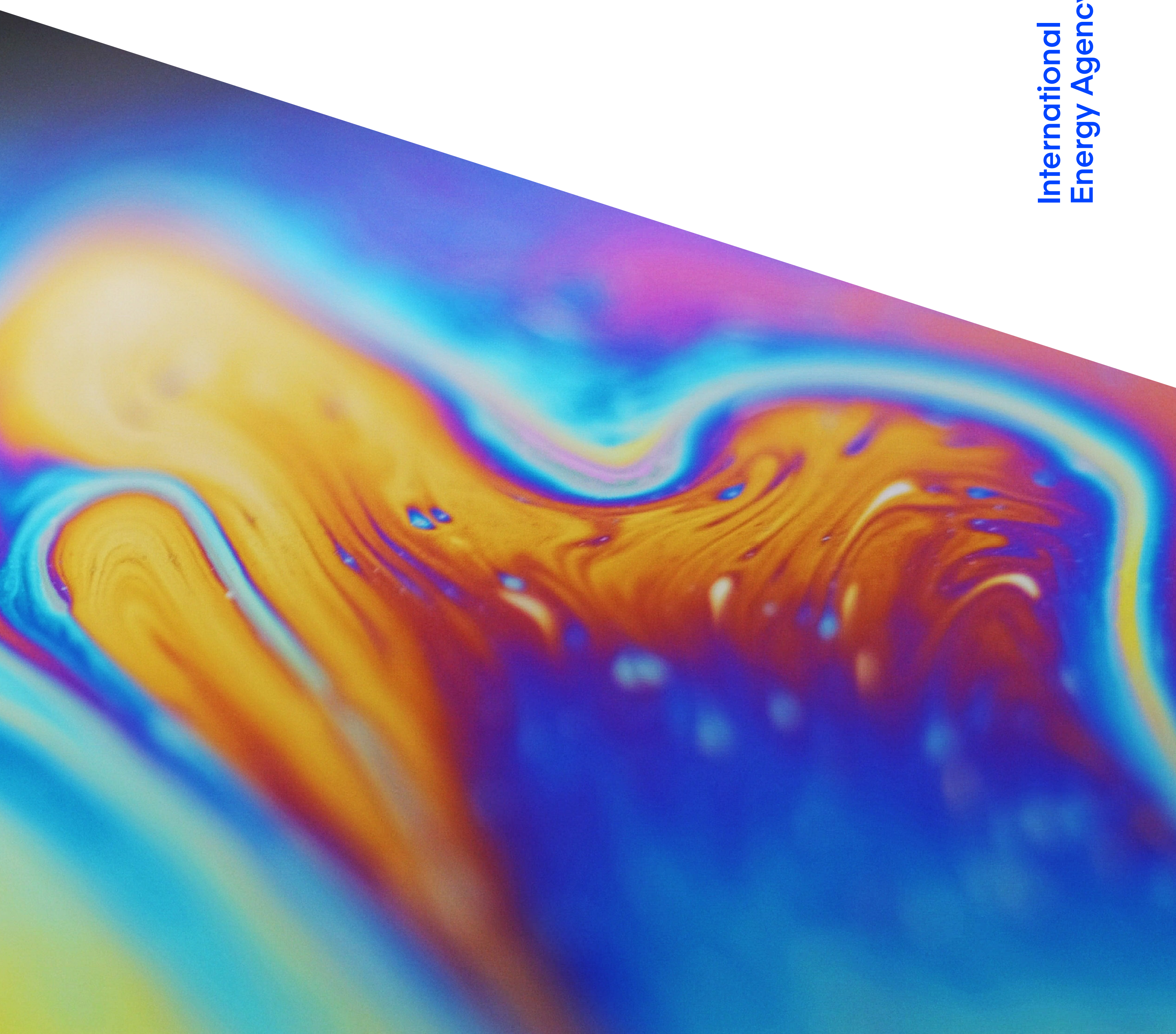
Delivering Sustainable Fuels

Pathways to 2035

International Energy Agency



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Abstract

Sustainable fuels – including liquid biofuels, biogases, low-emissions hydrogen and hydrogen-based fuels – offer multiple benefits for the energy sector. They complement electrification and energy efficiency in energy transitions, and are particularly important for sectors that continue to be reliant on fuel-based solutions such as aviation, shipping, and parts of road transport and industry. Sustainable fuels can also enhance energy security, strengthen environmental sustainability and stimulate economic development, particularly in rural areas.

If fully legislated and implemented, current and proposed national and international policies would put the use of sustainable liquid and gaseous fuels on a path to nearly double from 2024 levels by 2030 and quadruple by 2035. Progress must occur on multiple fronts to increase uptake and foster a large and diverse set of sustainable fuel pathways. This calls for a shared global vision for sustainable fuels, along with targeted policies to bridge costs gaps with conventional fuels, innovation to expand production potential, robust and mutually agreed carbon accounting methodologies to ensure that sustainability criteria are met, long-term investment in infrastructure, and more accessible financing, especially in emerging and developing economies.

This report was prepared in support of Brazil's COP30 Presidency and its Climate Action Agenda. It presents a sectoral analysis of global pathways for accelerating the deployment of sustainable liquid and gaseous fuels to 2035. It also summarises cumulative policy experience to date, identifies key technology and infrastructure requirements for scaling up deployment, and highlights resulting benefits that extend well beyond emissions reductions. Finally, the report outlines priority policy actions for governments seeking to adopt sustainable fuels to achieve measurable emissions reductions, strengthen domestic energy security and foster new opportunities for economic development.

Acknowledgements, contributors and credits

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Executive summary

Sustainable liquid and gaseous fuels offer multiple benefits

Sustainable fuels – including liquid biofuels, biogases, low-emissions hydrogen and hydrogen-based fuels – offer multiple benefits for the energy sector. They complement electrification and energy efficiency in energy transitions, and they are particularly important for sectors that continue to be reliant on fuel-based solutions such as aviation, shipping, and parts of road transport and industry. Sustainable fuels can also enhance energy security, stimulate economic development and strengthen environmental sustainability.

Greater use of sustainable fuels can bolster energy security by diversifying fuel supply and reducing fossil-fuel import dependence. Sustainable fuels can be produced from domestic resources in many countries, reducing exposure to volatile international oil and gas markets and supply risks. In 2024, liquid biofuels lowered transport fuel import dependence by 5-15 percentage points in relevant importing countries, and global oil demand was around 2.5 million barrels per day lower than it would have been without their contribution.

Sustainable fuels can be a catalyst for economic development, particularly in emerging and developing economies. Expanding their production and use can open new income streams, drive industrial growth, accelerate technology deployment and create job opportunities across the entire value chain. Such opportunities are especially important in rural and underserved communities, where projects can build local capacity and support youth employment.

With well-designed policies, sustainable fuels can achieve major lifecycle emissions reductions compared with conventional fuels. Actual reductions depend on choices made across the supply chain. Measures include the adoption of sustainable farming practices, using carbon capture utilisation and storage (CCUS), switching to renewable energy for processing, or powering electrolysers with dedicated low-emissions electricity. By 2035, most existing and emerging fuel pathways could reach very low lifecycle greenhouse gas intensity (gCO_2/MJ), and in some cases even deliver net carbon removal, provided that performance-based policies that drive continuous improvements are implemented.

Liquid and gaseous renewable fuels already play a visible role in today's global energy landscape. They are particularly relevant for transport, where they represent 4% of total energy demand. Liquid biofuels dominate current use, with emerging contributions from biogases and low-emissions hydrogen. Nearly 80%

of liquid biofuel use is covered by GHG performance requirements today, although regional uptake varies widely, reflecting differences in policy support, sustainability criteria, feedstock availability and infrastructure readiness. While representing only 1.3% of total energy consumption globally, in certain countries the contribution of renewable fuels can be much higher, notably in Brazil, where their share approaches 10%.

Innovation has significant potential to narrow the cost gap with conventional fuels

Today, sustainable liquid and gaseous fuels are generally more expensive than the fossil fuels they replace, though cost parity can already be achieved in certain cases. Commercial fuels such as ethanol, biodiesel, renewable diesel and biogas often rely on policies to narrow the gap, for example through carbon credits that reflect their lower GHG intensity. In some markets – as with ethanol in Brazil and the United States – they can even be cheaper than fossil alternatives.

New fuel pathways are being developed that can address local feedstock constraints and harness regional resources. Emerging pathways, such as alcohol-to-jet, synthetic hydrogen-based fuels, and gasification-based biofuels, remain in the early stages of commercialisation. Costs are currently high, but they are expected to fall significantly as deployment drives economies of scale for key technologies such as electrolysers, along with greater standardisation, innovation, more competitive markets and lower financing costs. Policy frameworks need to remain flexible and technology-open to support the market entry of emerging fuels that diversify feedstocks, primary energy sources and strengthen supply resilience.

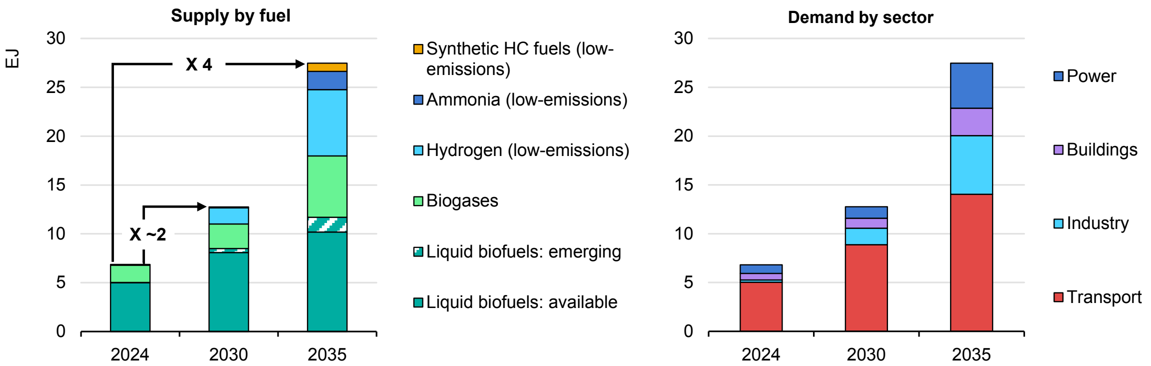
Despite higher costs, sustainable fuels are expected to have a limited impact on end-use consumer prices. Due to modest blending levels by 2035 and/or small shares of energy in final costs, the price impact on a car made with low-emissions steel, a cup of coffee made from beans produced with low-emissions fertilisers, or goods transported by a low-emissions containership is estimated to be below 1% in each instance. As for aviation, a 15% blending share of sustainable aviation fuels (SAF), would increase the ticket price of a flight by 5-7%, depending on the contribution of relatively more expensive emerging technologies. Still, even moderate price increases can weigh heavily on low-income households, making it important to protect the most price-sensitive products and consumers while pursuing diversification and emissions reductions in these industries.

Sustainable fuels could quadruple globally by 2035

If existing and announced policies are implemented, a fourfold increase in the global use of sustainable fuels by 2035 is ambitious yet achievable. Between 2010 and 2024, global demand for sustainable liquid and gaseous fuels doubled. Current trends and barriers point to continued gradual progress in this decade. Policy holds the key for more accelerated growth: full implementation of existing and announced policies and targets, plus the removal of market barriers, could lead to a near-doubling of sustainable fuel use in just six years, attracting investment in additional production capacity to meet new demand.

Going forward, based on a sectoral analysis, transport remains the main driver of demand to 2035. Demand from industry and power generation also expands rapidly after 2030, underpinned by the use of low-emissions hydrogen in the chemical, refining and steel sectors. By 2035 sustainable fuels would cover 10% of all global road transport demand, 15% of aviation demand and 35% of shipping fuel demand. National shares, mixes and volumes would still vary widely depending on regional conditions.

Sustainable fuel supply by fuel and demand by sector in the accelerated case, 2024-2035



Note: For assumptions and definitions, see Figure 5.7.

In the accelerated case, the portfolio of sustainable fuels shifts in line with changing demand patterns. Liquid and gaseous biofuels, which today account for almost all sustainable fuel consumption, would remain important, meeting about two-thirds of total sustainable fuel demand in 2035. By contrast, low-emissions hydrogen and hydrogen-based fuels – currently only about 1% of the total – would expand rapidly after 2030, contributing roughly half of the growth in sustainable fuel use between 2030 and 2035.

Accelerated deployment would bring significant socio-economic benefits. Cumulative investments between 2024 and 2035 could reach USD 1.5 trillion across all sustainable fuel types. Employment opportunities would increase in parallel, directly creating nearly 2 million jobs in regions where these fuels are produced. This would bring new options for economic development, particularly in emerging and developing economies.

Policy priority areas to accelerate deployment

The policy environment for sustainable liquid and gaseous fuels is highly complex. It covers a wide range of technology pathways that vary significantly in cost, technological readiness, infrastructure needs and development challenges. Progress must occur simultaneously on multiple fronts to increase diversification, boost uptake in established markets, mobilise the resource base in new markets, and foster emerging and new technologies.

Based on best practice experience, the IEA recommends six priority actions that can help accelerate sustainable fuel use by 2035. They are:

1) **Establish roadmaps, targets and support policies** that are tailored to regional contexts and aligned with broader energy goals, while keeping a technology-open approach.
2) **Increase demand predictability** to increase market confidence and attract investment.
3) **Cooperate in developing transparent and robust carbon accounting methodologies** to enhance comparability and future interoperability, and enable performance-based policies and incentives that reward continuous progress in measurable emission reductions.
4) **Support innovation to narrow cost gaps** – particularly to accelerate economies of scale and cost reductions for emerging technologies.
5) **Develop integrated supply chains and address infrastructure needs** to unlock long-term economic development opportunities.
6) **Make financing more accessible** – especially in emerging and developing economies – to de-risk investment and unlock the vast potential for sustainable fuels in these regions.

International cooperation and enhanced stakeholder engagement are key to accelerating sustainable fuel deployment and matching regional strengths with global demand. This report is prepared in support of Brazil's COP30 Presidency. It also considers the ongoing work under the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) to advance the global uptake of sustainable fuels in aviation and shipping. International cooperation will also be important in the areas of technical support and capacity building as well as RD&D.

Chapter 1. Introduction

Fuels are a cornerstone of the global energy system, providing energy-dense, easily transportable carriers that underpin a broad spectrum of economic activities. In their different forms, fuels supply around 90% of global energy today. Their production is highly centralised, with a relatively small number of countries and companies responsible for most of the world's output. Almost 80% of total oil production in 2024 came from just ten countries. Despite progress in diversifying energy sources, fossil fuels still meet 95% of transport sector energy demand and remain dominant in other sectors such as chemical feedstocks.

The first global stocktake of the 28th United Nations Climate Change Conference (COP28) in Dubai underscored the urgent need for deep, rapid and sustained GHG emissions reductions. It called on all parties to contribute to "transitioning away from fossil fuels in energy systems, in a just, orderly and equitable manner, accelerating action in this critical decade." Sustainable liquid and gaseous fuels – including **liquid biofuels**, **biogases**, **low-emissions hydrogen** and **hydrogen-based fuels** – play a key role in implementing this ambition. They complement electrification and energy efficiency by helping reduce fossil fuel demand, particularly in transport and in industrial sectors where electrification remains costly or is not yet available. They also improve domestic energy security by reducing reliance on fossil fuel imports and can provide new economic opportunities in regions where they are used and produced. When sustainably supplied, they can significantly cut fossil fuel-related GHG emissions.

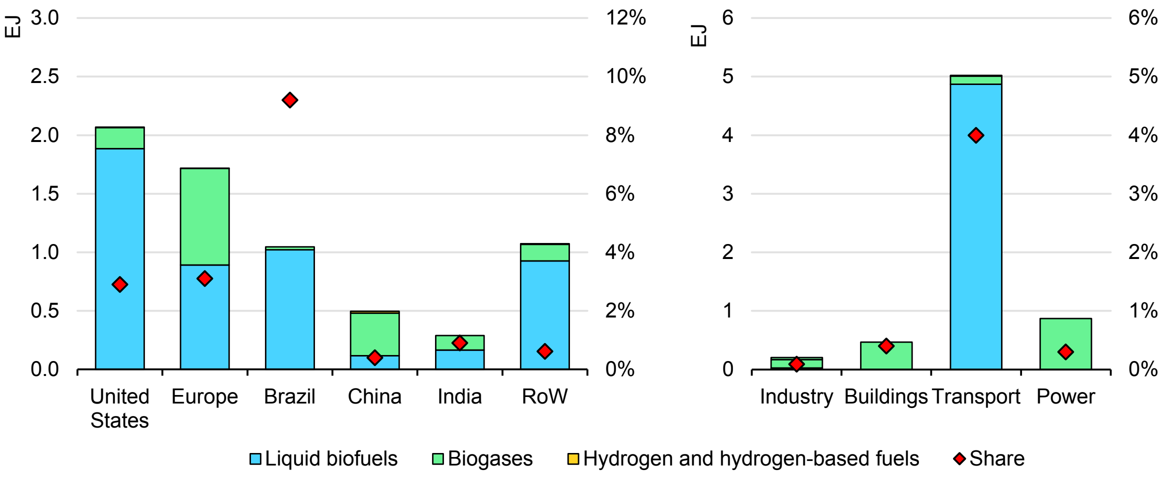
Box 1.1 Fuel pathways and sustainability criteria covered in this report

This report focuses on sustainable fuels and chemicals that can substitute for unabated fossil fuels and feedstocks across sectors and end uses. The scope covers supply pathways for **liquid and gaseous fuels** as well as sustainable **chemical intermediates**. The direct use of modern solid biomass (e.g. wood pellets, wood chips and agricultural residues) for heat and power production is excluded from the scope. However, the report does consider pathways that involve converting solid biomass into liquid or gaseous biofuels and biochemicals through thermochemical and biochemical processes.

