The choice of technology directly impacts operating costs, the need for integration with refineries or gas networks, and the speed of market deployment.

Feedstock selection—such as food crops, vegetable oils and waste fats, lignocellulosic biomass, organic waste, and CO_2 streams—determines lifecycle emissions intensity, socio-environmental risks, and eligibility for low-carbon certifications. Second-generation feedstocks and residues tend to present lower risks of competition with food and better sustainability profiles, but require more complex logistics and pre-treatment. On the other hand, conventional raw materials may offer lower initial costs, but with greater impacts on land use and potential for indirect land use change (**iLUC**), often cited as a critical issue in first-generation biofuels. Public policies and market mechanisms should prioritize robust greenhouse gas (GHG) accounting criteria and environmental safeguards

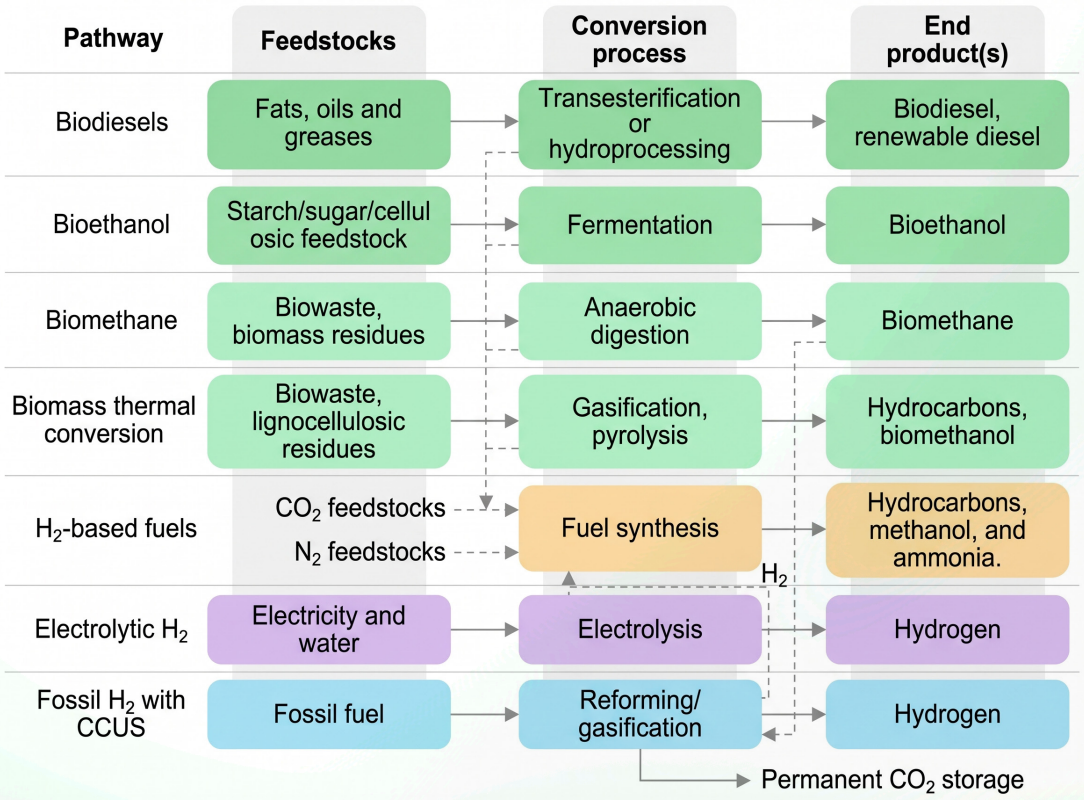


Figure 2. Production pathways for liquid and gaseous sustainable fuels. Source: Adapted from [4].

to guide investments. In the Brazilian context, the recent amendment to Article 225 of the Federal Constitution, which now provides for a favorable tax regime for biofuels and low-carbon hydrogen (§1, VIII), is an important example of this convergence. By ensuring lower taxation compared to fossil fuels, this provision creates a structural competitive advantage in favor of low-carbon technologies, aligning fiscal policy with the decarbonization agenda.

Technological Maturity

The transition between technological pathways and the evaluation of feedstocks requires considering not only environmental and economic suitability, but also the technology readiness level (TRL) of each alternative. **Figure 3** summarizes these TRLs for selected pathways and helps guide investment and scaling priorities.

