Alternative fuels: from niche solutions to pillars of the Energy Transition

This white paper explores the role of low-carbon fuels in decarbonizing hard-to-abate transport sectors, particularly aviation and maritime. The document examines regulatory frameworks, market dynamics, bio-based and synthetic fuel pathways, and key deployment challenges. Its goal is to identify actionable priorities that can accelerate the transition from niche solutions to scalable, sustainable fuels, supporting emissions reduction without compromising safety or global connectivity.

Our experience. Your growth.

The long distance challenge: scaling low carbon fuels for global transport

The journey to net-zero has no single route. Energy efficiency, renewables, electrification, hydrogen, CCUS and low carbon fuels all have a role to play. But for sectors that cannot simply plug into a power socket, the transition is considerably more complex. Aviation and maritime transport sit at the centre of this challenge.

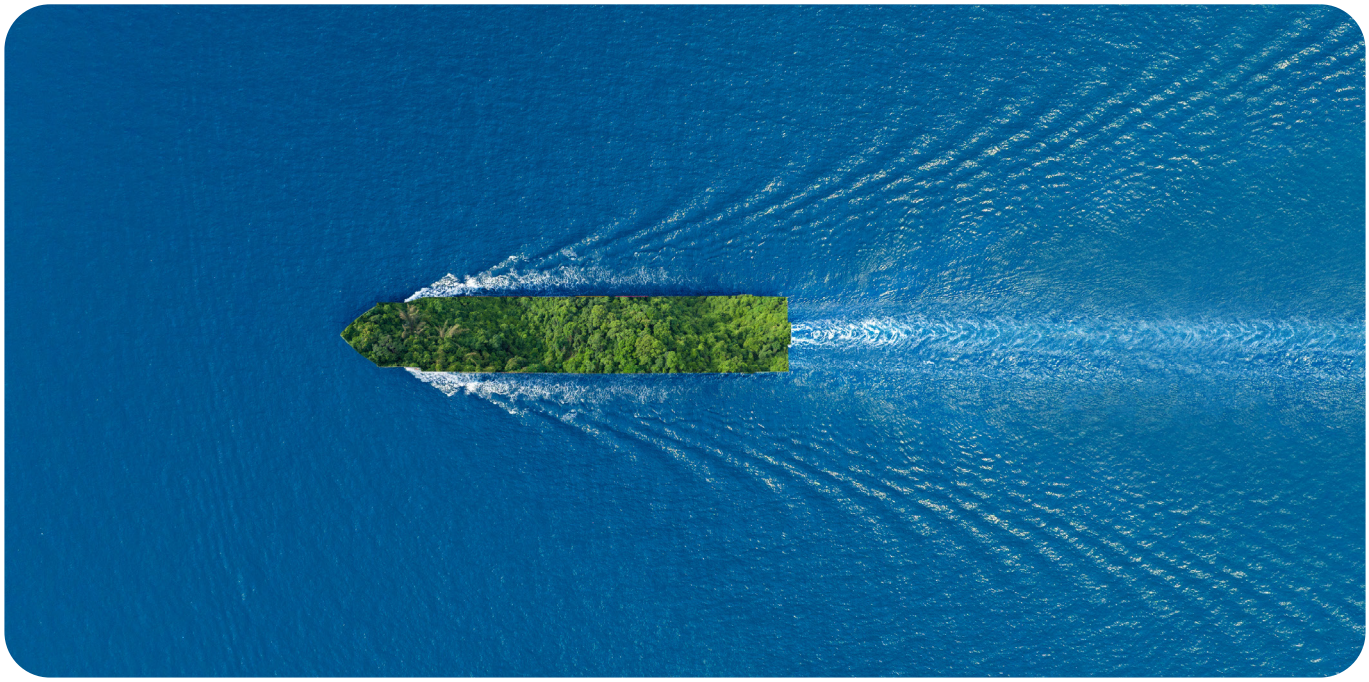
These sectors move people and goods across continents and oceans, relying on energy-dense fuels that can deliver long range, heavy payloads and high reliability. High energy demand, strict safety requirements and global operations leave few viable alternatives to liquid and gaseous fuels, at least in the near to medium term.