For a fuel to be sustainable, it needs to have low GHG intensity over its lifecycle, measured in grammes of CO_2 equivalent per megajoule of fuel (gCO_2/MJ). All fuel pathways considered in this report have the potential to meet the abovementioned criteria by 2035 at the latest, when supported by performance-based policies designed to drive continuous improvement (see Fig 4.3). Sustainable fuels also need to comply with a set of non-GHG criteria, such as preservation of biodiversity, sustainable water management, compliance with social safeguards.

While still a small share of total energy consumption today, sustainable liquid and gaseous fuels are already affecting the global energy landscape in a range of applications, particularly in road transport. Global oil demand is already approximately 2.5 million barrels per day lower than it would be without the contribution of sustainable fuels. Sustainably produced liquid biofuels account for the vast majority of current sustainable fuel use, with emerging contributions from biogases and low-emissions hydrogen. However, adoption varies widely by region due to differences in policy support, sustainability criteria, feedstock availability and infrastructure readiness.

Figure 1.1 Use of sustainable liquid and gaseous fuels by country and sector, 2024



Note: RoW = rest of world. Sustainable fuels make up 1.3% of total final energy consumption globally.
Source: IEA (forthcoming), World Energy Outlook 2025.

Combined demand for sustainable liquid and gaseous fuels is projected to grow steadily under current market conditions but is facing several challenges. Although supply announcements have surged in recent years, many projects have also been delayed or cancelled due to weak demand signals, financing difficulties, postponement of incentives, regulatory uncertainty, and operational or permitting challenges. Overcoming these barriers and scaling up deployment calls for a shared global vision for sustainable fuels, targeted policies to bridge the cost gap, innovation to expand production potential, robust and mutually agreed carbon accounting methodologies, long-term investment in infrastructure, and more accessible financing, especially in emerging and developing economies.

Box 1.2 Sustainability criteria in regulatory frameworks

In different regulatory frameworks, sustainability most often refers to a fuel's lifecycle GHG emissions intensity or GHG savings potential, but it can also encompass other criteria. Several jurisdictions define legally binding requirements for sustainability, and only fuels that meet those criteria can be called sustainable, making them eligible for state aid and/or counting towards national or regional targets and mandates.

These frameworks were first developed for biofuels. Many include minimum GHG reduction thresholds to ensure that biofuels deliver meaningful transport sector decarbonisation. Other approaches, such as California's Low Carbon Fuel Standard (LCFS), do not impose a minimum threshold but instead reward fuels in proportion to their GHG emission reductions, incentivising continuous improvement by supporting biofuels with lower carbon intensity. Additionally, some regulations set limits to certain types of feedstocks. Examples include crop-based fuels and crops with high indirect land use change (iLUC) risk in the European Union's Renewable Energy Directive (RED), and feedstocks imported from countries outside North America in the United States Renewable Fuel Standard. Regulations can also favour certain types of feedstocks, such as waste and residues whose energy contribution can be double counted in the European Union's RED. Requirements can also differ across different sectors. In the European Union, for example, the same fuel can have different GHG emission saving thresholds depending on its end use.

Biofuel sustainability requirements in selected policy frameworks

	GHG reduction thresholds and/or targets	Feedstock criteria
United States (RFS)	Minimum 20% reduction in conventional biofuels compared with fossil fuels, 50% for advanced fuels and 60% for cellulosic biofuels.	Crops not allowed from areas forested previous to 2007.
European Union (RED III)	For transport, minimum 50% reduction compared with fossil fuels when operational before 2015; 60% when start of operations is 2015-2020; 65% in or after 2021. For electricity, heating and cooling, minimum 80% reduction after 2026.	Not allowed from nature-protected areas, high-biodiversity or high-carbon-stocks land, old-growth forests or heathlands. Reference year for land conversion is 2008.
CORSIA	Minimum 10% reduction compared with fossil fuels.	Not allowed from land converted after 2008 from primary forest, wetlands and peat lands.

California (LCFS)	No minimum threshold. Annual target for transport mix. Carbon credits generated by low-emissions fuels proportional to their CI reduction. Targets: 30% reduction from 2010 CI level by 2030 and 90% by 2045.	Not specified.
Brazil (RenovaBio)	No minimum threshold. Annual target for fuel pool. CBIO carbon credits generated proportional to GHG emission reduction. Targets: 4.6% reduction from 2018 level by 2026; 11.37% by 2034.	No conversion of natural vegetation after 2018; zero deforestation; palm oil cultivation limited to ZAE areas.

Notes: RFS = Renewable Fuel Standard. LCFS = Low Carbon Fuel Standard. CI = carbon intensity. RED = Renewable Energy Directive. ZAE corresponds to oil palm agroecological zoning.
Source: IEA (2024), Carbon Accounting for Sustainable Biofuels.

As new sustainable fuel pathways reach commercialisation, specific sustainability requirements are also being developed. For hydrogen and its derivatives, for instance, a growing number of certification schemes are emerging (there are 50 in existence today), many of which can be applied as voluntary schemes.

Within regulatory frameworks, the EU RED sets specific requirements for renewable fuels of non-biological origin (RFNBOs). Criteria cover the conditions under which the electricity consumed in their production is generated, including rules on additionality as well as temporal and geographical correlation. In addition, RFNBOs must achieve at least a 70% lifecycle GHG emission reduction, assessed through a methodology similar to that applied to biofuels.

As more types of sustainable liquid and gaseous fuels enter the market – in some cases involving hybrid pathways that combine different sources of hydrogen, CO_2, electricity or feedstocks – it is essential to ensure that carbon accounting criteria are clear and flexible enough to accommodate diverse production processes, and coherent across different fuel policies. For expanded discussion, see IEA (2024) Towards Common Criteria for Sustainable Fuels.

This report is prepared in **support of Brazil's COP30 Presidency**, particularly to contribute to the work of Climate Action Agenda Activation Group 4 on transitioning away from fossil fuels in a just, orderly and equitable manner. It is also relevant for the Activation Group 2 on accelerating zero and low-emission technologies in hard-to-abate sectors. It examines how sustainable fuels can help to implement the transition away from fossil fuels, focusing on sectors that continue to be more reliant on fuel-based solutions for their decarbonisation.

The report summarises cumulative experience to date on policies that support sustainable fuels, identifies key technology and infrastructure requirements to accelerate their scale-up, and highlights resulting benefits that extend well beyond emissions reductions. It also presents sectoral analysis of a global pathway for the accelerated deployment of sustainable liquid and gaseous fuels to 2030 and 2035. Finally, the report lays out policy priorities for governments wishing to adopt sustainable fuels to deliver sustained emissions reductions while improving domestic energy security and creating new economic development opportunities.

Chapter 2. Policy experience

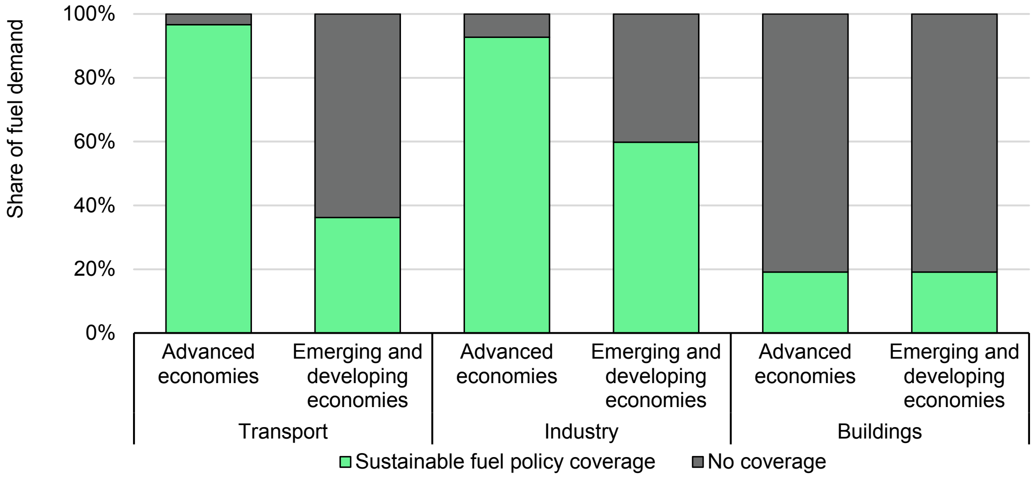
Highlights

- As of 2024, **half of total global fuel demand** was covered by sustainable fuel support policies such as blending mandates, carbon intensity reduction requirements and financial incentives for production and use.
- **Sustainable liquid and gaseous fuel policies span nearly a century**, beginning with Brazil's first ethanol blending mandate in 1931, providing lessons for expanding supply in established and new markets and for deploying emerging technologies.
- In **established markets**, policy priorities include incentivising continuous improvement; ensuring supply security and affordability; and minimising remaining adoption barriers. For example, in the United States, the Renewable Fuel Standard considers energy security and affordability when setting obligations, while complementary rules and programmes remove barriers to wider adoption – for example, waivers supporting E15 use and the Higher Blends Infrastructure Program.
- **Expansion to new markets** can happen relatively quickly with co-ordinated action, clear demand-side policies and the adoption of established technical and environmental standards. India, for example, expanded ethanol production and use tenfold in less than a decade, becoming the world's third-largest ethanol market through high-level targets and coordinated supply-and-demand policies.
- **Emerging technologies** can be deployed in existing and new markets. Policy priorities in this area include reducing investment risks for first-of-a-kind plants; creating stable long-term demand; and ensuring new fuel pathways can participate in existing frameworks.
- **International co-operation and collaboration** can help shape and amplify domestic policies by facilitating knowledge sharing; creating a global vision; aligning carbon accounting methodologies; and establishing international markets for fuel use in road, rail, shipping and aviation.
- **Integrated policy frameworks** anchored by clear long-term demand, complemented by targeted measures and aligned internationally – can drive market growth, innovation and adoption of sustainable fuels in new sectors.

Over nearly a century, governments have used a range of policy tools to harness the benefits of sustainable liquid and gaseous fuels, narrow the cost gap with fossil alternatives, build feedstock supply chains, and set technical and environmental standards. Fossil fuel subsidies, valued at over USD 600 billion globally in 2023, can also act as a barrier to sustainable fuel deployment. Governments have therefore introduced a range of policy tools including mandates, financial incentives, carbon pricing, regulatory requirements and removing fossil fuel subsidies to address these issues.

As of 2024, nearly half of total global fuel demand was covered by sustainable liquid and gaseous fuel policies, including blending mandates, carbon intensity reduction requirements and financial incentives for production and use. Nearly all developed countries have implemented policies to support their use in the transport and industry sectors. These approaches not only address price gaps but also guide production, consumption, sustainability requirements, certification and innovation to meet long-term goals for energy security, economic development and emissions reductions. For liquid biofuels, performance-based standards and GHG thresholds now cover 80% of global biofuel demand, with near-universal coverage in developed economies.

Figure 2.1 Fuel demand covered by sustainable liquid and gaseous fuel supply and demand policies by sector and economy type, 2025



Notes: Shares based on sector total final energy demand including all gaseous, solid and liquid fuels. Policies include mandates, quotas, carbon intensity reduction requirements and incentives (tax breaks, contracts for difference, fixed pricing and capital support for new projects). A single sustainable fuel policy in a single sector would count towards coverage for the sector as a whole. For instance, India's fixed pricing support for ethanol counts as sustainable fuel coverage for the transport sector.

Sources: Adapted from IEA internal biofuels and hydrogen policy databases; IEA (2025), Outlook for Biogas and Biomethane; and IEA (2025), World Energy Balances.

Brazil introduced the first ethanol mandate in 1931, and since then governments have gradually expanded to a wider range of fuel pathways. From the United

States' longstanding ethanol programmes to biomethane expansion across several EU member states and emerging support for low-emissions hydrogen, a diverse set of approaches has been employed to scale sustainable liquid and gaseous fuel use across income groups, geographies and sectors.

While most policies focus on individual fuels or sectors, many share features that can be applied more broadly to other fuel types and areas. Accumulated experience from around the world provides a practical foundation to design future policies for a diverse range of fuel pathways and markets.

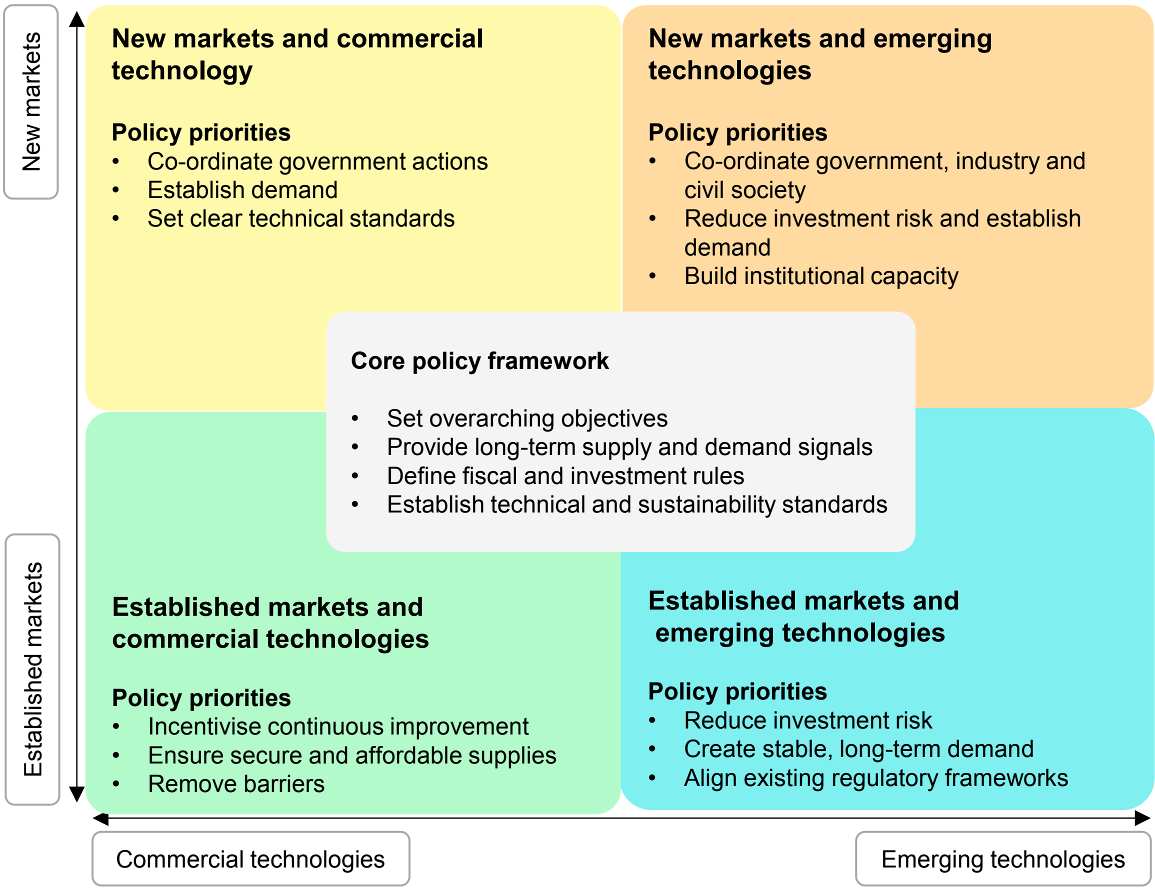
All sustainable liquid and gaseous fuels can benefit from a core policy framework, including an overarching strategy, long-term supply and demand measures, financial frameworks and clear sustainability criteria. Yet these core policies alone cannot overcome all barriers to deployment. Creating new markets and supporting emerging technologies often requires additional measures to reduce risk, while deeper market penetration can raise concerns over supply security and affordability.

Given the diversity of market conditions and technologies, global experiences can be grouped according to two dimensions: market maturity (from new to established) and technology readiness (from emerging to commercial). **Established markets** refer to sectors in a specific region where a sustainable liquid or gaseous fuel, or a close substitute, is already in use, is regulated and is supported by established supply chains and infrastructure (e.g. ethanol in Brazil and biomethane in Denmark). Meanwhile, **new markets** refer to sectors in which the fuel is not yet widely used – or is not established in the given region – requiring significant regulatory support, infrastructure and supply chain development (e.g. biodiesel in India, and ammonia in maritime transport).

On the technology side, **commercial technologies** refer to technology readiness level (TRL) 9[1] and emerging technologies to TRL 7 or 8. This framework helps governments identify policy package priorities – from de-risking early innovation to supporting efficient deployment in competitive markets.