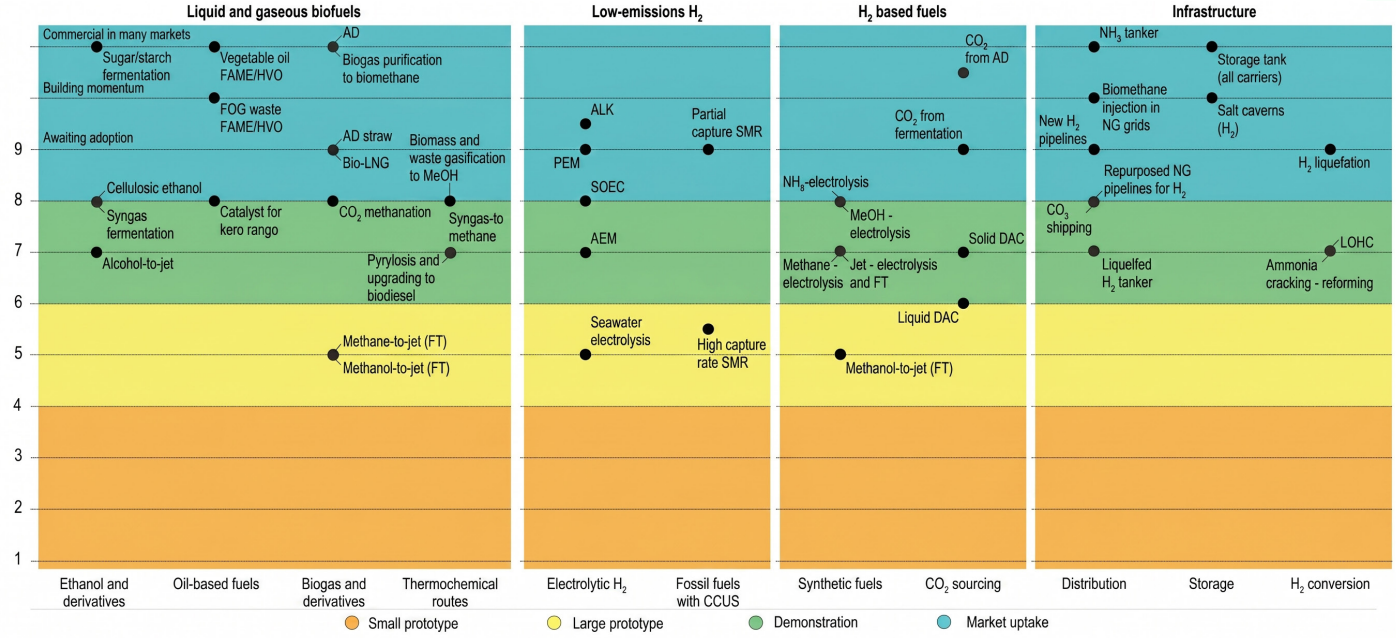


Figure 3. IEA Technology Readiness Levels (TRLs) for selected pathways. Source: Adapted from [4].
Notes: Based on the updated IEA TRL scale, in which the highest level is TRL 9. To provide additional insight into progress beyond TRL 9, three additional adoption levels are used: "awaiting adoption," "gaining momentum," and "commercial in many markets." See the IEA Global Hydrogen Review 2025 for further details.
AD = anaerobic digestion. AEM = anion exchange membrane electrolyzer. ALK = alkaline electrolyzer. CCUS = carbon capture, utilization, and storage. DAC = direct air capture. FAME = fatty acid methyl ester. FOG = fats, oils, and grease. FT = Fischer–Tropsch. H_2 = hydrogen. HVO = hydrotreated vegetable oil. LOHC = liquid organic hydrogen carrier. MeOH = methanol. NH_3 = ammonia. NG = natural gas. PEM = proton exchange membrane electrolyzer. SMR = steam methane reforming. SOEC = solid oxide electrolyzer cell. VRE = variable renewable energy.

Analyzing the maturity of each technology, it becomes clear that not all pathways have the same level of readiness for commercial deployment. While processes such as hydrotreated vegetable oil (HVO/HEFA) production and ethanol fermentation have high TRLs and already operate at industrial scale, pathways such as e-fuels (synthesis from renewable hydrogen and captured CO_2) and some advanced thermochemical conversion variants still remain at lower TRLs, requiring demonstration at scale and cost reductions.

Figure 3 organizes these differences visually, enabling a quick comparison of which pathways can be scaled up in the short term and which require support policies and R&D&I to reach commercial maturity.

Understanding TRL levels also reshapes how feedstocks and policy interventions are prioritized. Mature and abundant feedstocks (for example, waste oils for HVO or sugars for ethanol) can be

mobilized with lower technical risk and shorter timelines, whereas feedstocks that enable emerging pathways (such as captured CO_2 combined with green hydrogen) depend simultaneously on the advancement of critical components—electrolyzers, carbon capture, and catalytic synthesis—which have different TRLs and their own cost trajectories.

Thus, **Figure 3** not only signals the readiness of each pathway but also highlights technological bottlenecks that must be addressed in parallel (e.g., electrolyzer scaling, integration of FT units, biomass pre-treatment) for the entire value chain to become viable.