Today, the transport sector accounts for around one quarter of global energy-related CO_2 emissions, with aviation and shipping together responsible for approximately 4–5%, a share expected to increase as mobility and trade expand. Yet, sustainable fuels remain marginal: around 5 EJ out of 125 EJ of global transport energy demand, mainly biofuels used in road transport. In shipping, oil still supplies 99% of fuel demand, while in aviation sustainable aviation fuels (SAF) represent just 0.1%.

According to the IEA Net Zero Scenario, the demand for low-emission fuels, including liquid biofuels, biogases, hydrogen and e-fuels, will need to double from today's levels by 2030, and double again by 2050.

Alternative fuels offer a unique value proposition, particularly drop-in solutions that can leverage existing fleets and infrastructure. They can significantly reduce lifecycle GHG emissions and unlock new industrial and economic opportunities, especially in regions rich in renewable energy or sustainable biomass.

Yet progress remains slow. Limited feedstocks, high costs, immature supply chains and fragmented regulation continue to constrain deployment. The challenge is not only technological, it is financial, regulatory and infrastructural. With operations in more than 70 countries and deep experience across energy systems, transport and certification, RINA has a front-row view of both the barriers and the solutions emerging globally. This white paper focuses on aviation and shipping, analyzing regulatory drivers, bio-based and synthetic fuel pathways, market dynamics, and ten priority actions to move low-carbon fuels from niche to scale, cutting emissions without compromising performance, safety or global connectivity.



Policy is moving faster than market

Policies and regulations are among the strongest forces driving the energy transition. They set directions, shape markets, attract investment and push innovation forward, especially in the maritime and aviation.

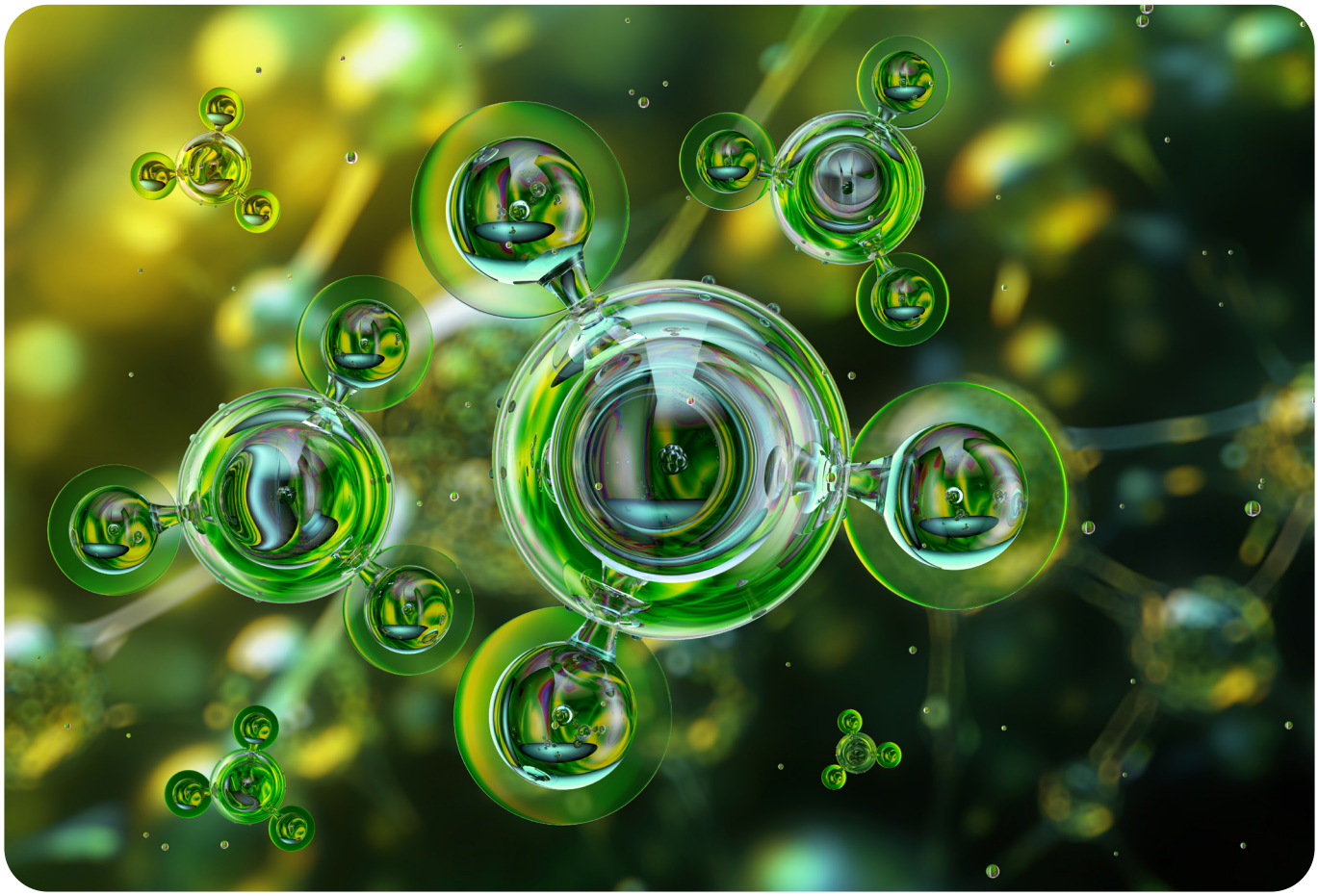
Europe has developed one of the world's most advanced policy frameworks for renewable and low-carbon fuels, anchored in the Renewable Energy Directive (RED), which defines sustainability criteria, lifecycle GHG thresholds and certification rules. This foundation now enables sector-specific regulations to accelerate deployment at scale.