[1] The IEA updated TRL scale from 1 to 9 provides additional insight into progress after reaching TRL 9 in the form of three different adoption levels: "awaiting adoption", "building momentum" and "commercial in many markets".

Figure 2.2 Proven sustainable liquid and gaseous fuel policy approaches by market status and technology readiness



Notes: "Established markets" refer to sectors in a specific region where a sustainable fuel, or a close substitute, is already in use, is regulated and is supported by established supply chains and infrastructure. "New markets" refer to sectors in which the fuel is not yet widely used – or is not established in the given region – requiring significant regulatory support, infrastructure and supply chain development. "Commercial technologies" are at TRL 9 and "Emerging technologies" at TRL 7 or 8.

The following sections outline IEA-recommended policy priorities for each of the five groups in Figure 2.2, based on analysis of nearly 2 000 policies tracked in the Renewables market report series, the Global Hydrogen Review series, the Outlook for Biogas and Biomethane and the State of Energy Innovation report. Though each fuel has distinct characteristics, the underlying policy logic is often transferable. For example, emerging technologies – whether hydrogen-based fuels, liquid biofuels, or biogases – require de-risking through similar policy tools including production incentives, capital support and guaranteed demand.

Although grounded in historical experience, this analysis also serves a forward-looking purpose: to illustrate that the tools needed to deploy sustainable liquid and gaseous fuels at scale already exist – and have been applied to various geographies, sectors and fuel types. It also demonstrates how international collaboration can complement domestic policies and help accelerate global deployment by supporting diverse technology and market combinations, building on regional opportunities and available resources. Finally, consideration is given to how all actions can be integrated to expand their supply.

Policy frameworks in established markets

In the United States, Brazil, Canada and countries across Europe, longstanding policy frameworks, mature supply chains and sustained business investments provide a strong foundation for continued expansion. Commercially available sustainable liquid and gaseous fuels (TRL 9) include ethanol, biodiesel, renewable diesel, biojet and biogases. In these established markets, policy priorities are to incentivise continuous improvement, ensure secure and affordable supplies and address remaining barriers to greater adoption.

Established markets also offer opportunities for emerging technologies such as hydrogen, hydrogen-based fuels, cellulosic ethanol and Fischer-Tropsch-based fuels. Policy priorities include reducing investment risks for first-of-a-kind plants, creating stable long-term demand and aligning regulations and policies to accommodate new fuels.

Commercial technologies in established markets

Established markets provide strong opportunities to expand the deployment of commercial sustainable liquid and gaseous fuels and enhance their performance. As adoption rates rise, however, greater focus is needed on affordability, supply security, and addressing barriers to broader use. A wide variety of policy priorities and tools can be used to expand commercial fuel pathways in established markets.

Table 2.1 Policy priorities and selected examples for established markets and commercial technologies

Policy priority	Description and tools	Selected examples
Incentivise continuous improvement	Policies aim to reward GHG, cost and sustainability performance by requiring fuel producers to compete on performance or price. Tools include: • Low-carbon fuel standards. • Credit trading systems. • Competitive contracts for difference (CCfDs). • Auctions. • Performance-based incentives.	**California's low-carbon fuel standard** sets GHG intensity reductions with credit trading and broad sustainable fuel participation. The **UK Renewable Transport Obligation** sets a renewable fuel mandate with credit trading. **Italy** has established competitive auctions to convert existing biogas CHP plants to biomethane plants.

Policy priority	Description and tools	Selected examples
Ensure affordable supplies	Policies in addition to those listed above that limit consumer costs and government funding and protect business competitiveness. Tools include: • Adjustable tax credits. • Direct producer subsidies. • Flexible mandates. • Buyout ceilings. • Cross-subsidies. • Credit reserves.	**Indonesia** funds biodiesel use through palm oil export revenues. The **United States** provides clean fuel production tax credits based on carbon intensity. **Brazil** uses flexible mandates and tax rates to mitigate price spikes and limit cost exposure. The **European Union** makes ongoing modifications to the Energy Taxation Directive which supports renewable fuel competitiveness.
Ensure secure supplies	Policies ensure stable and diverse supply chains for sustainable liquid and gaseous fuels. Tools include: • Fuel storage obligations. • Inclusion in national energy planning. • Investment support for infrastructure. • Feedstock diversification incentives. • Credit banking. • Emergency policy flexibilities.	**Japan** includes sustainable liquid and gaseous fuels in its national strategic energy plan. **Brazil** requires ethanol storage and has expanded ethanol transport infrastructure such as pipelines. The **European Union** sets sustainability criteria to ensure long-term, sustainable supply. The **United States** sets annual volume obligations with its Renewable Fuel Standard based on market availability, energy security and other assessments. **India** has diversified ethanol feedstocks away from primarily sugar cane and molasses to stabilise supply.
Remove barriers	Policies target specific constraints to scale-up, including fuel compatibility, distribution infrastructure, feedstock limitations, and vehicle or equipment standards. Tools include: • Infrastructure retrofit grants. • Vehicle incentives. • Fuel standards. • Sustainability certification schemes. • Improving yields and diversifying feedstocks.	**Brazil, India** and the **Philippines** offer support for flex-fuel vehicles, while **France** provides tax breaks for E85 retrofits, allowing for higher ethanol blending. **Denmark, France, Italy** and other countries have established grid-injection protocols for biomethane.

In many countries, measures to enhance competition, ensure affordable and secure supplies, and remove barriers are integrated into single policies or are part of a co-ordinated package to expand supply and use.

Case study 1: Expanding ethanol use in Brazil

Brazil's ethanol sector remains one of the most enduring examples of successful sustainable liquid fuel deployment. Since its first blending mandate in 1931, Brazil has built a robust ethanol industry through a combination of public policy, private investment and institutional learning. In 2024, ethanol accounted for nearly 50% of all gasoline-type fuel used in road transport – supported by a policy framework that has evolved over time to focus on competition, supply security, affordability and expansion. To boost ethanol use, Brazil has focused on:

- **Incentivising continuous improvement:** Introduced in 2017, Brazil's RenovaBio programme prioritises energy and GHG efficiency, with targets for emission reductions, a national carbon credit market and certification for production performance. It also invested in better yields through crop breeding, irrigation and fertiliser improvements. These tools incentivise producers to optimise operations while maintaining supply reliability.
- **Enhancing supply security:** Brazil integrates biofuels into its national energy strategy, supports dedicated investment funds for production and distribution infrastructure, and uses flexible mechanisms to adapt to market conditions. Biofuels are also embedded in land-use planning to balance agricultural and environmental priorities.
- **Containing consumer costs:** Flexibility is central to Brazil's ethanol policy. Blending is currently allowed up to 30% with provisions to increase to 35% if it is technically and economically feasible. Blending rates can be adjusted according to cost and availability if necessary. Taxation of ethanol and gasoline is also used as a lever to maintain affordability, with rates modified depending on price dynamics.
- **Enabling high-ethanol use:** In the early 2000s, Brazil introduced tax incentives for flex-fuel vehicles, which now account for nearly 80% of the light-duty vehicle fleet. This enabled ethanol use to exceed mandate levels and provided resilience during oil price shocks. By allowing E100 use, FFVs created a flexible and scalable market for domestically produced ethanol.

Brazil is just one example of expanding ethanol supply at scale. The United States, the European Union, Canada, India and many other countries have also successfully scaled ethanol production and use via mandates and financial support, often with clear sustainability guard rails.

Emerging technologies in established markets

Established markets offer growth potential for emerging technologies because, once commercialised, they can leverage the benefits of existing regulatory frameworks, financing mechanisms and supply chains.

Table 2.2 Policy priorities for established markets and emerging technologies

Policy priority	Description and tools	Selected examples
Reduce investment risks for first-of-a-kind plants	Policies that help reduce investment risks include: • Production incentives. • Grants and cost sharing. • Low-interest loans. • State investment. • Tax exemptions. • Green bonds. • Sustainability-linked loans.	**India's** Pradhan Mantri JI-VAN Yojana provides up to 20% of project capital costs for selected emerging technologies. **Brazil's** BNDES Mais Inovação Programme and Climate Fund provide low-interest loans for emerging technologies. The **European Union's** Innovation Fund supports innovation in net zero mobility with EUR 40 billion available between 2020 and 2030. **In Canada,** British Columbia's LCFS Initiative Agreements provide capital cost support for emerging technologies funded via compliance credits.
Create stable long-term demand	Policies that help establish demand include: • Sub-mandates. • Contracts for difference. • Public procurement. • Offtake guarantees.	The **EU ReFuel Aviation** establishes long-term sub-targets for renewable fuels of non-biological origin (RFNBO). The **US RFS** provides dedicated credits for cellulosic fuels (D3 Renewable Identification Numbers [RINs]) that cellulosic ethanol and biomethane are eligible for. D3 RINs trade at a higher value.
Align existing regulatory frameworks	Ultimately, emerging technologies will need to be included in existing regulatory frameworks. Modifications often involve: • Including processes for new technology pathways and approvals. • Updating technical, safety and environmental standards for new fuels. • Adapting tax codes and other supports for new fuels.	**India's** National Biofuel Policy includes emerging technologies, so they also benefit from guaranteed pricing, long-term offtake agreements, feedstock approvals and other benefits. **Canada's** Clean Fuel Regulations include provisions for approving technologies or processes as new pathways.

Case study 2: Commercialising renewable diesel in the European Union

In 2007, Neste built the world's first commercial-scale renewable diesel facility (170 kt/yr) at its Porvoo refinery in Finland in anticipation of EU and domestic biofuel blending requirements. Today, renewable diesel is the fastest-growing transport biofuel, accounting for 50% of the total transport biofuel increase between 2023 and 2030. Its success stems from efforts to reduce investment risks; early demand support; and the alignment of existing regulatory frameworks for quick expansion in established markets. The following actions helped commercialise and expand renewable diesel production and use.

- **Reducing investment risks for first-of-a-kind plants:** Neste funded the USD 80-million renewable diesel project in tandem with a USD 560-million investment in diesel upgrades at the facility. Several factors helped de-risk the project. The renewable diesel facility was integrated into an existing refinery, leveraging established infrastructure, and Neste had already demonstrated fuel product compatibility through earlier trials. At the time of the final investment decision, the Finnish government provided long-term strategic guidance to Neste through its board of directors. This continued during construction and commissioning of the facility, supported by the government's 50.1% shareholder stake in Neste.
- **Creating stable long-term demand:** Following the facility's completion, a public procurement and testing programme was launched with participation from Helsinki City Transport, the Helsinki Metropolitan Area Council and Proventia. Through the public procurement programme, Neste Oil secured a tax exemption for fuel used for public services, a benefit not extended to other biofuels. In 2010, the European Union introduced a 10% renewable energy target in transport, with double-counting provisions under its Renewable Energy Directive for fuels derived from waste and residues – provisions that benefited Neste's production pathway.
- **Aligning existing regulatory frameworks:** Several regulatory frameworks were modified to enable renewable diesel participation. In the European Union, the Renewable Energy Directive and Fuel Quality Directive incorporated renewable diesel, with guidance on default GHG emissions savings and blending thresholds. Meanwhile, California's Low Carbon Fuel Standard included GHG pathways for renewable diesel as early as 2009 and Canada recognised co-processed fuels in 2010. Technical fuel standards were also revised, introducing a 100% blending standard for renewable diesel in the European Union and confirmation of renewable diesel eligibility for existing standards in the United States.

The Neste case study is just one example of commercialising hydrotreated vegetable oil (HVO) technology. In Sweden, Topsoe and Preem began producing HVO from tall oil and other residue feedstocks in 2010-2011. In Italy, Eni and Honeywell UOP completed the world's first conversion of a petroleum refinery to a dedicated biorefinery at Porto Marghera in 2014. Other technology providers, including Axens, Chevron Lummus Global, Exxon Mobil Corporation, Shell and other companies, have also developed commercial-scale HVO processes.

Policy frameworks to support new markets

While established markets offer considerable growth potential for sustainable liquid and gaseous fuels, it will be essential to develop new markets to realise their full potential. In fact, commercial technologies can be scaled up relatively quickly in new markets, including sectors, regions and sectors within regions, because risks, financing and successful policy approaches are already well understood. For example, once clear market rules were established in India, it grew from being a marginal ethanol user to the world's third-largest market in less than 10 years. Supply and demand can be established relatively quickly in new markets through co-ordinated action, clear demand-side policies and the adoption of established technical and environmental standards.

The most challenging policy environment arises when governments attempt to commercialise emerging technologies while simultaneously establishing new markets (e.g. low-emissions ammonia in shipping and renewable hydrogen in the steel industry). In these situations, it is necessary to harmonise technology and market development in an environment of high uncertainty. Policy priorities should therefore focus on co-ordinating government, industry and civil society action; reducing investment risks; establishing demand; and strengthening institutional and skills capacities.

Commercial technologies in new markets

When commercial pathways are introduced into new markets, successful endeavours often involve clear strategies with targets, programme objectives and co-ordinated government actions; established demand; and technical and environmental standards.

Table 2.3 Policy priorities for commercial technologies in new markets

Policy priorities	Description and tools	Selected examples
Co-ordinate government actions	Fuel, energy and climate strategies, roadmaps or programmes help outline objectives, legislated targets and a resource base, and co-ordinate government actions when aiming to establish a new market.	**India's** National Policy on Biofuels sets targets, feedstock use and government co-ordination across 11 ministries to 2030. **Italy's** 2018 interministerial decree co-ordinated ministry efforts to expand biomethane.
Establish demand	Tools include: • Mandates. • Quotas. • Public procurement. • Performance-based standards. • Contract for difference.	The **EU** FuelEU Maritime and ReFuelEU Aviation regulations set long-term targets for the maritime and aviation sectors. **Brazil** introduced blending mandates for biodiesel in the transport sector in 2005. **Japan** has set start dates for E10 blending (2030) and E20 blending (2040) with compatible vehicle supply requirements. **India** has established a compressed biogas blending mandate requiring 1-5% blending of CBG in transport and piped natural gas from 2025-26 onward.
Institute technical and environmental standards	Approaches include: • Technical fuel standards. • Sustainability requirements. • Safety and operational standards.	The **European Commission** released "common rules for the internal market in natural gas" in 2009, including requirements for biogas and biomethane as well as guidance on mass balance, guarantees of origin and mutual recognition in its Renewable Energy Directive. In parallel, the Fuel Quality Directive (FQD), introduced in 2008, helped establish technical specifications for road fuels, enabling higher renewable fuel blends. **India's** Automotive Industry Standard for ethanol vehicles builds on international experience. In **North America** biodiesel blending standards were introduced for B100 in 2002 (ASTM D6751), B5 in 2008 (ASTM D975) and B6-B20 (ASTM D7467) helping expand biodiesel use.

Case study 3: Introducing biomethane in the US transport sector

In the United States, the transport sector is the largest biomethane growth area, accounting for two-thirds of forecast 2023-2030 expansion. Co-ordinated action at the federal and state levels, demand-side policies and technical and environmental standards have enabled an already-commercial technology to expand into a new sector.

- **Co-ordinating government action:** In 2014, the US Department of Agriculture released a Biogas Opportunities Roadmap to co-ordinate government activities for biomethane, including Department of Energy commitments to strengthen vehicle support programmes for biomethane; Environmental Protection Agency (EPA) reclassification of biomethane under the Renewable Fuel Standard (RFS); expanded carbon accounting assessments; the creation of an interagency biogas opportunities working group; and targeted actions to improve interconnection and injection standards. In California, the Bioenergy Interagency Working Group co-ordinated state-level efforts to align lifecycle carbon accounting, vehicle fuelling infrastructure, and safety standards for biomethane grid injection.
- **Instituting demand-side policies:** Two key policy actions have helped drive biomethane demand in the US transport sector. In 2014, the EPA reclassified biomethane from specific feedstocks as eligible to generate D3 cellulosic biofuel RINs, enabling certain biomethane producers to access credits trading at nearly four times higher than the 2024-2025 average of those previously available under the D5 advanced biofuel category. Biomethane was technically eligible under California's Low Carbon Fuel Standard (LCFS) from its inception, but uptake remained limited until the California Air Resources Board (CARB) clarified standards in 2019 (see discussion in next bullet). The combined value of LCFS credits and D3 RINs amounts to over USD 200/MWh – four times typical production costs – based on average credit values from 2014 to 2023. Credit values for biomethane are particularly high because it offers very low carbon intensity and qualifies for D3 RINs, a category that few other commercial fuels fall into.
- **Aligning technical and environmental standards:** Participation in the RFS and California LCFS required clarification of safety, technical and carbon accounting standards. For example, in 2014 the California Public Utilities Commission adopted monitoring and reporting requirements for biomethane injection in gas grids. In 2019, CARB issued guidance on a book-and-claim accounting system. Both actions were critical to enable broader biomethane participation under the LCFS. At the federal and California levels, GREET lifecycle assessment model pathways were also developed to establish carbon intensity.

Emerging technologies in new markets

In some cases, policy packages must be designed to commercialise new technologies while simultaneously developing new markets. In these situations, priorities should include co-ordinating a broad set of stakeholders, establishing niche demand with targeted support policies, and setting clear technical and environmental standards.