In terms of technological maturity, diesel, natural gas, ethanol, and methanol are at a fully commercial stage (TRL 9), while the use of ammonia as a fuel and hydrogen in engines remains at intermediate levels, with strong development expected through 2030. These factors reinforce that the competitiveness of each energy carrier depends not only on cost per unit of energy, but also on its operational, regulatory, and infrastructural feasibility within the energy transition horizon.

A careful analysis of technologies and TRLs helps guide practical decisions in industrial policy and financing—prioritizing projects that can be rapidly implemented to create markets and operational experience, while allocating public funding and incentives to demonstration projects and the scaling of low- to mid-TRL pathways that offer greater long-term emissions reductions.

Production Costs

This Technical Note aims to provide a detailed analysis of the production costs of sustainable fuels compared to fossil fuels, in order to understand their economic viability and identify where policy and regulatory support is most needed.

By comparing the costs of sustainable fuel technologies with benchmark prices for fossil fuels, the goal is to offer an objective basis for governments, regulators, and investors to assess the "green premium" and design effective mechanisms—such as blending targets, carbon pricing instruments, and favorable tax regimes—capable of closing this competitiveness gap and ensuring that decarbonization occurs in an economically efficient and secure manner.

There is a significant disparity between the costs of different commercial sustainable fuel pathways and their fossil equivalents. Among the more mature technologies, sugarcane and corn ethanol stand out as the most competitive options today. Their costs often overlap with or fall below fossil fuel benchmark prices, indicating that in regions with favorable conditions—such as Brazil and the United States—these biofuels have already reached cost parity without the need for excessive subsidies.

On the other hand, pathways such as biodiesel and renewable diesel (HVO) produced from used cooking oil (UCO) generally present production costs that exceed those of fossil benchmarks. The analysis of the figure shows that, although technologically mature, these fuels require supportive policies to bridge the economic gap. Their competitiveness often depends on recognizing their lower carbon intensity through credits or regulatory incentives, which help offset their higher production costs compared to fossil diesel.

The scenario is more challenging for the aviation sector and for biomethane. Sustainable aviation fuel (SAF) stands out as the highest-cost option among the commercial pathways presented, remaining significantly above the price of fossil jet fuel, which reinforces the need for scale gains and

innovation. Biomethane, in turn, shows a wide cost variation; although it can compete with natural gas under specific conditions, its large-scale economic viability is often tied to robust regulatory frameworks and the pricing of avoided methane emissions.

Table 1 - Fuel comparison for 2025, 2026 benchmark, and projections for 2030, with and without carbon costs

Product	LHV (MJ/kg)	Price 2025 (US$/kg)	Base Price 2026 (US$/kg)	2026 Price + CO_2 (US$/kg)	Base Price 2030 (US$/kg, est.)	2030 Price + CO_2 (US$/kg)	US$/MJ 2025	US$/MJ 2030	Ref.
Natural Gas	50.0	0.1659	0.1801	0.4382	0.1801	0.4606	0.0033	0.0036	LHV [16]; 2025 [18,20]; 2026 [42]; 2030 [20]; CO_2 [35,37]
Thermal Coal	24.0	0.1300	0.1235	0.3324	0.0950*	0.3220	0.0054	0.0040	LHV [16]; 2025 [13]; 2026 [38]; 2030 proxy [13,38]; CO_2 [35,37]
Green Hydrogen	120.0	3.9700	3.0800	3.0800	1.8500	1.8500	0.0331	0.0154	LHV [21]; 2025 [22,23]; 2026 [39]; 2030 [14,33,34]; CO_2 [35]
Green Ammonia	18.6	0.6150	0.6090	0.6090	0.5100	0.5100	0.0331	0.0274	LHV [25]; 2025 [27,43]; 2026 [40]; 2030 [14,27,43]; CO_2 [35]
Green Methanol	20.0	1.0000	1.0000**	1.0000**	0.7000	0.7000	0.0500	0.0350	LHV [17]; 2025 [15]; 2026 proxy [15]; 2030 [15,30]; CO_2 [35]
Sugarcane Ethanol	26.8	0.6459	0.7240	0.7240	0.6459*	0.6459*	0.0241	0.0241*	LHV [17]; 2025 [9]; 2026 [41]; 2030 proxy [9]; CO_2 [35]
Diesel	43.0	1.1773	1.3082	1.6013	1.1621	1.4807	0.0274	0.0270	LHV [16]; 2025 [31]; 2026 [42]; 2030 [32]; CO_2 [35,37]
Marine Bunker Fuel (VLSFO 0.5% S)	41.24	0.5350	0.4650	0.7515	0.5350*	0.8464	0.0130	0.0130*	LHV [44]; 2025 [45]; 2026 [46]; CO_2 [35,37,47]

* 2030 values marked with * are proxies: the best available reference was used for each case, including the World Bank projection for coal and constant real prices for ethanol and marine bunker fuel, due to the absence of robust public projections through 2030 in the cited sources.
** For green methanol in 2026, the value was kept equal to the most recent open benchmark used in the note, due to the lack of a consolidated public annual series for 2026.