In maritime transport, FuelEU Maritime introduces progressively tighter limits on the GHG intensity of onboard energy, from -2% in 2025 to -80% by 2050. The regulation is technology-neutral but favours RFNBOs such as e-methanol and e-ammonia, which benefit from double counting until 2033.

Non-compliance carries financial penalties and, ultimately, the risk of exclusion from EU ports. At global level, the International Maritime Organization's revised GHG Strategy targets at least -20% emissions by 2030 and -70% by 2040 compared to 2008.

Aviation follows a similar path. ReFuelEU Aviation mandates rising SAF blends—2% by 2025, 6% by 2030 and 70% by 2050, with at least half from RFNBOs. The EU ETS reinforces this shift by phasing out free allowances by 2026, turning emissions into a direct cost for operators.

Globally, from the UK's Jet Zero Strategy to Japan's and Brazil's "Fuel of the Future" laws, the message is consistent: decarbonization is becoming a license to operate.



How fast must sustainable fuels scale?

Today, sustainable fuels in transport are dominated by road biofuels, with global supply around 5 EJ, roughly 4% of total transport energy demand.

In shipping, sustainable fuels are almost absent. Under the IEA accelerated scenario, the sector will require over 3 EJ by 2035, covering about 35% of global shipping fuel demand, split roughly 45% biofuels and 55% hydrogen-based fuels.