Table 2.4 Policy priorities for emerging technologies in new markets

Policy priorities	Description and tools	Selected examples
Co-ordinate stakeholder groups	Roadmaps, strategies, consultations and visions can all help stakeholders understand the national context and determine actions to commercialise technologies and establish markets in the public, private and civil society sectors.	Various government agencies and stakeholder groups formulated the SAF Grand Challenge Roadmap in the **United States** to expand the SAF supply and reduce costs. **Japan's** basic hydrogen strategy establishes public and private actions required to expand hydrogen production.
Reduce risks and establish demand	Supply and demand policies aligned with technology maturity are necessary to both nurture new technologies and establish new markets. Approaches include: • Mandates. • Quotas. • Procurement and performance-based standards. • Grants. • Tax incentives. • Production incentives. • Loan guarantees. • Other de-risking measures.	ReFuelEU Aviation sets requirements for aviation fuel suppliers in the **European Union** to gradually increase the share of SAF blended into conventional aviation fuel. **Japan** provides financial support for projects through its hydrogen Contract for Difference programme and CAPEX support for infrastructure. **H2Global** hosts double auctions (supply and demand) using a contract-for-difference mechanism to help develop the hydrogen market.
Build institutional and skills capacities	Commercialising technologies and expanding the market will require new institutional capacities and a skilled workforce, which can be developed through: • Dedicated agencies or cross-ministry programmes. • Open-access data platforms. • Demonstration hubs. • Certified verifiers and registries. • Training programmes. • University-industry partnerships.	**Australia's** hydrogen hub development programme helps reduce production costs, encourages innovation and enhances skills and training. **China's** Action Plan for Green Development of Shipbuilding (2024-2030) outlines institutional and capacity-building needs. **Japan's** raBit association unites private sector research efforts to improve feedstock cultivation, biofuel system efficiency and production systems.

Case study 4: Using hydrogen for low-emissions steelmaking in Sweden

Sweden pioneered hydrogen-based steel production at a time when there was no market for low-emissions steel and the technology was still in its infancy (TRL 5). It launched a pilot plant (the HYBRIT project) in 2016, with operations beginning in 2020. Efforts to realise production of 1.2 Mt per year began in 2022, with full operations expected in 2027.

Furthermore, in early 2024, Stegra reached a final investment decision for a larger 2.5-Mt plant with a planned start date in 2026 and a proposed expansion to 5 Mt by 2030. (For context, Sweden's total steel production in 2024 was 4 Mt.)

A combination of stakeholder co-ordination, an ambitious policy framework, support for emerging technologies, carbon pricing, and a mixture of grants and guarantees enabled this progress in Sweden.

- **Co-ordinating government, industry and civil society activities:** In 2016, the Fossil-free Sweden Initiative was launched to bring together industry, civil society and government to promote collaboration and build consensus towards a common vision for emissions reductions. In 2017, the Climate Policy Framework was passed, enshrining into law net zero GHG emissions by 2045. While this framework was not specific to steel, it provided strategic policy guidance and certainty for the entire energy system.
- **Reducing investment risks and securing demand:** In 2018, the Swedish government introduced the Industrial Leap programme to support the industry sector transition to low-emissions alternatives. In 2023, this programme granted SEK 3.1 billion (USD 310 million) to the HYBRIT pilot plant out of a total investment of SEK 20 billion (USD 2 billion). For HYBRIT, nearly 20% of the capital cost was financed from public funding, with 80% in the form of grants. For Stegra's commercial plant, the share of public funding was the same (20%) but there was less (40%) in the form of grants from the Swedish government and the European Commission. The remainder was loaned as debt from multilateral development banks and export credit agencies.
- Guarantees were also important, with the Swedish National Debt Office providing 80% coverage for HYBRIT and 95% for Stegra's financing arrangements. Stegra also secured offtake agreements for 60% of the plant's production for five to seven years before final investment decisions from various companies in the automotive, steel processing and residential sectors. Initially, 18 different companies signed as offtakers, lowering the overall risk for Stegra, as offtakers were willing to pay a premium of up to 20% to meet their emissions reduction targets.
- **Building institutional and skills capacities:** The HYBRIT initiative is a common research platform that encompasses technical and market steel transition research, helping establish a broad knowledge base in Sweden.

Beyond these direct incentives, Sweden has an emissions trading system with prices of USD 65-95/tCO_2 in 2025, which will increase as emissions reduction targets tighten. Sweden also has one of the lowest wholesale electricity prices in the European Union, improving the economics of low-emissions steel, as this remains the primary cost for these types of projects. With a grid-emissions intensity of just 18 gCO_2/kWh (among the lowest in the world), Sweden enables grid-connected electrolysis.

International collaboration

International co-operation and collaboration can help shape and amplify domestic policies by facilitating knowledge sharing, creating a global vision, aligning standards and certification systems, and establishing markets for international fuel use in shipping and aviation.

- **The G7, G20 and COP:** Multilateral fora serve as strategic venues for setting global priorities. For example, the Global Biofuels Alliance was launched under India's 2023 G20 presidency; Brazil's 2024 G20 Leaders' Declaration emphasised sustainable fuel deployment in hard-to-abate sectors; and Italy's 2024 G7 Leaders' Communiqué committed support to scale up investment in sustainable liquid and gaseous fuels. Meanwhile, the COP30 action agenda seeks to accelerate zero- and low-emissions technology deployment in hard-to-abate sectors.
- **The International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO).** In 2016 ICAO adopted CORSIA, and in 2019 introduced its lifecycle emissions methodology, which underpins emissions reporting and offsetting for more than 130 participating countries by 2026. More recently, in 2025, the IMO approved its draft net zero framework, introducing carbon intensity targets and market-based measures with phased implementation through 2035.
- **The Clean Energy Ministerial (CEM):** CEM serves as a high-level forum to advance clean energy transitions through public-private collaboration. It hosts several dedicated sustainable fuel initiatives, including the Biofuture Platform, the Hydrogen Initiative, Clean Energy Marine Hubs, the CCUS Initiative and the Industrial Deep Decarbonisation Initiative, each targeting key sectors such as bioenergy, hydrogen, shipping and industry. Additionally, CEM recently launched a Future Fuels action plan.
- **Mission Innovation (MI):** MI is a global initiative to catalyse action and investment in research, development and demonstration of new technologies to make clean energy affordable, attractive and accessible to all. Its action-oriented "missions" include the Zero-Emission Shipping Mission, the Clean Hydrogen Mission, the Net Zero Industries Mission, the Carbon Dioxide Removal Mission, and the Integrated Biorefineries Mission.

- **The World Economic Forum (WEF)**: The WEF's numerous sustainable liquid and gaseous fuel initiatives focus on public-private co-operation. For instance, the First Movers Coalition aggregates corporate purchase commitments to create early demand for near-zero-emissions technologies in hard-to-abate sectors. The Future of Clean Fuels convenes industry representatives, policy makers and financiers to unlock market adoption of bio-based and hydrogen-derived fuels by facilitating public-private partnerships, while the Green Fuel Forward campaign seeks to boost SAF demand in the Asia-Pacific region. Other relevant initiatives include Transitioning Industrial Clusters and Airports of Tomorrow.
- **International standardisation bodies:** Global fuel standardisation bodies such as the European Committee for Standardization (CEN) and the American Society for Testing and Materials (ASTM) provide harmonised specifications, testing methods and certification pathways to reduce market-entry barriers for sustainable liquid and gaseous fuels. Examples include the ASTM D7566 specification for SAF production pathways and CEN standards for biomethane grid injection that reduce transaction costs and enable scale-up by making sustainable fuels fungible across markets. Further work could include internationally recognised finished-fuel standards for mid-level (E20-E30) blends of ethanol in gasoline to clarify fuel compatibility for vehicle manufacturers.
- **Bilateral agreements:** Countries also leverage bilateral co-operation to advance sustainable fuel technology progress, policy design and market development. For example, Brazil and Indonesia have partnered on sustainable biofuel production and land-use practices, Japan and India have agreed to a clean energy partnership, which includes sustainable liquid and gaseous fuels, and Germany and South Africa signed a co-operation agreement on green hydrogen.

Box 2.1 Brazil and Japan's Initiative for Sustainable Fuels and Mobility (ISFM)

In 2024, Brazil and Japan launched the Initiative for Sustainable Fuels and Mobility (ISFM) to support emissions reductions and encourage a just and inclusive transition. Leveraging expertise from both countries, the initiative aims to advance technical collaboration, policy alignment and international dissemination in the deployment of sustainable liquid and gaseous fuels and high-performance mobility equipment.

The initiative focuses on the entire value chain, supporting a diverse portfolio of fuels (e.g. bioethanol, HEFA fuel and e-fuels); supply chain integration; energy-efficient end-use technologies (e.g. hybrid vehicles and flex-fuel engines); certification systems; and public-private partnerships.

In 2025, the two countries signed a memorandum of co-operation and developed an ISFM action plan to enhance knowledge sharing on sustainable fuels and enrich international dialogue leading up to COP30.

The ISFM demonstrates how international collaboration can aid domestic policy development, expand international dialogue and provide greater policy certainty for investors.

Integrating sustainable fuel policies

The foregoing analysis organised policy objectives into four categories surrounding a core policy framework to clarify their roles at varying levels of technological and market maturity. In practice, however, policies rarely operate in isolation. Expanding sustainable liquid and gaseous fuel supplies depends on integrated policy packages that span several (or all) categories at once. Such packages sustain existing markets, create new demand, nurture emerging technologies and define rules for participation in broader frameworks. Integration matters because fuel markets evolve dynamically (i.e. innovation, demand creation and trade advance simultaneously), so policies that address only one dimension risk leaving critical gaps. Moreover, fuel production technologies may also span several quadrants incorporating commercial and emerging technologies while serving new and established markets. Integrated policy packages are therefore critical to unlock investment and establish markets at scale.

At the foundation are long-term demand signals – such as long-term, technology-open, rising mandates and performance-based standards – anchored by clear sustainability, technical and fiscal rules. These policies provide the certainty needed to mobilise investment and scale up production. When designed to be technology-open, that is inclusive of new fuels and flexible enough to evolve, they can also stimulate innovation and support the gradual entry of technologies and markets that are not yet competitive on their own. In this way, core policy frameworks act as anchors that other, more targeted measures can build upon.

Table 2.5 Selected examples of core sustainable liquid and gaseous fuel policy frameworks

Policy priorities	Objectives
European Union	The EU Renewable Energy Directive (RED), first adopted in 2009 and now in its third revision, sets **overarching objectives** for renewable energy use across all sectors. It provides, in most instances, **long-term demand signals** through renewable energy and GHG intensity targets that apply economy-wide, with specific provisions for transport, heating, electricity and industry. The framework establishes **sustainability and lifecycle GHG criteria**, along with certification systems, to ensure renewable fuels deliver verifiable emissions reductions. **Fuel quality and technical standards** are defined through EU and national regulations to enable integration into existing energy systems and cross-border trade. In parallel, the European Union has advanced fiscal frameworks through the **Energy Taxation Directive** and the **EU taxonomy for sustainable activities**, which define the investment and taxation rules that shape the competitiveness of sustainable liquid and gaseous fuels.
Brazil	Brazil's Future Fuels Programme outlines the **strategic role** of sustainable liquid and gaseous fuels in energy security, decarbonisation, and industrial policy. Building on longstanding ethanol and biodiesel mandates, the RenovaBio programme (2017) provides **long-term demand** signals through decarbonisation targets for fuel distributors, operationalised via tradable CBIO credits. **Sustainability rules** are defined through lifecycle GHG intensity certification and land-use safeguards. **Fiscal measures** include differential fuel taxation, concessional credit lines, and loan programmes that support investment in biofuel production and infrastructure.
United States	The US Renewable Fuel Standard, established in 2005 and expanded in 2007, set **long-term objectives rooted in energy security and later emissions reduction for** the transport sector. It provides annual Renewable Volume Obligations that act as **durable demand signals**, supported by sustainability safeguards such as **lifecycle GHG thresholds and land-use rules**. **Fuel quality** is defined separately through ASTM standards, while **fiscal measures –** delivered through tax legislation and, more recently, the Inflation Reduction Act **–** shape investment incentives.
Canada	Canada's Renewable Fuel Regulations (2010) created initial ethanol and biodiesel blending mandates. The Clean Fuel Regulations (2022) build on this by establishing, **long-term,** annual lifecycle GHG intensity reductions for liquid fuels in the transport sector, enforced through a credit trading system. **Technical and sustainability criteria** rely on lifecycle carbon intensity methods, with fuel quality defined by the Canadian General Standards Board. **Fiscal measures** include green finance tools such as Canada's Green Bond Framework and ongoing sustainable investment guideline development.

Because core policies alone rarely offer sufficient value for early-stage projects, emerging technologies often require targeted time-bound support – capital grants, concessional financing, tax incentives, and infrastructure programmes that reduce first-of-a-kind risks. Such policies can also allow for competition across fuel pathways based on performance requirements. The aim is not to create permanent parallel systems, but to enable new technologies to demonstrate their viability and eventually compete within the broader demand framework. Similarly, establishing demand in new markets such as aviation and maritime transport may initially require sector-specific mandates, sub-targets or credit systems. Over time, however, alignment with core frameworks – through consistent carbon accounting, technical standards and sustainability rules – ensures coherence and avoids market fragmentation.

Finally, integrated packages benefit from international collaboration. Shared targets, common carbon accounting methodologies and interoperable fuel-quality and sustainability standards reduce transaction costs and enable fuels to compete in international markets. Collaboration also allows for policy and technology learning, helping emerging markets avoid redundant efforts and strengthening the credibility of emissions reductions worldwide.

Together, integrated frameworks combine long-term demand, transitional support for emerging technologies, sector-specific measures for new markets and international co-operation. Their temporal nature means the balance of measures shifts over time, but the principle of coherence remains. While the approach differs by region, the EU Renewable Energy Directive, Brazil's blend mandates and RenovaBio programme, India's National Policy on Biofuels, and the US mix of federal tax credits, RFS obligations and state-level LCFS programmes all integrate support for these fuels across all four quadrants.

Chapter 3. Technologies and costs

Highlights

- The main sustainable liquid and gaseous **fuel pathways have major differences** in cost, technology readiness, infrastructure needs and development challenges.
- **Biofuels** are currently the most developed and cost-effective fossil fuel alternative, with ethanol and biodiesel reaching cost parity in some markets. However, substantial efforts are needed to expand and diversify feedstock supplies, commercialise new technologies and improve comparability of carbon accounting methodologies to aid large-scale deployment.
- **Low-emissions hydrogen** can substitute for unabated fossil-based hydrogen in industry and for new hydrogen applications. Falling cost of renewables contribute to its appeal, but progress is hindered by insufficient demand-side policies and significant infrastructure investment needs.
- **Hydrogen-based fuels** add to the diversity of sustainable fuel options. They typically require less new infrastructure than hydrogen but are around 50% more expensive to produce. Their scalability is constrained by access to low-cost sources of CO_2 feedstocks, with the exception of ammonia that is inherently carbon-free.
- Sustainable liquid and gaseous fuels are **generally more expensive** than their fossil counterparts, e.g. around 3.8-fold in the case of electrolytic hydrogen, 2.7-fold for electrolytic ammonia, and 3.7-fold for biomethanol. While costs are expected to decline with technological learning, these fuels are likely to remain more expensive than fossil fuels over the coming decade.
- The per-GJ cost of some new sustainable fuel pathways can be much higher than for unabated fossil fuels. However, the **impact on consumers will likely be limited** by the initially low blend ratios and the small share of energy costs in the final price. For example, ticket prices in aviation may increase by less than 10% percent, while the effect is below 1% for vehicles produced with low-emissions steel or goods transported on ammonia-powered ships.
- New fuel pathways and combinations continue to develop, **unlocking new opportunities**. Policy frameworks must remain flexible and technology-open to enable market entry for innovative fuels.