Methodological notes

- Carbon price adopted: 2026 = US$ 92/tCO_2 and 2030 = US$ 100/tCO_2. The 2026 value was obtained through linear interpolation of the high trajectory indicated in the World Bank (2024 Guidance Note on Shadow Price of Carbon) [35].
- Direct emission factors used for fossil fuels: natural gas = 56,100 $kgCO_2$/TJ, bituminous coal = 94,600 $kgCO_2$/TJ, and diesel and gas oil = 74,100 $kgCO_2$/TJ [37]. For marine bunker fuel/VLSFO, an emission factor of 3.114 tCO_2/t fuel was adopted [47].
- The "+ CO_2" columns apply carbon costs only to direct fossil combustion emissions. For green hydrogen (gH_2), green ammonia (gNH_3), green methanol, and ethanol, no additional carbon cost was considered in this table, under the assumption of certified low-carbon or biogenic pathways.
- Values marked with an asterisk (*) are proxies already adopted in the note due to the absence of robust, publicly available projections for the time horizon considered.
- For green methanol in 2026, the value was kept equal to the most recent open benchmark used in the note, due to the lack of a consolidated public annual series for 2026.

Additional note: gray hydrogen

Additional benchmark – gray hydrogen (SMR without capture): LHV of 120 MJ/kg [21], typical emissions intensity of 10 to 12 $kgCO_2$-eq/kg H_2 [48], and a cost of around US$ 3/kg in recent European contexts, highly sensitive to natural gas prices, project scale, and location [49].

Units & Conversions

- 1 MMBtu = **1,055.06 MJ**.
- Natural gas prices were converted from US$/MMBtu to US$/MJ and then to **US$/kg** considering an **LHV ≈ 50 MJ/kg**.
- Ethanol (CEPEA): "ex-mill" price in **US$/L** converted to US$/kg using a density of **0.789 kg/L**, with **LHV = 26.8 MJ/kg**.
- Diesel: average **EIA price (Aug. 25, 2025)**, in **US$/gallon**, converted to **US$/L** by dividing by 3.785 and then to US$/kg using a density of 0.832 kg/L.
- Reference average LHVs: H_2 = 120, NH_3 = 18.6, MeOH = 20, Ethanol = 26.8, Diesel = 43, Gas = 50, Coal = 24 MJ/kg.

Primary Sources

- EIA – Annual Energy Outlook 2025 [12,20].
- EIA – Short-Term Energy Outlook (STEO) [32,42].
- *World Bank – Commodity Markets Outlook: April 2025* [38].
- *IIEA – The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector* [14].
- *IEA – The Role of E-Fuels in Decarbonising Transport* [30].
- *BloombergNEF (BNEF) – Hydrogen Supply Outlook 2024: A Reality Check; Hydrogen Market Outlook 2024; and Scaling Hydrogen: The Case for Low-Carbon Methanol* [15,33,34].
- CEPEA/ESALQ – Ethanol indicators [9,41].

Projections for 2030

Projections for 2030 point to a structural shift in the competitiveness between fossil fuels and low-carbon alternatives, driven by technological advances and incentive policies, including carbon pricing instruments. According to the International Energy Agency (IEA) [14], average production costs for green hydrogen are expected to decline significantly, falling from a current range of around US$ 3.5 to 5.0/kg — observed in recent auctions in India (IOCL/SECI, 2025) [22,23]— to approximately US$ 1.5 to 2.2/kg by 2030. This trajectory broadly reflects the combination of reduced electrolyzer CAPEX and lower renewable electricity costs discussed in previous sections.

Reports from BloombergNEF (2024) [34] indicate that the average cost of solar and wind electricity in highly competitive regions (Brazil, Chile, and the Middle East) is expected to range between US$ 15 and 25/MWh by 2030, contributing to a gradual reduction in the costs of derived molecules such as green ammonia (gNH_3) and green methanol (gMeOH). For ammonia, the IEA projects prices between US$ 400 and 620/t, while green methanol is expected to reach around US$ 700/t, equivalent to US$ 0.51/kg and US$ 0.70/kg, respectively.

These reductions reposition clean fuels at an increasingly competitive level, especially when considering the economic effects of carbon pricing on fossil fuels.

Production Costs (Emerging Pathways vs. Fossil Benchmark)

The assessment of the economic competitiveness of new technological pathways, as illustrated in **Figure 4**, reveals a scenario of significant cost disparity in the short term. At present, there is a pronounced "green premium," where the production costs of synthetic fuels (RFNBOs—Renewable Fuels of Non-Biological Origin, in European terminology) and certain bioenergy pathways are well above the benchmark prices of fossil fuels.