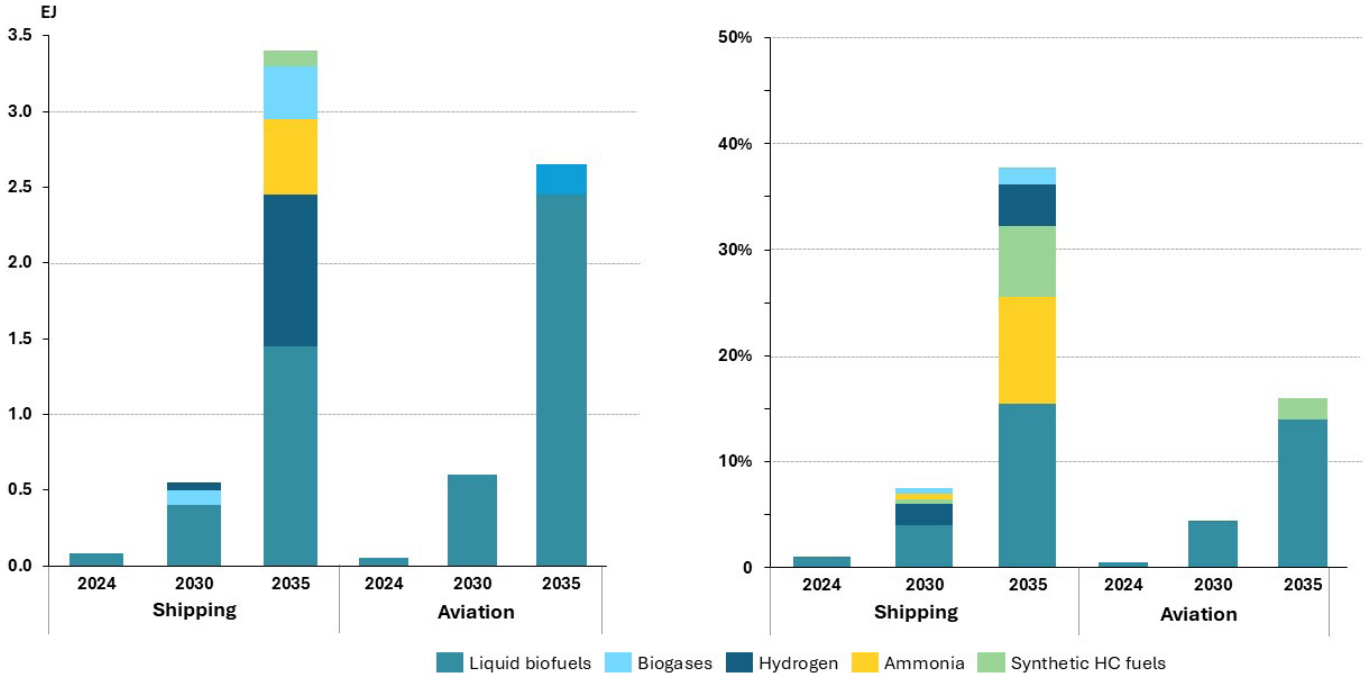


Figure 1: Sustainable liquid and gaseous fuel use by fuel type for selected transport modes – accelerated case, 2024-2035. Left: Sustainable fuels use; Right: Share in total fuel use [IEA]

Aviation faces an even steeper climb. It has recorded the fastest energy demand growth in transport (+17% between 2015 and 2024), yet SAF penetration remains negligible. In an accelerated scenario, SAF could reach 15% of global aviation fuel demand by 2035 (around 2.6 EJ), still largely bio-based, with synthetic fuels scaling later as costs decline and infrastructure matures.

What Are Sustainable Fuels?

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Sustainable liquid and gaseous fuels cover a broad family of energy carriers produced from renewable feedstocks and low-carbon processes. Most fall into three categories:

- Biofuels, derived from biomass (e.g. biodiesel, biojet, biomethane)
- Low-emission hydrogen
- Hydrogen-based synthetic fuels, such as e-kerosene, e-methanol and e-ammonia

Each pathway has distinct maturity levels, cost structures and scale-up challenges.