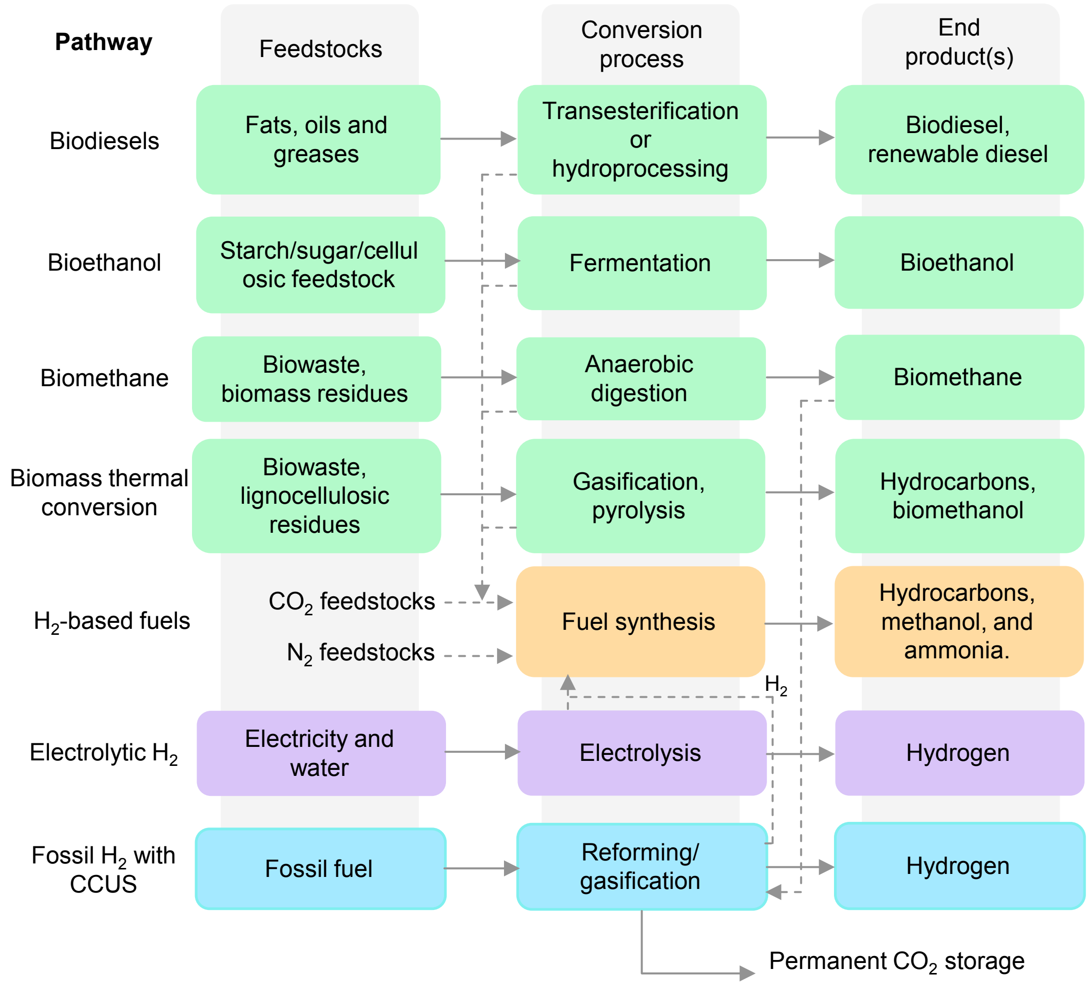
Technologies and feedstocks

Sustainable liquid and gaseous fuels can be produced through a range of pathways, reflecting the wide diversity of feedstocks and conversion methods available. Despite their wide variety, most pathways fall broadly into three main fuel families:

- liquid and gaseous biofuels derived from biomass
- low-emissions hydrogen
- hydrogen-based synthetic fuels.

Each category encompasses multiple technology types at different stages of maturity, with varying cost profiles and specific scale-up challenges.

Figure 3.1 Possible production pathways for sustainable liquid and gaseous fuels



IEA. CC BY 4.0.

Notes: H_2 = hydrogen; CCUS = carbon capture, utilisation and storage.

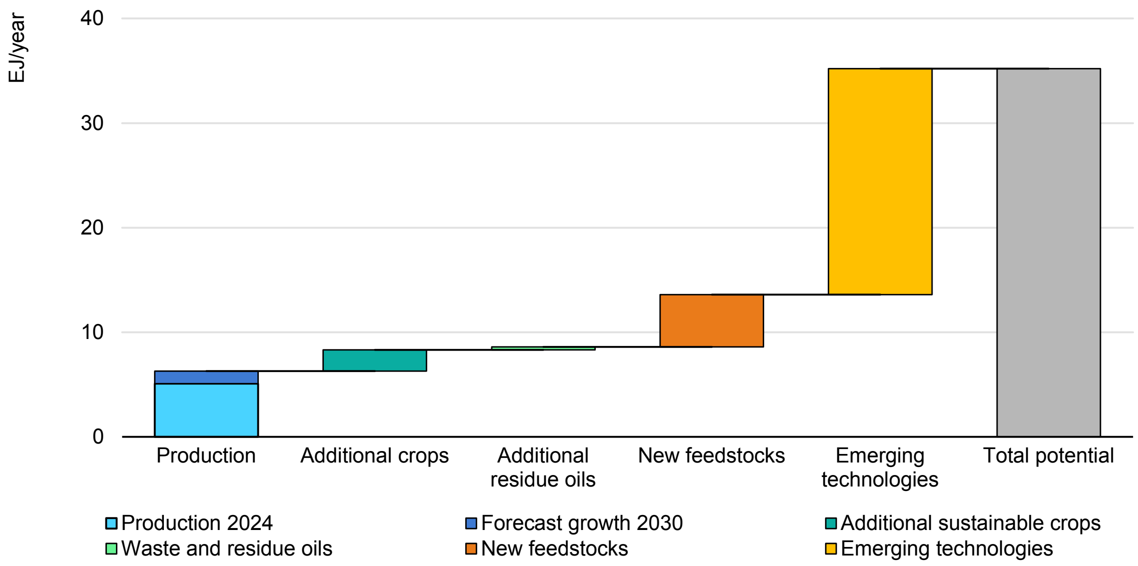
Liquid biofuels, used mainly in road transport and in lower volumes in aviation and maritime shipping, have reached the widest commercial use and are among the most affordable options available today. While some are subject to limitations on blending with fossil fuels when used in current engines (e.g. ethanol and biodiesel), others are "drop-in" and can fully replace their fossil fuel counterparts (e.g. renewable diesel). Regarding feedstocks, the European Union has placed maximum limits on the share of feed- and food-based biofuels allowed in transport, and other countries and states have included feedstock type caps (see Box 1.2).

Commercial-scale production is derived primarily from agricultural crops (e.g. corn, sugarcane, soybean oil, palm oil and rapeseed oil) and waste and residue oils and fats (e.g. used cooking oil and tallow). Oil-based feedstocks are required for their versatility to produce fuels for road, aviation and maritime transport, resulting in an increase in demand for them over the last several years. However, the available supply of feedstocks derived from waste oils and fats is limited, and expansion possibilities could be almost exhausted by 2030. There has been controversy over possible fraud in the supply chain of certain waste-based oil fuels sold to the European Union to qualify for Renewable Energy Directive (RED) incentives, prompting calls for stricter oversight and robust traceability systems implementation.

Production from other agricultural crops (e.g. sugarcane and corn) is less stressed, but ethanol use in road transport is constrained by blending limitations for gasoline engines. While some countries are revising their standards and allowing higher blends (Brazil 30%, United States 15%), flex-fuel vehicles, which can run on high-ethanol/gasoline blends (E100 in Brazil, E85 in the United States), are technologically mature and have been widely adopted in Brazil and the US Midwest. Beyond road transport, the shipping sector could offer additional markets for ethanol as sustainable maritime fuel. The alcohol-to-jet fuel pathway can open the door to ethanol use in aviation, albeit with added investment and fuel cost.

Additional feedstocks can be made available by applying new, sustainable cultivation practices. Crop feedstocks such as maize, sugarcane and soybeans could be expanded without additional land by improving agricultural yields in certain regions, or by planting new palm oil trees to replace old ones, for example.

Figure 3.2 Current and future production and feedstock potential for liquid biofuels



Notes: "Additional crops" includes intensification of current crops with no overall increase in cropland use for bioenergy production and no use of forested land. "New feedstocks" includes cover crops and cultivation of marginal and degraded land. "Emerging technologies" refers to other organic feedstocks (agricultural and forestry residues, municipal solid waste, short-rotation woody crops and forestry plantations) that require the development of new processing technologies.

Sources: Production 2024 and forecast growth from IEA (2025), Renewables 2025, "Additional crops" and "New technologies" from the IEA (2022), World Energy Outlook 2022, "Additional residue oils" and "New feedstocks" from Clean Skies for Tomorrow Coalition (2020).

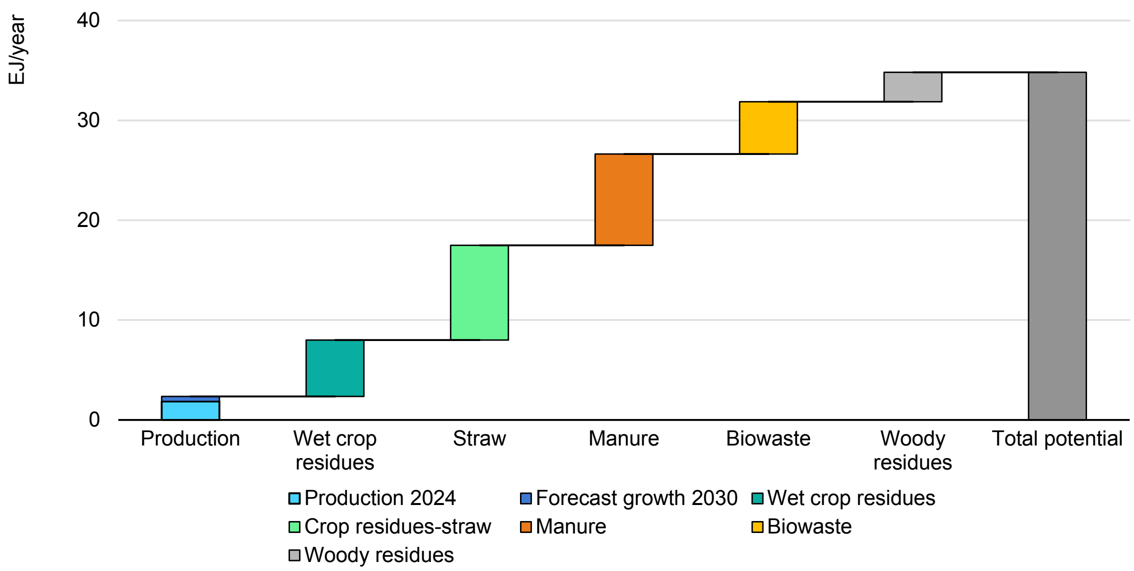
More feedstocks compatible with current transformation processes can be derived from cover crops and crops grown on marginal and degraded land, which would not compete with agricultural land. Biofuel markets can also create synergies between food and fuel applications, as larger demand for fuels will lead to investments for increased production, as observed under the US Renewable Fuel Standard.

Moreover, the development of new technologies would also allow for liquid biofuels to be made from a broader range of residues and waste (e.g. forest residues and municipal solid waste). The untapped potential of these feedstocks is significant, although accessing them at an affordable price can be difficult in some regions. Commercialisation of new technologies, such as biomass or municipal solid waste gasification with the Fischer-Tropsch synthesis, is also complex, with many projects struggling to get past the demonstration stage.

Although ethanol, biodiesel and renewable diesel are derived mainly from crops, technological advances have enabled their production from waste and residues, offering lower GHG intensities and avoiding the use of additional cropland. Commercial-scale production from used cooking oil, tallow and other fatty wastes is now a reality, and ethanol made from cellulosic material has also reached the market with small volumes from niche feedstocks, as demonstrated by Raízen's use of sugarcane bagasse and by several producers in the United States employing corn kernel fibre. However, exploiting other, more abundant sources of cellulosic feedstock (e.g. cereal straw) remains technologically challenging and economically less viable.

Gaseous biofuels, particularly **biogas** and its upgraded form **biomethane**, have reached wide commercial deployment in many countries, including Germany, France, Italy, Denmark, the Netherlands, the United Kingdom and the United States. More recently, their strategic importance has been recognised by the People's Republic of China (hereafter "China"), India and Brazil, which view biogases as effective tools to reduce energy system emissions, curb natural gas import reliance, support rural economies, and promote economic circularity.

Figure 3.3 Current and future production and feedstock potential for gaseous biofuels



Notes: "Wet crop residues" refers to harvest and processing residues from sugarcane, sugar beets, oil crops, potatoes, cassava and yams. "Crop residues-straw" covers harvest residues from cereals and grains. "Biowaste" includes the organic fraction of municipal solid waste and gardening, sewage sludge and industrial processing waste. "Woody residues" indicates wood processing residues and logging residues.
Sources: IEA (2025) Renewables 2025, IEA (2025) Outlook for Biogas and Biomethane.

Traditionally, biogas production has been closely linked to the treatment of organic waste streams such as animal manure, wastewater sludge and, more recently, food waste diverted from landfills, and crop residues. By treating animal manure, biogas systems also prevent methane emissions from uncontrolled decomposition, resulting in additional emissions reduction contributions. Landfill gas is still an important and affordable source of biogas in the United States and other countries. However, recent policies are favouring better environmental practices such as separately collecting organic municipal waste, to divert it from landfills and treat it via anaerobic digestion or other valorisation processes such as composting.

Recent assessments indicate that untapped biogas feedstock potential is considerable (estimated at nearly 1 000 billion cubic metres of natural gas equivalent per year – around 36 EJ/yr) using current anaerobic digestion technologies. About 80% of this potential is in emerging markets and developing economies, led by Brazil, China and India. The European Union is already exploiting 40% of its potential, while the rate in China is less than 10% and in India it is 5%. Thus, rather than a lack of feedstock availability, the main bottlenecks to biogas and biomethane development are logistical challenges involved in gathering the required quantities and qualities of waste relatively close to production facilities. Some innovative approaches are appearing to deal with this, for example the hub-and-spoke models to aggregate feedstocks in Denmark. In other regions such as India, China or Brazil, the relatively limited gas network, sometimes far from production areas, poses a challenge to deployment of biomethane.

Biogas can be used directly as a source of heat and to produce power, while biomethane is interchangeable with natural gas and can be used in the existing natural gas grid and end-use equipment. This feature makes it very versatile, as it can provide a low-emissions fuel in the industry and residential sectors, as well as in transport for natural gas-powered fleets. Additionally, biomethane can be used as a feedstock to produce biomethanol or be reformed in existing natural gas plants to produce hydrogen.

Electrolytic hydrogen can be produced from electricity and water and thus is not limited by feedstock availability. The main barriers to wider commercial adoption include access to low-cost, low-emissions sources of electricity with high-capacity factors, and the relatively high capital costs of electrolysers. The conversion of electricity to hydrogen via electrolysis has low efficiency (60% on a lower heating value basis), making production costs highly sensitive to the price of electricity. Technology learning can eventually increase electrolysers efficiency and drive down CAPEX, but electrolytic hydrogen is expected to remain more expensive than unabated fossil-based hydrogen. Electrolytic production requires water, not only as a feedstock but also for cooling, which can be potentially problematic in some regions that have abundant low-cost renewable electricity but are water stressed. However, water for this process can often be supplied through seawater desalination.

Table 3.1 Main resources required to produce selected sustainable fuels

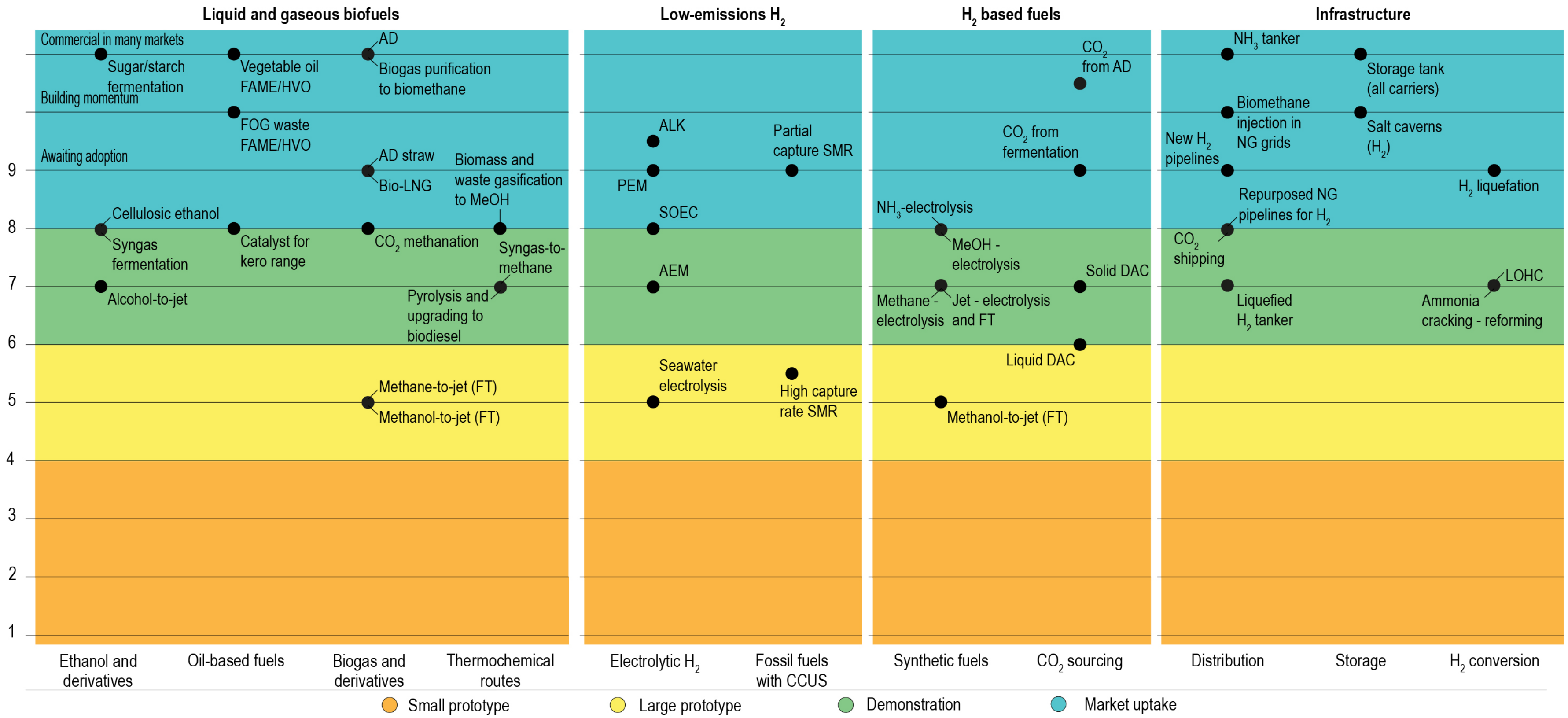
Fuel	Key resources required
Liquid biofuels	• Crop feedstocks • Waste and residue oils • Municipal solid waste, agricultural and lignocellulosic waste and residue feedstocks within a short collection radius
Biogases	• Waste and residue feedstocks within a short collection radius • Agricultural land to apply digestate (if not transformed)
Electrolytic H_2	• Low-emissions electricity generation potential • Water (potentially from desalination plants) • Critical materials for variable renewable power generation, batteries and electrolysers, if needed
Hydrogen from fossil fuels with CCUS	• Natural gas or coal • For sequestration, access to permanent underground storage
Hydrogen-based fuels	• Sustainable point source of CO_2 • Low-emissions hydrogen availability

Low-emissions hydrogen can also be produced from **natural gas with carbon capture, utilisation and storage**. A low GHG intensity can be achieved if the CO_2 from existing or new plants is captured at high rates (e.g. 95%) and methane leakages in the production and transport of the natural gas are minimised. While producing low-emissions hydrogen from natural gas with CCUS can be less costly than the electrolytic route, it requires access to CO_2 transport infrastructure and suitable geological storage, limiting short-term deployment opportunities. Additionally, all types of low-emissions hydrogen require the development of new, dedicated infrastructure and storage for hydrogen trading.