At this early stage, the levelized cost is strongly influenced by the lack of economies of scale and the high initial capital costs, placing these sustainable alternatives at the top of the global cost curve.

A breakdown of the economic drivers shows that the viability of electrofuel pathways (such as e-ammonia, e-kerosene, and e-methanol) is highly sensitive to the price of renewable electricity and the CAPEX of electrolyzers. In contrast, biomass-based pathways currently present slightly lower costs but are affected by feedstock price volatility.

The graphical analysis highlights that while fossil fuels maintain a stable competitive ceiling, emerging pathways require substantial structural investments to reduce the price gap—particularly in carbon capture and green hydrogen production.

Current and future production costs of selected emerging sustainable fuel pathways and corresponding benchmark prices of fossil fuels

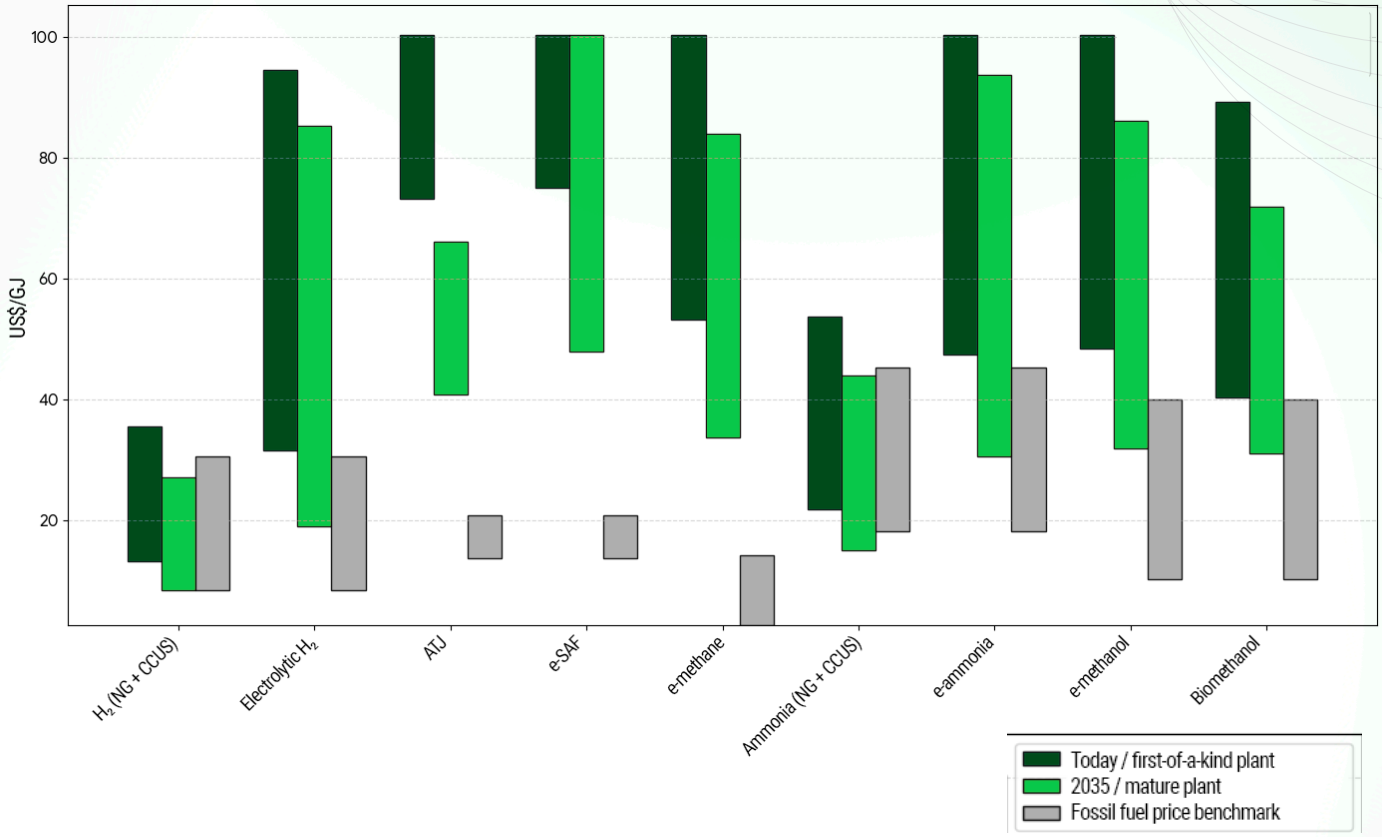


Figure 4. Current and future production costs of selected emerging sustainable fuels. Source: Adapted from [4]
Notes: Dark green: Today / first-of-a-kind plant; bright green: 2035 / mature plant; gray: fossil fuel price benchmark. ATJ = alcohol-to-jet fuel. NG = natural gas. SAF = sustainable aviation fuel. CCUS = carbon capture, utilization, and storage. Costs for H_2 (NG + CCUS) include CO_2 capture, transport, and storage. Fossil fuel price benchmarks are pre-tax, FOB (Free On Board), wholesale prices. Costs for emerging fuels represent production costs. The natural gas price benchmark is based on average 2023 wholesale prices. Electrolytic H_2 refers to hydrogen produced from solar photovoltaic and wind energy. Biomethanol corresponds to the gasification of lignocellulosic biomass. Cost estimates for first-of-a-kind and mature plants apply to ATJ, e-SAF, e-methane, e-ammonia, e-methanol, and biomethanol.

Projecting the scenario to 2035, a trend of convergence becomes evident, driven by technological learning and the maturation of the supply chain. A substantial reduction in the production costs of renewable pathways is expected, narrowing the gap with fossil fuels. However, the persistence of a residual differential suggests that pure economic market parity may not be universally achieved within the next decade without the intervention of regulatory mechanisms, such as carbon pricing, which are essential to cover the remaining risk premium observed in the data.

Figure 5, which compares the delivery costs of renewable hydrogen and ammonia across different transport modes (onshore pipelines and long-distance maritime routes), is particularly relevant to assessing the feasibility of a "global hydrogen market." It shows that the competitiveness of hydrogen-based pathways does not depend solely on production costs at the source, but is strongly influenced by how the molecule is transported and used at the destination. This perspective is crucial for defining national strategies for participation in global green hydrogen, green ammonia, and e-methanol value chains.