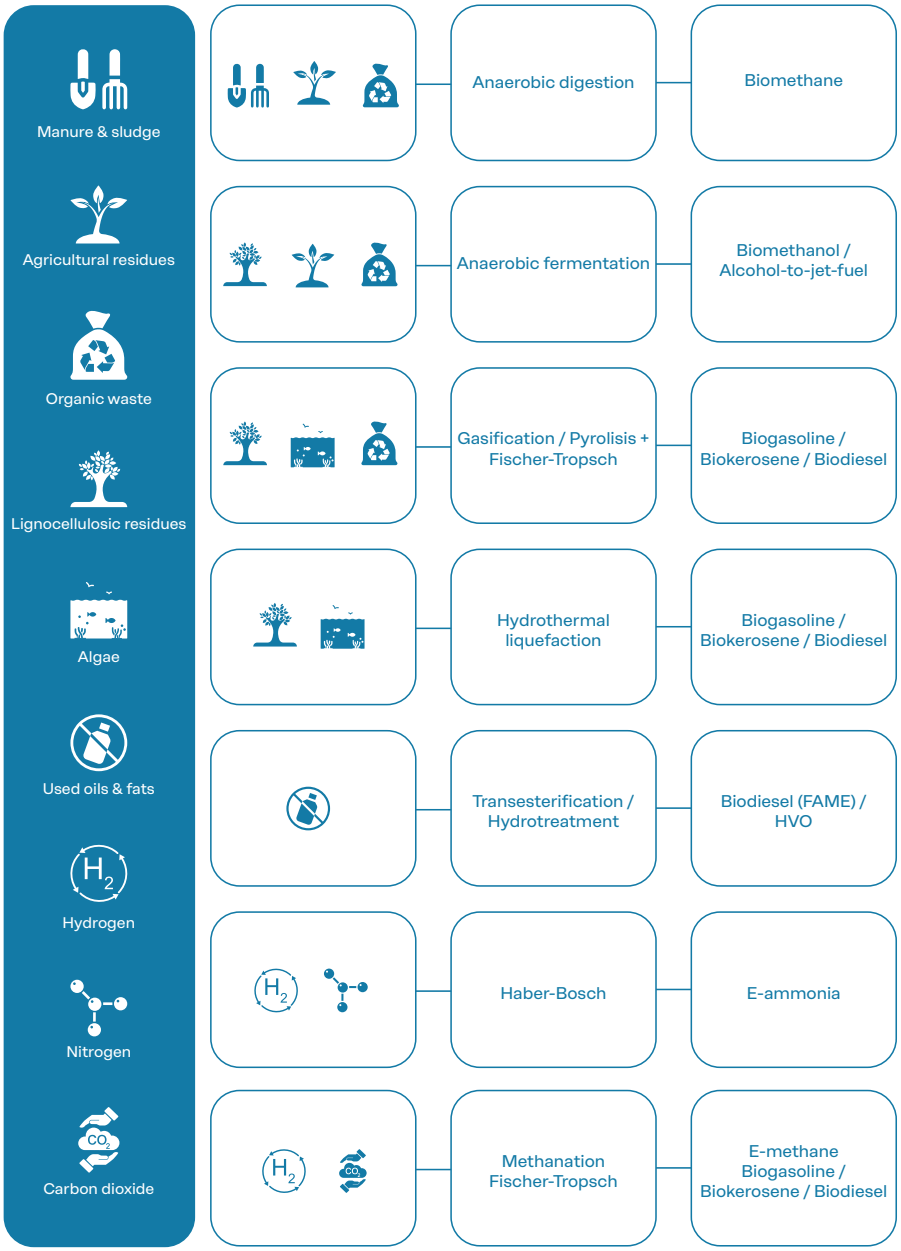

Figure 3: Possible production pathways for sustainable fuels

Biofuels: mature, flexible but limited

Biofuels are the most commercially advanced option today and often the lowest-cost low-carbon alternative, especially in the short term. Many are drop-in fuels, compatible with existing engines and infrastructure.

Biofuels can be produced from a wide range of renewable biological resources. Current commercial production relies mainly on agricultural crops (corn, sugarcane, palm oil) and waste or residues such as used cooking oil, tallow and agricultural waste. These are typically classified as first- and second-generation biofuels. New pathways are emerging, including algae-based fuels and advanced bioconversion processes.

However, feedstock availability is the binding constraint. Sustainability concerns—land use, biodiversity, food competition—are driving stricter rules, particularly in Europe. Scaling biofuels therefore requires strengthening upstream feedstock supply, logistics and conversion efficiency, while maintaining robust sustainability safeguards.