Low-emissions hydrogen can be used directly as a feedstock in chemical reactions (for example, in the chemical sector, hydrotreating in refineries or reduction of iron ore) or be further converted into **hydrogen-based synthetic fuels and feedstocks**. The main pathways under development are low-emissions ammonia (for fertilisers, chemicals and shipping), e-methanol (for chemicals and shipping), kerosene for aviation (which also produces synthetic gasoline and diesel as coproducts), and e-methane (to replace natural gas).

Except for ammonia, all these synthetic fuels require CO_2 as a feedstock in their production. CO_2 can be sourced from capturing biogenic CO_2 (e.g. from ethanol fermentation or biogas anaerobic digestion), which are low-cost and low-emissions, but availability is currently limited and scattered. Other emerging technologies such as direct air capture (DAC) offer potentially unlimited CO_2 feedstock supplies, but technology readiness levels are low and costs are very high.

Figure 3.4 IEA technology readiness levels (TRLs) for selected pathways



Notes: Based on IEA's updated TRL scale, where the highest level is TRL 9. To provide additional insights into progress after reaching TRL 9, three additional adoption levels are used: "awaiting adoption", "building momentum" and "commercial in many markets". See IEA Global Hydrogen Review 2025 for more details.AD = anaerobic digestion. AEM = anion exchange membrane electrolyser. ALK = alkaline electrolyser. CCUS = carbon capture, utilisation and storage. DAC = direct air capture. FAME = fatty acid methyl ester. FOG = fats, oil 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 electrolyser. SMR = steam methane reforming. SOEC = solid oxide electrolyser cell. VRE = variable renewable energy.

Sources: IEA (2025), Global Hydrogen Review 2025 and IEA Clean Energy Technology Guide.

While commercially available pathways are mature and relatively cost-competitive, their limitations to expand to the extent needed to transition away from fossil fuels makes it necessary to develop new sustainable fuel pathways. The extent to which these pathways could be developed will vary depending on location. Some regions will have more abundant biomass supplies – or opportunities to expand supplies through agricultural practices or untapped feedstocks – while others will have access to cheap renewable electricity for hydrogen and hydrogen-based fuels. Differences in fuel demand across regions are also among the determining factors.

Box 3.1 Availability of sustainable CO_2 for e-fuel production

Producing carbon-containing hydrogen-based fuels such as e-methanol, e-methane, e-SAF, and other synthetic hydrocarbons requires access to low-emissions hydrogen and affordable sustainable CO_2. Careful accounting of lifecycle emissions associated with capturing and supplying CO_2 to the fuel production site, as well as rigorous and transparent certification standards, are required to guarantee the sustainability of the CO_2 source.

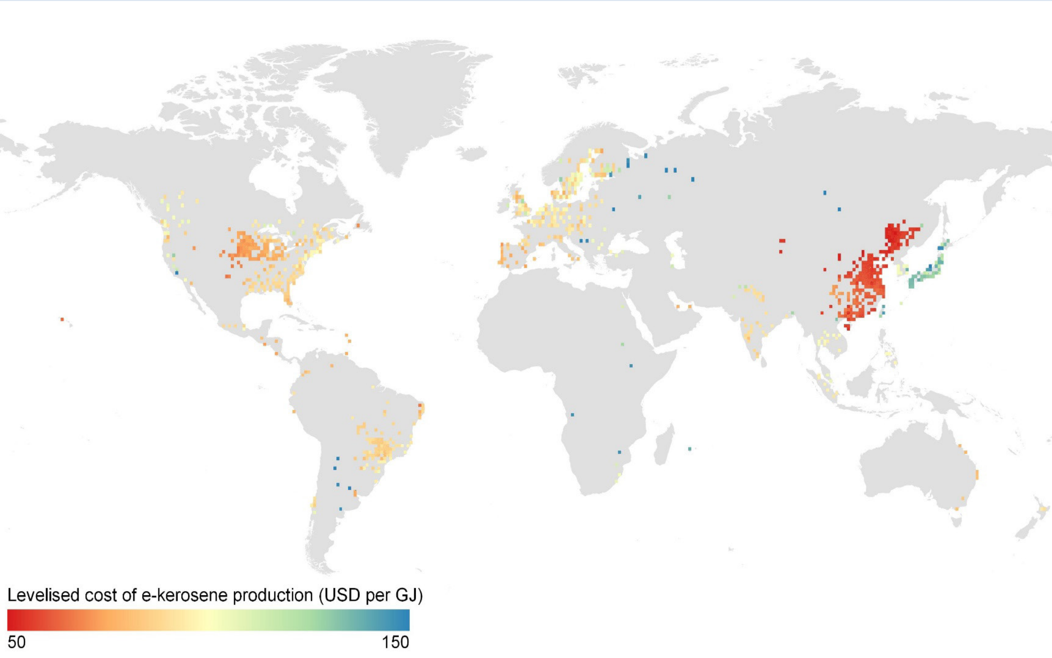
CO_2 captured from direct air capture (DAC) facilities offers some siting flexibility, with the potential to co-locate a new DAC plant with a low-emissions hydrogen production site. However, the cost is very high, with DAC-based removals currently trading at around USD 500/tCO_2 and long-term estimates for the levelised cost of capture ranging from USD 200/tCO_2 to USD 300/tCO_2. This strongly affects e-fuel economics, as the production cost of e-kerosene rises by nearly USD 55/bbl for every USD 100/t increase in the CO_2 feedstock price. Furthermore, DAC technology is yet to be deployed at scale. The largest operating site today has the capacity to capture just over 6 000 tCO_2/yr, and another one with a capacity of 500 000 tCO_2/yr is currently under construction.

Capturing CO_2 from existing biogenic facilities is a lower-cost, more readily available alternative to DAC. Today, just over 2 Mt of biogenic CO_2 is captured per year, mostly from fermentation units in bioethanol plants in the United States and Europe due to their high CO_2 concentrations and resulting low cost of capture (USD 20-30/tCO_2 to purify and compress 1 tonne of CO_2), with large-scale projects capturing and storing 200-500 ktCO_2 per year. Plants upgrading biogas to biomethane also emit relatively pure CO_2 as part of the upgrading process, resulting in a similar cost of capture, and a few have installed CO_2 purification and compression units, although their much smaller scale (5 000 tCO_2/yr on average) limits their potential for e-fuel production.

Low-cost CO_2 is also not necessarily co-located with areas of low-cost hydrogen potential. A spatial analysis shows that only 2% of biogenic CO_2 from bioethanol and biomethane plants is in areas where potential electrolytic hydrogen costs could fall below USD 3/kg in 2030, while a higher share would require the deployment of cost-effective CO_2 transportation infrastructure. Far greater volumes could be captured from waste incinerators, heat and power plants, and pulp and paper facilities, but at a greater cost (USD 80-120/tCO_2).

An additional constraint on the availability of sustainable CO_2 for e-fuel production is competition with CO_2 storage and, indirectly, the selling of CO_2 removal credits it can generate. Today, all captured biogenic CO_2 is sold for industrial use or for enhanced oil recovery (EOR), with the exception of three large-scale facilities in the United States that inject CO_2 into dedicated storage sites that are near the plants. Having access to storage sites, whether by virtue of co-location or through cost-effective CO_2 transport infrastructure, strongly affects decisions on whether to use or store CO_2.

Levelised cost of producing e-kerosene with biogenic CO_2 from operating plants and electrolytic hydrogen from renewable electricity, 2030



Notes: Hydrogen production is based on the lowest-cost option for producing hydrogen from solar PV, onshore wind, or hybrid solar PV-onshore wind systems. Technology assumptions are based on the IEA Stated Policies Scenario for 2030. This analysis considers only biogenic CO_2 from plants that have CO_2 volumes greater than 100 000 tonnes per year or are part of a cluster of plants (within a 30-km radius) emitting a combined 100 000 tCO_2 per year. Biogenic emissions sources are bioethanol plants (global), biomethane upgraders (Europe and the United States only), biomass-fired power plants (global), waste incinerators (global), and pulp and paper plants (global). The assumed levelised costs of capture are USD 25/tCO_2 for bioethanol, USD 30/tCO_2 for biomethane, and USD 85/tCO_2 for other plants. Jülich Systems Analysis performed the levelised cost of hydrogen analysis using the ETHOS model suite.

Source: IEA analysis based on data from Forschungszentrum Jülich, Global Energy Monitor (2024), European Biogas Association (2024), Argonne National Laboratory (2024), Fastmarkets (2024).

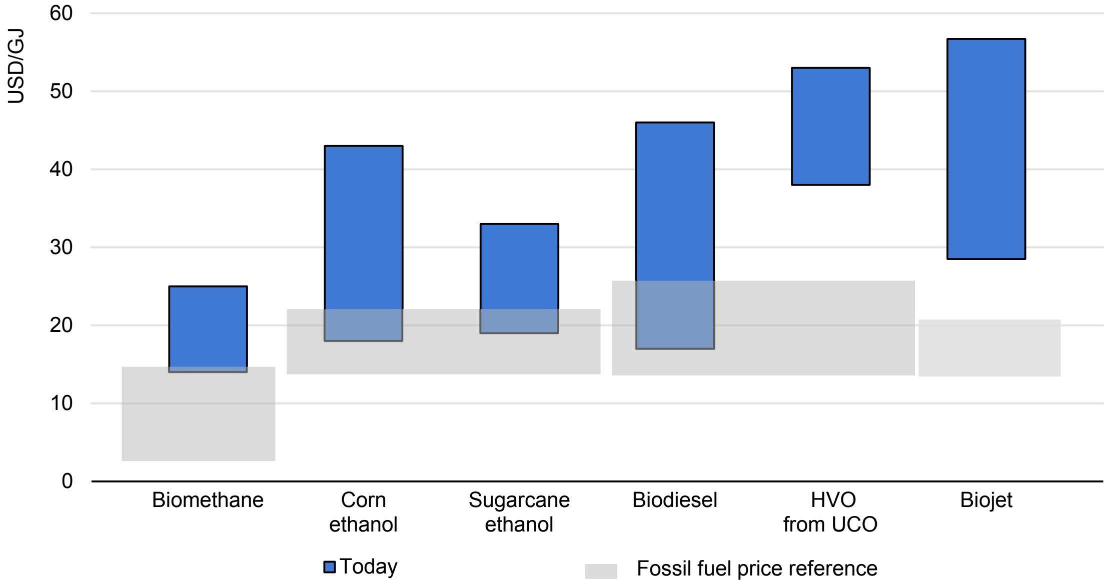
Production costs

Commercial sustainable liquid and gaseous fuels are generally costlier than the fossil fuels they replace, but cost parity can be achieved in some circumstances, although costs are highly feedstock- and region-specific. For example, ethanol made from sugarcane and corn, and biodiesel from vegetable oils, can be priced similar to their fossil fuel equivalents, and ethanol is at times less expensive than gasoline. Other commercialised fuels such as biodiesel and renewable diesel (also known as hydrotreated vegetable oil [HVO] or hydroprocessed esters and fatty acids [HEFA] fuel) made from used oils and fats can be more expensive, but the cost gap can be closed with carbon credits, owing to their lower GHG intensities (e.g. in California and Germany), or other regulatory incentives (such as double-counting towards the mandated renewable energy target in the European Union).

A recent example of this type of regulation is the International Maritime Organization (IMO) Net-Zero Framework being developed for international shipping. It will require vessels emitting above the annually set GHG threshold to earn “remedial units” by contributing to the IMO Net Zero Fund or to acquire “surplus units” at a capped price from ships that emit below the targets, providing additional revenues to users of lower-carbon-intensity fuels. The framework also introduces a mechanism that makes ships using zero or near-zero GHG technologies eligible for financial rewards disbursed by the IMO Net Zero Fund, supporting and incentivising sustainable fuel development.

Biogas and biomethane can be employed in a variety of end-use sectors, but their cost-competitiveness often relies on supportive regulatory frameworks. For example, blending mandates and ongoing development of green certificates for use in industry and buildings have proven successful in developing the sector. In addition, carbon pricing is an especially effective form of support for biomethane produced from animal manure, as this process avoids large amounts of methane emissions with high global warming potential. For example, at a carbon price of USD 70/tCO_2 – aligned with current EU ETS prices – up to 400 bcm of biomethane worldwide can be competitive with natural gas.

Figure 3.5 Global production cost ranges for selected commercial sustainable fuel pathways and corresponding fossil fuel reference prices



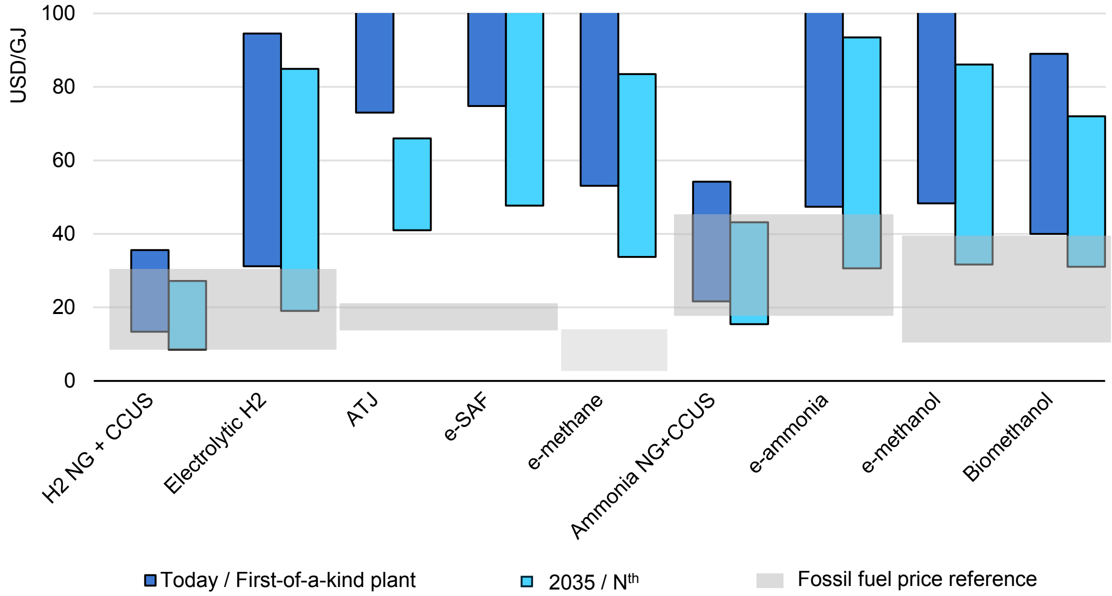
Notes: HVO = hydrotreated vegetable oil. UCO = used cooking oil. Fossil fuel references, ethanol, biodiesel, HVO and biojet depict pre-tax, Free On Board (FOB), wholesale prices. Biomethane depicts production cost. The natural gas reference price range is the 2023 wholesale price.

Emerging fuel pathways – electrolytic hydrogen, alcohol-to-jet fuel, synthetic hydrogen-based fuels and fuels produced through gasification of lignocellulosic feedstocks or municipal solid waste (MSW), among others – are being developed to address feedstock limitations or to take advantage of regional conditions. However, these technologies are still in the early stages of commercialisation, and capital and operational costs are currently high.