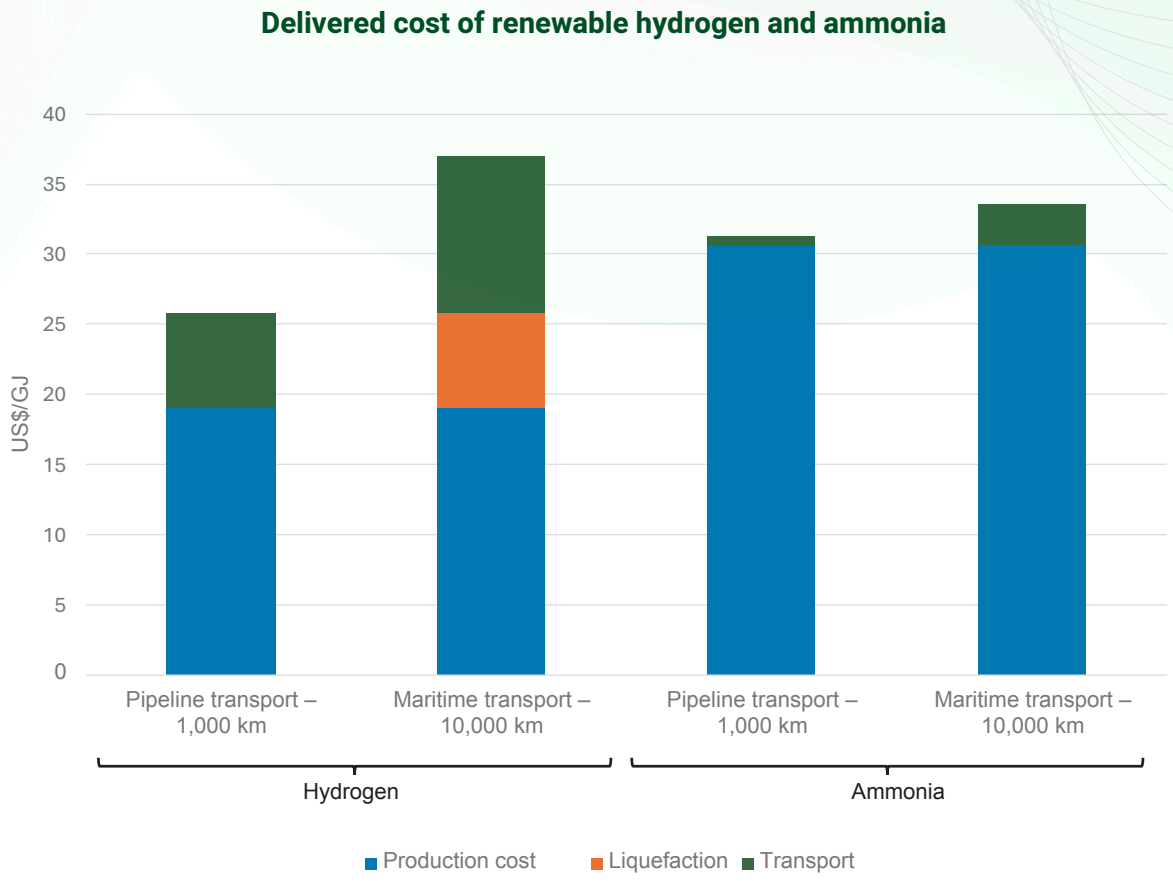


Figure 5. Delivered cost of renewable hydrogen and ammonia. Source: Adapted from [4].
Notes: Based on electrolytic hydrogen and ammonia from variable renewable power production costs for an Nth plant. Hydrogen maritime transport costs include an export storage tank, a liquid hydrogen tanker, an import storage tank, and a regasification plant. Ammonia maritime transport costs include an export storage tank, a tanker, and an import storage tank. Ammonia is used as a final product. Hydrogen pipeline transport cost assumes a new 20-inch pipeline and includes compression costs.

Economic constraints on the maritime transport of pure hydrogen

A structural vulnerability of the hydrogen economy becomes evident: the high cost of maritime transport of liquid hydrogen (LH_2). While pipeline transport over regional distances (on the order of 1,000 km) adds roughly 10% to the final cost, long-distance maritime transport (on the order of 10,000 km) can increase total costs by around 60%. This is mainly due to the energy-intensive liquefaction process, which requires cooling to approximately −253°C, as well as the associated logistical complexity (cryogenic vessels and tanks, in-transit losses, and regasification at the destination).

A critical reading of the figure suggests that the concept of a global liquid hydrogen market analogous to LNG, under current technological conditions, is economically challenging. In practice, pure hydrogen tends to behave more as a regional vector—competitive in contexts with land-based connections (new pipelines or repurposed gas infrastructure)—rather than as a long-distance maritime commodity.

Ammonia as a preferred logistical vector in international trade

When comparing the cost bars associated with maritime transport, ammonia emerges as the most robust logistical vector for transoceanic routes. Although its production cost is, in principle, higher than that of hydrogen at the point of origin—due to the additional Haber-Bosch synthesis step—the delivered cost over long distances proves to be competitive, and in several scenarios lower than that of liquid hydrogen.

This is explained by its higher volumetric energy density, the existence of established infrastructure for ammonia transport, and lower cryogenic complexity. The figure itself, however, notes that "ammonia is used as a final product," meaning the comparison is more favorable when ammonia is consumed directly (fertilizers, maritime fuel, or co-firing in power plants).

When the end-use requires hydrogen at the destination, the cost and energy losses associated with cracking ammonia back into hydrogen must be included, which partially reduces this advantage. Even so, the figure supports the view that, for end-uses compatible with direct ammonia consumption, it tends to be the preferred vector for long-distance maritime trade.