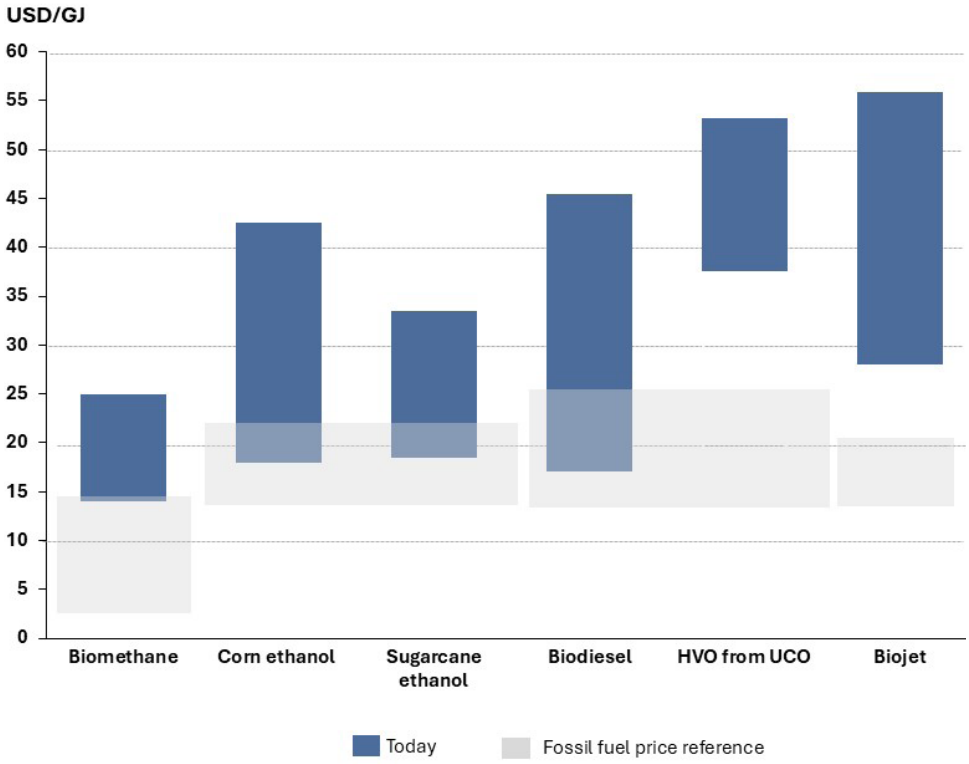

Figure 4: Global production cost ranges for biofuels and corresponding fossil fuel prices [IEA]

Synthetic Fuels: High Potential, Early Stage

Synthetic fuels, or synfuels, e-fuels, Renewable Fuels of Non Biological Origin, combine renewable hydrogen with captured CO_2 to produce e-kerosene, e-methanol, e-ammonia and other fuels. They offer a long-term pathway to deep decarbonization, especially where biomass is limited.

Today, their deployment is constrained by high costs, limited hydrogen and CO_2 availability, and immature value chains. In aviation, power-to-liquid fuels provide a clear drop-in route. In shipping, the picture is more complex: fuels such as e-methanol and e-ammonia are not non-drop-in fuels and require new engines, specific arrangement of the fuel containment system – piping and tanks, retrofits and dedicated bunkering infrastructure, making coordination across the value chain essential.