Electrolytic hydrogen remains expensive at USD 30-95/GJ (USD 3-11/kg), well above the unabated fossil-based hydrogen price of USD 8-30/GJ (USD 1-3/kg). Converting hydrogen into ammonia adds to the cost, while synthetic fuels with longer molecules (e.g. e-SAF) remain among the most expensive options – often exceeding USD 80/GJ (USD 3/litre). Such high costs reflect the process’s early-stage technological development, low production volumes and lack of mature supply chains. However, costs are expected to decline with greater operational experience, larger manufacturing capacities and falling renewable electricity prices.

Although the rapid scale-up of solar PV and wind power has led to significant cost reductions – making them the cheapest sources of new electricity generation in most regions – sustainable liquid and gaseous fuels are unlikely to follow a similar cost trajectory. This is due to their significant feedstock cost component (in the case of biofuels) and energy-intensive processing requirements (in the case of electrolytic hydrogen and derivatives). As a result, these fuels will remain heavily dependent on policy support to close the cost gap with unabated fossil fuels.

Figure 3.6 Current and future production costs of selected emerging sustainable fuel pathways and corresponding fossil fuel reference prices



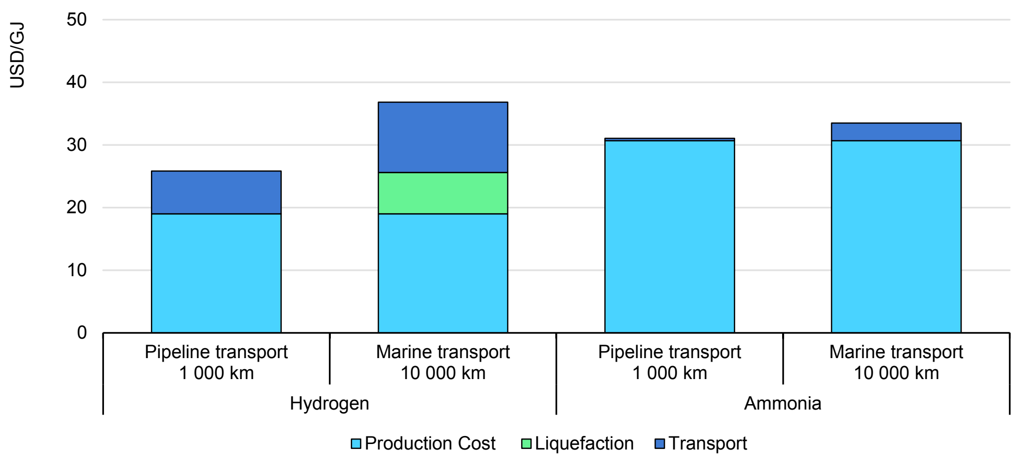
Notes: ATJ = alcohol-to-jet fuel. NG = natural gas. SAF = sustainable aviation fuel. CCUS = carbon capture, utilisation and storage. H_2 NG + CCUS costs include CO_2 capture, transport and storage. Fossil fuel price references are pre-tax, Free on Board (FOB), wholesale prices, while costs for emerging fuels are production costs. The natural gas reference price range is based on 2023 wholesale prices. “Electrolytic H_2” refers to hydrogen produced from solar PV or wind power. “Biomethanol” corresponds to lignocellulosic biomass gasification. “First-of-a-kind plant” and “Nth plant” production cost estimates apply to ATJ, e-SAF, e-methane, e-ammonia, e-methanol and biomethanol.

Some fuels, such as renewable diesel, biomethane – blended or pure – and ethanol – in low blends – are interchangeable with existing fuels and do not require changes to end-use equipment or additional investments in infrastructure (other than natural gas grid connections for biomethane, or additional storage in the case of some biofuels). Thus, the cost of using these drop-in fuels is largely reflected in their price.

In contrast, large-scale investments in infrastructure and end-use equipment are required to establish commercial-scale value chains for hydrogen, ammonia and methanol, especially to expand their use beyond current industrial applications. While ammonia and methanol are already internationally traded today for use in the chemical industry, such that some ports and shipping companies have gained experience in handling and storing these fuels, employing them more widely in shipping requires significant investments in distribution, bunkering and vessels (conversions and new builds). Furthermore, all infrastructure must comply with new toxicity and safety requirements.

In addition, new, dedicated infrastructure and storage will need to be developed to trade all types of low-emissions hydrogen. This would raise its final cost by around 10% if it is transported by short-distance pipeline, and by 60% if it is shipped (including the cost of liquefaction).

Figure 3.7 Delivered cost of renewable hydrogen and ammonia



Notes: Based on electrolytic hydrogen and ammonia from variable renewable power production costs for a 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-inches pipeline, and includes compression costs.
Source: IEA internal analysis based on IEA (2024) Global Hydrogen Review 2024.

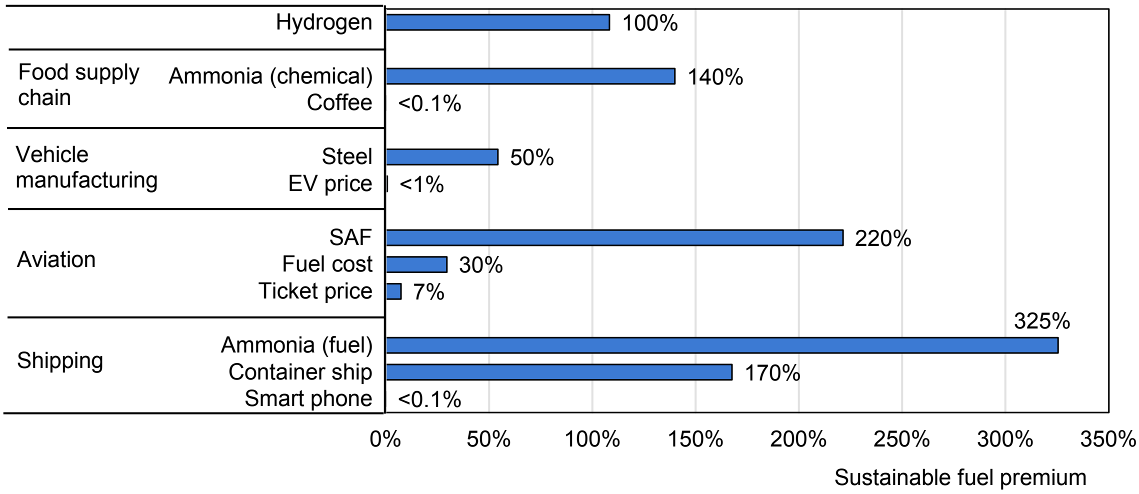
Impact on consumer prices

Although the cost of emerging fuel pathways will initially be very high – in some cases three to five times higher than unabated fossil fuels – the price impact on end consumers will be mitigated by low blending rates to begin with, and by the small contribution of energy costs in final product prices.

For example, in the **food supply chain**, low-emissions hydrogen can be used to produce low-emissions ammonia and nitrogen-based fertilisers to boost crop yields. Naturally, the hydrogen cost will have an impact on the final cost of the agricultural products – and therefore on the price of food. However, for example, considering average fertiliser application and yields for coffee production by region, the impact on the price of a cup of coffee would be less than 1%.

Meanwhile, **sustainable aviation fuel** (SAF) (from all production routes) currently costs 2-10 times more than fossil-based kerosene. However, for a blending share of 15% SAF in 2035 (of which four-fifths would be biojet and one-fifth synthetic kerosene) and considering that fuel represents 25-30% of total flight costs, the SAF-related ticket price increase would be around 7%.

Figure 3.8 Cost impact of sustainable fuel use along selected value chains



Notes: EV = electric vehicle; SAF = sustainable aviation fuel. Profit margins are not included. Under “Food supply chain”, low-emissions ammonia is assumed to replace conventional ammonia in fertiliser production for coffee cultivation. Conventional ammonia cost is 25 USD/GJ and low-emissions ammonia cost 60 USD/GJ. Under “Vehicle manufacturing”, low-emissions steel is produced by direct reduction of iron ore using low-emissions hydrogen. For “Aviation”, assumptions include blending of 15% SAF (of which four-fifths is biokerosene at 1500 USD/t and one-fifth synthetic SAF at 4300 USD/t). Conventional kerosene cost is 690 USD/t. For “Shipping”, low-emissions ammonia is assumed to replace heavy fuel oil. Container ship cost includes vessel, bunkering and fuel costs. Heavy fuel oil cost is 550 USD/t and low-emissions ammonia is 60 USD/GJ.

For **industrial materials**, low-emissions hydrogen is set to play a critical role in reducing steelmaking emissions. Producing low-emissions steel today, using direct reduction of iron ore (DRI) with low-emissions electrolytic hydrogen, would be around 50% more expensive than producing traditional steel. However, this premium drops to around 1% when passed on to the final price of an electric vehicle.

In the case of **goods transported in container ships**, the extra cost associated with replacing heavy oil-fuelled shipping with 100% low-emissions ammonia, including vessel and bunkering modifications and increased fuel costs, can be more than four times higher. However, the impact on the final product price can be lower than 1%.

Although cost impacts on final consumer prices are moderate, different end users can be expected to respond to these small price increases in a variety of ways. For example, a small additional fee can be relatively easily absorbed by aviation passengers, especially those flying in premium seats, or by large corporations that have already taken action by buying SAF certificates. For materials, the willingness to pay more for low-emissions vehicles has already been proven in the

EV market and is slowly being reflected in the growing number of carmaker offtake agreements for steel produced with low-emissions hydrogen.

However, other products may be more price-sensitive. For low-income households especially, even small cost increases can have a significant impact. Care should therefore be taken to protect the most price-sensitive products and consumers while still pursuing progress on reducing emissions in these industries.

In addition, price increases can vary across the value chain. For example, stakeholders such as farmers and manufacturers upstream in value chains are likely to experience higher costs, as they are more directly impacted by energy prices and by where their goods are traded globally in competitive markets. They may be too far from end consumers to be able to benefit from their willingness to pay more. Governments designing policies to stimulate these premium markets will therefore need to obtain a holistic view of the value chain to mitigate stakeholder risks.

Finally, governments have an opportunity to implement policies that stimulate markets for these end products through public procurement. As major buyers of vehicles, infrastructure, construction materials and food products, public authorities are in a unique position to create predictable demand for goods and services produced with sustainable fuels. Procurement programmes that prioritise low-emission steel in public buildings and transport fleets, food produced using low-emissions fertilisers in schools or military bases, or clean shipping services for government logistics can help bring these products to market at scale.

Chapter 4. Benefits

Highlights

- Sustainable liquid and gaseous fuels **can offer multiple benefits**, from improving energy security to advancing sustainability to creating new economic opportunities in the regions where they are used and produced.
- The resources needed to produce these fuels – such as sustainably grown crops, agricultural residues, organic waste and renewable electricity – **are more widely available** than fossil fuels in many countries.
- Using sustainable liquid and gaseous fuels for energy, and/or chemical feedstocks, **reduces reliance on fossil fuel imports**, mitigating exposure to international energy shocks from geopolitical conflicts, natural disasters and market volatility. For example, in 2024 liquid biofuels cut domestic transport fuel import dependence 5-15% for most countries.
- With performance-based policies in place, these fuels can reduce emissions in sectors and regions where electrification remains costly or is not yet readily available. Some biofuel pathways can also **achieve net-negative GHG balance**, effectively removing CO_2 from the atmosphere.
- When paired with best practices – supported by transparent and consistent frameworks, certification, and verification processes – sustainable liquid and gaseous fuels can provide environmental benefits beyond emissions reductions such as **improving soil health, water and air quality, land management, and circularity.**
- The production of sustainable liquid and gaseous fuels can also **support new investments, especially in emerging economies**, creating opportunities for sustainable economic development. In the accelerated case, cumulative investments grow to USD 1.5 trillion between 2024 and 2035.
- Decentralised supply chains and distributed production infrastructure **generate employment opportunities** in regions where these fuels are produced and used. These opportunities are especially important for rural and underserved communities. In the accelerated case, direct employment from these fuels more than triples – creating nearly 1.5 million new jobs by 2035.

Unlike conventional fossil fuels, sustainable liquid and gaseous fuels are produced mainly from renewable resources that are often available locally, diversifying the domestic energy supply and reducing reliance on imported fossil fuels. This boosts energy security and enables countries to better manage risks associated with volatile global energy markets, geopolitical tensions and supply disruptions.

These fuels are central to reducing emissions from global fuel demand and, in some cases, can even deliver a net-negative GHG balance. In addition to emissions reductions, they create opportunities to improve water and land management, enhance air quality, minimise waste and support the broader circular economy.

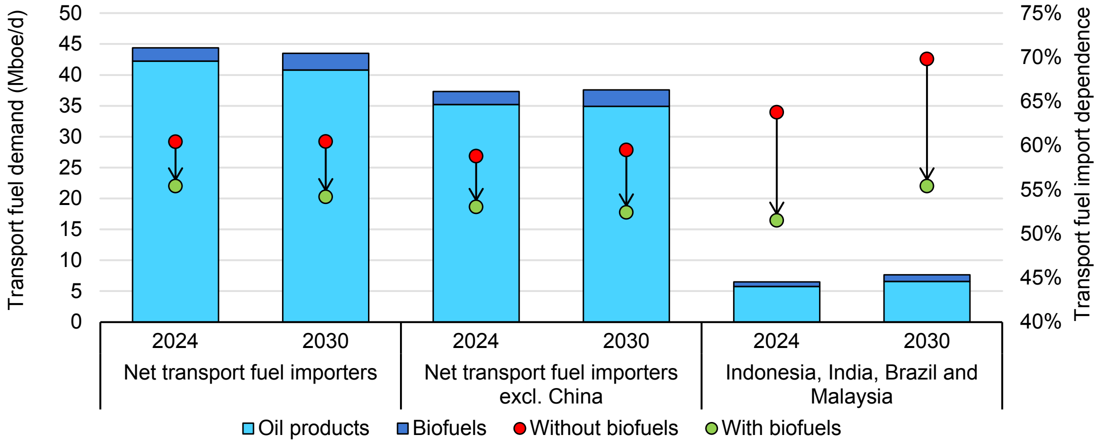
They also drive economic development by generating new income streams and attracting private investment, especially in emerging economies. This supports industrial growth, accelerates technology deployment, and creates job opportunities across the entire value chain – particularly in rural and underserved communities.

Energy security

Fossil-fuel-importing countries are particularly vulnerable to energy shocks caused by geopolitical conflicts, natural disasters and market volatility. Such disruptions can lead to price spikes, undermine access to affordable energy and create significant trade imbalances. Unlike fossil fuels, sustainable liquid and gaseous fuels are typically produced from domestically available resources such as crops, agricultural residues, organic waste and renewable electricity, which are more widely available than fossil fuels. For this reason, many countries are increasingly recognising the importance of these fuels to minimise long-term exposure to global fossil fuel markets, enhance domestic energy security, and ensure energy supply reliability and affordability.

Liquid biofuel use is already reducing reliance on gasoline and diesel imports. In 2024, liquid biofuels cut transport fuel import dependence 5-15% for most countries, and continued uptake is expected to further relieve dependency. For certain countries, the impacts are even more significant. In Indonesia, India, Brazil and Malaysia – some of the world's fastest-growing transport fuel demand markets – rising liquid biofuel use has curbed transport fuel imports considerably and improved energy security and access to clean energy.

Figure 4.1 Changes in transport fuel import dependency with biofuel uptake



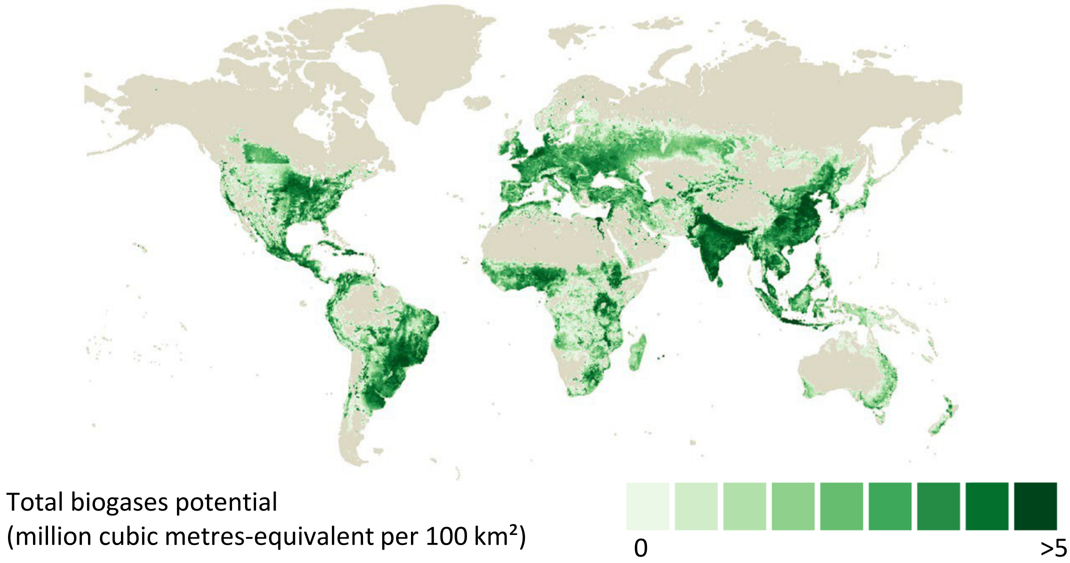
Notes: Transport fuel dependence is calculated as total net imports of oil products (gasoline, diesel and jet fuel), net imports of crude for domestically refined oil products, and net imports of biofuels (ethanol, biodiesel, renewable diesel and biojet) divided by the total final consumption of biofuels. The counterfactual scenario assumes that all biofuel consumption in a given year is directly replaced with imported oil products.
Source: IEA (2025), Oil 2025.