Dedicated infrastructure as a condition for competitiveness

The analysis of pipeline transport costs is based on the assumption of building or adapting dedicated infrastructure (for example, large-diameter gas pipelines), which implies a significant CAPEX investment effort. This reinforces the message that the competitiveness of renewable hydrogen produced in regions with abundant renewable resources depends not only on the cost per MWh at the source, but also on the ability to enable efficient transport corridors, either through pipelines or through conversion into derivatives such as ammonia.

In summary, producing low-cost hydrogen is not sufficient to ensure global competitiveness: the central challenge becomes how to deliver this energy efficiently and safely. The strategic implication is that the international market is likely to organize itself into two levels: **(i)** regional hydrogen markets, interconnected by pipelines and co-location of industrial demand; and **(ii)** a global market primarily based on more energy-dense and logistically favorable derivatives, such as ammonia, rather than pure liquid hydrogen.

Impact of the carbon market on relative competitiveness

The expansion of carbon pricing mechanisms is one of the most relevant factors for reshaping global energy costs through 2030. According to the World Bank's State and Trends of Carbon Pricing 2026 [3], direct carbon pricing instruments cover approximately 29% of global greenhouse gas emissions. Coverage is expected to continue expanding, although prices vary significantly across jurisdictions and instruments. For the purposes of this Technical Note, the range of US$ 50 to 100/tCO_2 in 2030 is adopted as an analytical benchmark [35].

Additional factors and macroeconomic conditions

In addition to carbon pricing and technological advances, the competitiveness of green pathways in 2030 will depend on four complementary drivers:

- **Scale and industrial integration:** The emergence of integrated hydrogen and derivatives hubs, such as NEOM (Saudi Arabia), Sines (Portugal), and Pecém and Suape (Brazil), reduces logistical costs and enables economies of scale. These hubs also attract private investment and secure long-term offtake agreements, anchoring reductions in the cost of capital.
- **Infrastructure and logistics:** The availability of dedicated pipelines, port terminals, and ammonia-capable vessels will be decisive in ensuring the

efficient transport of green molecules. As of May 2026, the Ammonia Energy Association's LEAD database listed 505 low-emission ammonia plant projects, or 612 when expansion phases are counted separately [11].