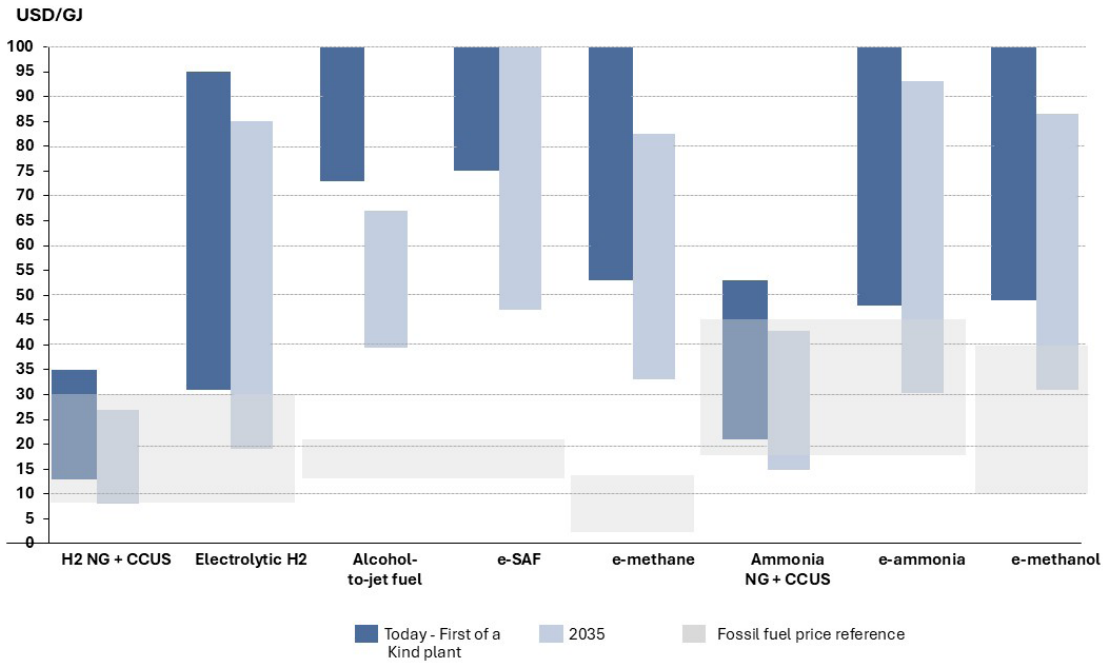

Figure 6: Current and future production costs of selected emerging sustainable fuel pathways and corresponding fossil fuel reference prices [IEA]

Why certification is a market enabler

Certification is the backbone of credible low-carbon fuel markets. Through lifecycle GHG accounting, it turns sustainability claims into verifiable, comparable data, giving regulators, investors and fuel users confidence in real emissions performance.

In Europe, the Renewable Energy Directive (RED) provides the common reference framework for this verification, defining sustainability criteria, lifecycle GHG thresholds and certification requirements for both biofuels and RFNBOs.

For biofuels, certification is well established. Schemes such as ISCC-EU, 2BS responsible feedstock sourcing, land-use impacts, supply-chain traceability, and compliance with regulatory GHG-reduction thresholds. These mechanisms have been essential in addressing risks linked to agricultural practices, indirect land-use change and widespread concerns about food versus fuel competition.

For synthetic fuels, certification introduces new challenges: proving renewable electricity use, CO_2 traceability, additionality, etc.

Yet today's global landscape remains fragmented, with overlapping schemes and inconsistent criteria, creating complexity for producers and investors. The EU has made significant efforts to harmonise methodologies through RED-based rules and mutual recognition of certification schemes, but greater international alignment will be essential to enable cross-border trade and support large-scale deployment.

Decalogue: priorities for a sustainable low carbon fuels market

Low carbon fuels are not a transitional option, but a structural pillar of decarbonization for hard-to-abate sectors. Scaling them requires coordinated action across policy, industry, innovation, infrastructure, finance and skills.
Drawing on RINA's cross-sector experience across energy, transport, infrastructure, and certification, this white paper identifies ten priority areas to accelerate development and deployment while reducing investment risk and market uncertainty.

1. Developing a Coherent, Long-Term Policy Framework
The deployment of e-fuels and advanced biofuels is fundamentally policy-driven. Given their current cost gap with fossil fuels, market uptake will not occur without long-term and credible policy intervention. Blending mandates, carbon intensity standards, production incentives, and carbon pricing mechanisms must be designed as a coherent package, rather than as isolated instruments, to create demand and de-risk capital-intensive investments.

International regulatory alignment is critical. Frameworks such as CORSIA for aviation, and the European FuelEU Maritime for shipping must evolve consistently to avoid market fragmentation, ensure regulatory certainty for global operators, and enable cross-border fuel trade. Policy instability or short-termism represents one of the main barriers to scale.

2. Ensuring Availability and Sustainability of Feedstocks
The scalability of e-fuels and biofuels is directly constrained by feedstock availability and sustainability performance.

For e-fuels, large-scale access to low-cost renewable electricity, renewable hydrogen, and reliable CO_2 sources, concentrated or atmospheric, is decisive.

For biofuels, scaling requires a progressive shift toward advanced feedstocks, including agricultural residues, waste streams, and non-food biomass. Strict sustainability criteria are not optional but market-enabling. They are essential to mitigate risks related to land-use change, biodiversity loss, and competition with food systems, while safeguarding social acceptance and regulatory credibility.

3. Accelerating Industrial-Scale Production Capacity
Penetration of e-fuels and advanced biofuels in aviation and maritime transport depends on rapid cost reductions enabled by industrial-scale deployment. Today, high capital intensity, long project lead times, and technology risk continue to slow investment decisions.

Key levers include scaling electrolyzer manufacturing, improving conversion efficiencies, integrating processes, and standardizing plant designs to reduce CAPEX and OPEX. Public financial instruments, such as grants, contracts for difference, guarantees, and risk-sharing mechanisms, remain essential to unlock first-of-a-kind and early commercial projects.

4. Supporting Innovation through R&D&I
Innovation remains a cornerstone of competitiveness. Priority areas span the entire value chain: improving electrolyzer efficiency and durability, reducing the energy intensity of synthesis pathways, and lowering the cost and complexity of CO_2 capture.

Large-scale pilot and demonstration projects are indispensable, not only to validate performance under real operating conditions, but also to accelerate learning-by-doing, reduce perceived risk, and build investor confidence. These projects play a strategic role in shaping future standards and certification schemes, ensuring that regulation evolves aligned with technology.

5. Updating Infrastructure for Transport and Storage
Production capacity alone is insufficient without enabling infrastructure for transport, storage, and distribution. For e-fuels in particular, the challenge is systemic, requiring coordinated development of hydrogen, CO_2, and fuel logistics.

Existing assets, ports, pipelines, terminals, and storage facilities, can often be repurposed or upgraded, while exporter countries will need new large-scale production hubs and dedicated shipping terminals. On the demand side, ports and airports must adapt fuel handling systems to safely manage new fuels and higher blend ratios.

Infrastructure planning must be performed together with production planning. Delays in logistics or storage can rapidly become bottlenecks. Shared infrastructure, industrial clustering, and public–private partnerships are increasingly recognized as cost-effective acceleration strategies, alongside streamlined permitting processes.

6. Expanding Shipping
As low-carbon fuels become global commodities, maritime transport will play a central role in connecting exporter regions with energy-importing markets. New trade routes are expected to emerge, spanning feedstocks, intermediates, and finished fuels.

Some fuels, particularly ammonia and hydrogen, require dedicated vessels equipped with advanced containment, refrigeration, and safety systems, implying significant investment in specialized fleets and terminals. Shipping infrastructure is therefore not a passive enabler, but an active component of the value chain, with implications for cost, safety, and scalability.

7. Ensuring End-Use Readiness in Aviation and Maritime Sectors
Fuel availability does not automatically translate into emissions reductions. Aircraft, vessels, engines, and onboard fuel systems must be technically ready to operate with higher blends or pure low-carbon fuels.

For some fuels, compatibility is already proven; for others, targeted research is still required on combustion behavior, materials compatibility, emissions profiles, and operational safety. Certification pathways, retrofit programs, and operational pilots are enablers to bridge the gap between fuel supply and actual deployment.

8. Harmonizing Certification and Traceability
A credible global market depends on harmonized certification schemes and robust lifecycle greenhouse gas accounting. Transparent and consistent methodologies are essential to assess emissions across the full value chain, from feedstock sourcing to end use, and to ensure comparability across regions and fuels.

Digital traceability systems are increasingly strategic tools, supporting compliance, preventing double counting, and enabling cross-border trade, particularly under regulatory frameworks that rely on verified emissions reductions. In this context, the EU's Union Database (UDB), introduced under the Renewable Energy Directive, represents a significant step forward: it creates a shared digital infrastructure to track sustainable fuels across the supply chain, strengthen traceability, and enhance mutual recognition of certified volumes across Member States.

9. Building an International Market Architecture for Sustainable Fuels
Given the geographic mismatch between renewable resource availability and fuel demand, low-carbon fuels are inherently international commodities. Coordinated international action is required to align sustainability criteria, harmonize standards, and facilitate trade.

Partnerships can act as powerful market accelerators, supporting infrastructure development, long-term offtake agreements and investment flows between producing and consuming regions, while reducing risk.

10. Strengthening Societal Engagement and Workforce Readiness
Reskilling, public trust and acceptance are another important component for large scale deployment.

Low-carbon fuels introduce new technologies, safety requirements, and operational practices across the value chain, from production and logistics to certification and end use. Targeted training, upskilling of existing personnel, and alignment between industry, standards bodies, and education systems are enablers to ensure safe operations, reduce implementation risk, and sustain public confidence.

Transparent risk communication, participatory planning, and evidence-based assessment of environmental and socio-economic impacts are essential to secure broad societal support.

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