- **Exchange rate risk and financing:** In Brazil's case, exchange rate volatility and the cost of dollar-denominated financing are critical factors. Risk mitigation policies and green funds (such as the Global Infrastructure Facility (GIF) and the Green Climate Fund) can reduce financial spreads and enhance the competitiveness of national projects.
- **International regulation and foreign trade:** The EU Carbon Border Adjustment Mechanism (CBAM) entered its definitive phase on January 1, 2026, introducing an additional cost associated with the embedded emissions of certain imported goods. This creates a competitive advantage for exporters with low-carbon electricity mixes, such as Brazil, particularly in sectors such as fertilizers, steel, and synthetic fuels.

In segments where the "green premium" remains high, demand-creation instruments can play a decisive role in enabling scale, consumption predictability, and risk reduction for new projects. Among these instruments, sectoral mandates, blending targets, long-term offtake agreements, and other mechanisms that signal firm demand for low-carbon fuels stand out. Recent literature from the IEA [50] shows that demand-side support policies are essential to stimulate the consumption of hydrogen and low-emission fuels, facilitate the conclusion of long-term offtake agreements, and unlock investment in supply—particularly in hard-to-abate sectors.



Final Considerations

The comparative analysis of energy costs and technological pathways presented in this Technical Note indicates that the transition to low-carbon fuels is not a long-term abstraction, but an ongoing process with concrete implications for investment decisions through 2030. In 2025, fossil fuels still hold a direct cost advantage in US$/MJ, supported by established infrastructure and mature supply chains; however, this advantage is steadily narrowing as the expected decline in green hydrogen, ammonia, and methanol costs is combined with economies of scale and the internalization—through regulatory and market instruments—of carbon costs and other negative externalities associated with fossil fuel use (such as local pollution and health impacts).

Projections indicate that by 2030, green hydrogen production costs may converge to the range of US$ 1.5–2.2/kg, while green ammonia and green methanol reach price levels compatible with large-scale industrial and logistics applications. When a carbon price of around US$ 100/tCO_2 is included, the competitiveness gap between fossil molecules and clean alternatives narrows significantly, bringing green hydrogen closer to gray hydrogen and enabling green ammonia and methanol to compete in sectors such as fertilizers, maritime transport, and the chemical industry. In this configuration, the "green premium" ceases to be an insurmountable barrier and becomes a residual differential that can be addressed through well-designed regulatory and contractual instruments.

From a logistics standpoint, the results reinforce a strategic conclusion: pure hydrogen is expected to function primarily as a regional vector, competitive in contexts with pipeline infrastructure and co-location of industrial demand, while ammonia emerges as the leading vector for long-distance maritime trade, particularly when used directly as an input or fuel. This suggests that the international low-carbon market will likely organize around hydrogen derivative chains—especially NH_3 and MeOH—rather than a global liquid hydrogen market analogous to LNG. For Brazil, this finding is particularly relevant given the opportunities to integrate green hydrogen and ammonia production into already established industrial and port hubs.

At the macroeconomic and regulatory level, the expansion of carbon markets, the implementation of the EU CBAM, and the advancement of sectoral decarbonization policies are expected to reprice carbon risk across emissions-intensive value chains. Countries with clean electricity mixes and abundant renewable resources are increasingly favored in attracting electricity-intensive industrial projects and in producing low-carbon fuels for export. In this context, Brazil has clear structural advantages to position itself as a competitive supplier of hydrogen and derivatives, provided it advances in building a stable regulatory framework, developing a robust carbon market, and enabling logistics and export infrastructure.

or ABIHV and its members, the findings of this Technical Note point to three priority lines of action: first, advocating for policies that accelerate reductions in the cost of capital for green hydrogen and green ammonia projects through instruments such as long-term contracts, public guarantees, and mechanisms to mitigate foreign exchange and credit risks; second, supporting the implementation of carbon pricing instruments that internalize the environmental costs of fossil fuels, narrow the

competitiveness gap between green and fossil-based molecules, and reduce the risk premium associated with new investments; and third, promoting the development of integrated hydrogen and derivatives hubs connected to industrial clusters and export ports, maximizing synergies among renewable generation, molecule production, and end-use demand.

In summary, the 2030 horizon marks the beginning of a new competitive configuration in which low-carbon fuels move beyond niche applications and become a structural component of decarbonization strategies for countries and companies. ABIHV considers that, if Brazil is able to align its natural advantages with an adequate regulatory and financial environment, the country can convert comparative advantage into lasting competitive advantage, consolidating itself as one of the leading global suppliers of green hydrogen, green ammonia, and other sustainable fuels.



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