Even when not domestically produced, these fuels still offer opportunities to improve energy security by expanding international trade partnerships. Regions with abundant biomass, renewable electricity and/or a competitive edge in producing certain sustainable fuels could forge new relationships with countries seeking to meet growing demand. For example, the Algeria-Germany Memorandum of Understanding on hydrogen is a bilateral supply and demand initiative designed to align Algeria's intention to expand renewable electricity and low-emissions hydrogen production with Germany's growing demand for low-emissions hydrogen for industry.

In recognising these benefits, governments are increasingly shaping policies and strategic frameworks to focus not only on emissions reductions but also on reducing reliance on imported fossil fuels. For example, in 2019 Korea released a Hydrogen Economy Roadmap emphasising the role of domestically produced hydrogen in reducing the country's reliance on fossil fuel imports. Similarly, in 2022 the European Union launched REPowerEU to cut reliance on imported natural gas and reduce supply disruptions. As part of this strategy, several European countries accelerated biomethane deployment, among other actions. Meanwhile, Japan's recently released Seventh Strategic Energy Plan recognises hydrogen, hydrogen-derived fuels and biofuels as important components in ensuring clean energy supply reliability and sustainability.

Further potential to reduce reliance on fossil fuel imports – and on broader global energy supply chains – exists, with many regions of the world having significant access to sustainable feedstocks and renewable electricity. For example, under favourable conditions biogas could replace as much as one-quarter of natural gas demand, with emerging markets and developing economies accounting for 80% of potential global production based on potential feedstock availability.

Figure 4.2 Geospatial analysis of global biogas potential



Source: IEA (2025), Outlook for Biogas and Biomethane.

Sustainability

The emissions reduction potential of sustainable liquid and gaseous fuels can be significant, offering opportunities to reduce the GHG intensity of fossil fuels themselves, through policy measures such as blending mandates, or by directly replacing them in sectors where they are used. Choices made along the supply chain – from feedstock to production technology to energy sources used during transport and distribution – impact their overall emissions reduction potential.

Table 4.1 Key measures to enhance the emissions reduction potential of sustainable fuels

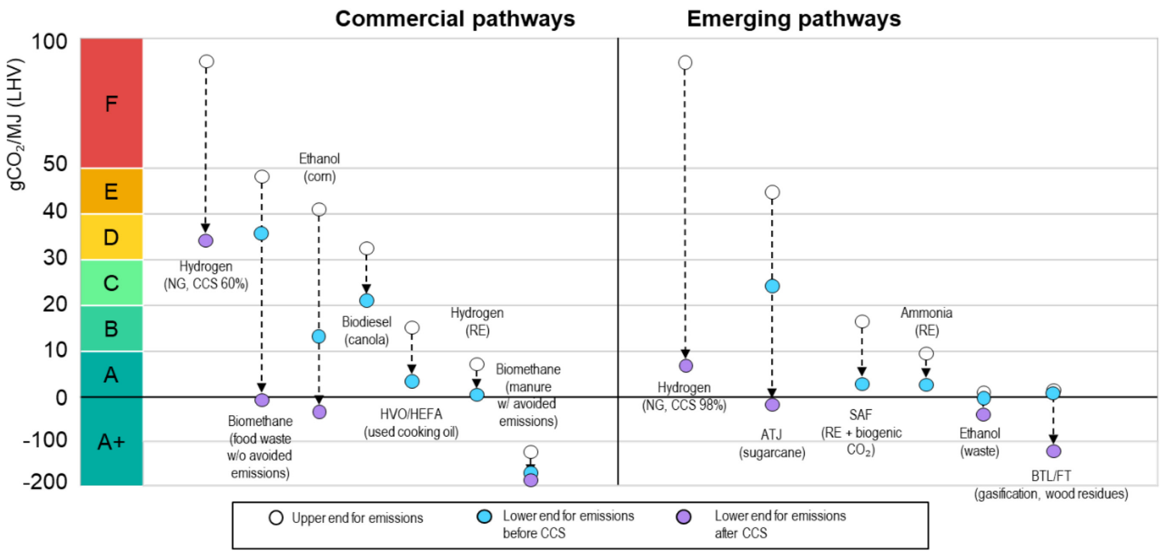
Pathway	Examples
Biofuels	Improving crop yields; using crops from multicropping or double cropping, or grown on degraded land; or waste and residues (e.g. forest residues, organic municipal waste, methane from landfills). Using low-emissions fertiliser and soil amendments (e.g. biochar) to grow feedstock. Using renewable energy in agricultural/forestry machinery to cultivate feedstocks, production processes and distribution of biofuels. Reducing fugitive methane from biogas systems. Capturing and permanently storing biogenic CO_2 emissions from biofuel production underground.
Hydrogen	Using low-emissions electricity for electrolysers. Capturing and permanently storing fossil fuel CO_2 emissions from hydrogen production underground. Minimising upstream and midstream methane emissions. Clustering production near existing industries or end users to minimise transport needs.
Hydrogen-based fuels	Optimising heat integration to enable the use of efficient high-temperature electrolysers. Using biogenic or air-captured CO_2 feedstock.

One approach to communicate the emissions reduction potential of sustainable liquid and gaseous fuels is the introduction of a tiered labelling system that enables side-by-side comparison of supply chain GHG intensity ranges across different fuel pathways. As an illustrative example, labelling could span from A to E in increments of 10 gCO_2/MJ, followed by a F label reaching up to 100 gCO_2/MJ. Fuels with net-negative GHG balance could be classified as A+.

Such a labelling system would support a technology-open approach to assessing the emissions reduction potential of different fuel pathways, thereby informing both policy and investment decisions. For instance, governments implementing low-carbon fuel standards – which require a gradual reduction in carbon intensity of fuel supplies – could use these labels as a foundational tool. Similarly, the labelling system could guide investors and consumers in the same way that energy-efficiency labels on appliances and buildings help them make more informed choices.

The labelling framework could also be periodically updated by tightening the bands (e.g. 5 gCO_2/MJ increments instead of 10) to reflect improvements in the GHG performance of fuel pathways, such as adoption of sustainable land management practices, greater use of waste feedstocks, deployment of CCUS and switching to renewable energy across the supply chain.

Figure 4.3 Lifecycle GHG emission ranges for selected fuel pathways



Notes: HVO = hydrotreated vegetable oil; HEFA = hydroprocessed esters and fatty acids; NG = natural gas; CCS = carbon capture and storage; ATJ = alcohol-to-jet fuel; SAF = sustainable aviation fuel; RE = renewable electricity; BTL = biomass-to-liquid; FT = Fischer-Tropsch. GHG intensities for the biofuel pathways from R&D GREET 2024 Rev1. Direct land use change is included, but indirect is excluded. CCS assumptions and other pathways based on IEA analysis. Removals through soil carbon accumulation are possible for some of the pathways but are not considered in this figure. Electrolysers are assumed to be powered by renewable electricity. Embodied emissions of renewable power are included (assuming 50/50 hybrid PV/wind power plant for upper end and hydropower plant for lower end). All values are for lower heating value. Emissions from transport and distribution of final fuel to end user are 2 gCO_2/MJ for liquid fuels and pipeline transport of methane, and 4 gCO_2/MJ for pipeline transport of hydrogen.

The environmental benefits of sustainable liquid and gaseous fuels can extend well beyond emissions reductions. Cultivating feedstocks using agricultural practices such as limited tilling or no-tilling, double cropping (e.g. growing soybeans with corn) or cover cropping can improve soil health, reduce erosion and optimise the use of land, water and other resources. Similarly, growing feedstocks on marginal or degraded land can contribute to land restoration and increase productive land use.

Such practices can also provide supplementary income streams for farmers and landowners. Intercropping and cover cropping are already widely used in Brazil to optimise land use for food, animal feed and fuel production. In Kenya, bio-oil feedstocks are being grown on marginal land and upgraded to sustainable aviation fuel.

Sustainable fuels can also support other forms of land management. For instance, using forest biomass can improve forest management by leveraging harvesting residues (e.g. branches and treetops) and unmerchantable timber (e.g. pest-infested or fire-damaged trees), which cannot be used for higher-value products and is often left in the forest. Using these feedstocks to produce sustainable fuels can enhance forest ecosystems by creating more space for sunlight and rainfall for growing trees, while also mitigating forest fire risks for nearby communities. In Canada, these types of projects are under way to improve forest management, reduce wildfires and provide economic development opportunities for rural Indigenous communities while producing sustainable liquid biofuels.

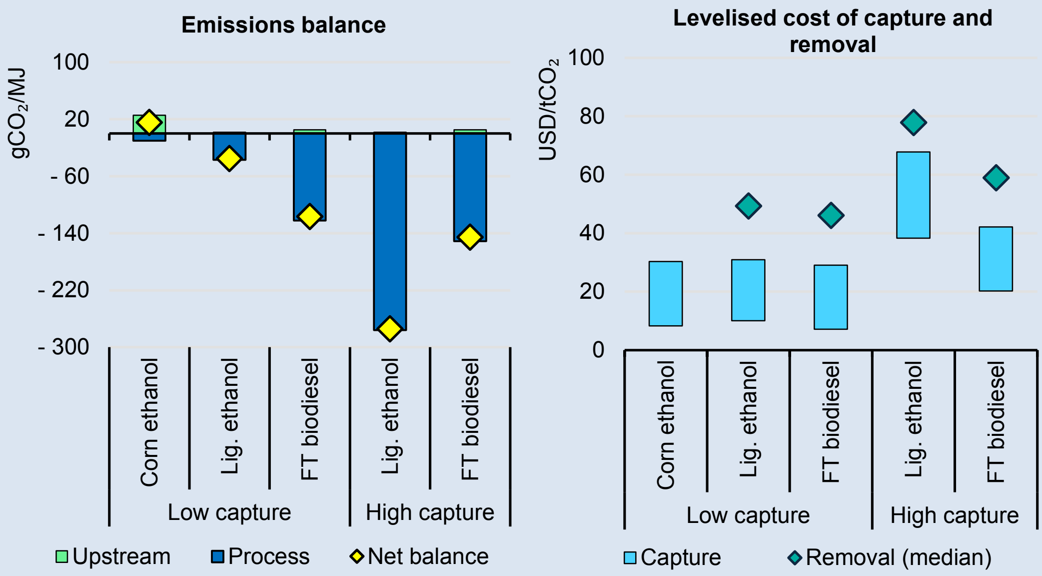
Box 4.1 Producing fuels with net-negative GHG balance

Among sustainable liquid and gaseous fuels, biofuels can provide net-negative GHG balance if producers use certain feedstocks and/or pair production with carbon capture and storage – reducing carbon emissions not only at the point of use but also possibly offsetting emissions in other sectors. For example, unmanaged manure generates methane (CH_4), a potent greenhouse gas. Capturing this gas and using it as fuel displaces fossil fuel use and prevents fugitive methane emissions. To account for these emission reductions, some sustainability frameworks assign methane avoidance credits to biogas and biomethane, reaching negative carbon intensity values such as −100 gCO_2/MJ in the European Union and -300 gCO_2/MJ in the United States.

Similarly, the capture and permanent storage of biogenic CO_2 emitted during the production of biofuels, such as CO_2 formed during ethanol fermentation, can result in the removal of carbon from the atmosphere. For example, roughly 1 $MtCO_2$ is currently captured and injected for geological sequestration from three conventional corn ethanol plants in the United States, potentially qualifying for removal. Around 30 $MtCO_2$ per year could be captured and stored from biofuels production by 2030, however less than 2 $MtCO_2$ per year is currently under construction or in operation. One project aims to connect around 60 bioethanol producers in the United States with CO_2 transport and storage infrastructure – totalling just under 20 Mt of biogenic CO_2 capture capacity – but permitting hurdles are causing delays.

Overall, ensuring these fuels provide net-negative emissions requires careful lifecycle assessment that involves tracking and verifying the entire value chain, with carbon removal potential heavily dependent on feedstock upstream emissions and the proportion of plant emissions that are captured. For lignocellulosic ethanol, between 35 and 275 gCO_2 of negative emissions can be generated per MJ of bioethanol produced, while biodiesel ranges from 115 to 145 gCO_2 per MJ produced. Capturing a higher share of plant emissions increases removal costs, as it requires capturing more diluted CO_2 streams at a higher capture cost. For example, reaching high removal potential can incur a 60% increase in removal costs for bioethanol and a 30% increase for biodiesel.

Levelised cost of capture, removal and emissions balance for carbon capture, utilisation and storage in biorefineries



Notes: CCUS = carbon capture, utilisation and storage. Lig. = lignocellulosic. FT = Fischer-Tropsch. Ranges account for variations in energy costs across regions. The cost of removal includes a USD 30/tCO_2 transport and storage fee, considers lifecycle emissions associated with biomass supply (upstream) and biofuels production (process), and is indicative of the global average.

Source: Adapted from IEAGHG (2021), Biorefineries with CCS.

Furthermore, when integrated into existing supply chains, these fuels can improve waste management and contribute to the broader circular economy. Using feedstocks such as municipal waste (e.g. organic waste, wood waste and construction materials) and agricultural residues (e.g. animal manure) can reduce waste in existing supply chains while providing feedstocks to produce sustainable fuels.

Some thermal processes like pyrolysis produce also biochar, a soil amendment that can enhance biodiversity, improve water retention and drainage, and increase soil carbon content. Biochar can also reduce GHG emissions by lowering the carbon intensity of the biofuel itself, or it can be sold for carbon credits – creating additional revenue opportunities for fuel producers. This improves waste management and contributes to the broader circular economy by valorising waste and returning organic materials to nature.

Similarly, animal manure can be used to produce biogas, improving on-farm waste management and generating renewable energy. The process also yields digestate, a nutrient-rich byproduct that can be used as a fertiliser to enhance soil health and reduce reliance on synthetic alternatives. Again, this not only supports the circular economy by reducing waste and returning nutrients to the soil but also creates economic opportunities for farmers – either by lowering fertiliser costs when used onsite or by generating additional income when sold. These types of opportunities are being recognised in countries around the world, including Finland, Denmark, Sweden, Spain, Brazil, the United States, Canada and South Korea.

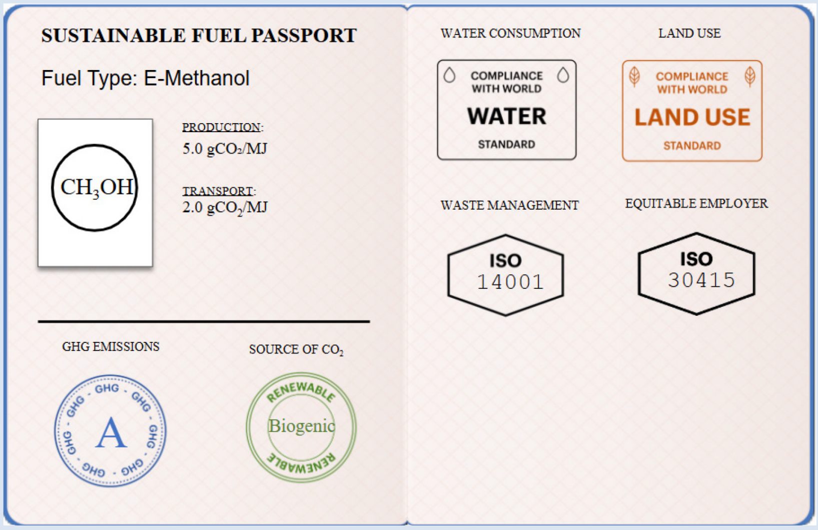
Box 4.2 A fuel passport to integrate multiple criteria

When produced using best practices, sustainable liquid and gaseous fuels can provide a range of environmental benefits. However, interpreting and verifying these benefits can be challenging given different international sustainability frameworks and regulations.

A "product passport" can help to bring all these criteria together, summarising a fuel's GHG intensity, resource use (e.g. water, land and waste management) and socio-economic contributions, using internationally agreed upon standards and certifications.

This would help illustrate how fuels meet certain standards, improving their interoperability and transparency, and support investment and policy decisions. As energy transitions progress, fuel passports could be updated to reflect desired changes to sustainability criteria, such as how fuels meet distinct biodiversity requirements or whether a specific fuel was produced in alignment with fair and equitable employment practices.

Example of the possible content of a product passport for ammonia



IEA. CC BY 4.0.

Source: Adapted from IEA (2023), Towards Hydrogen Definitions Based on Their Emissions Intensity.

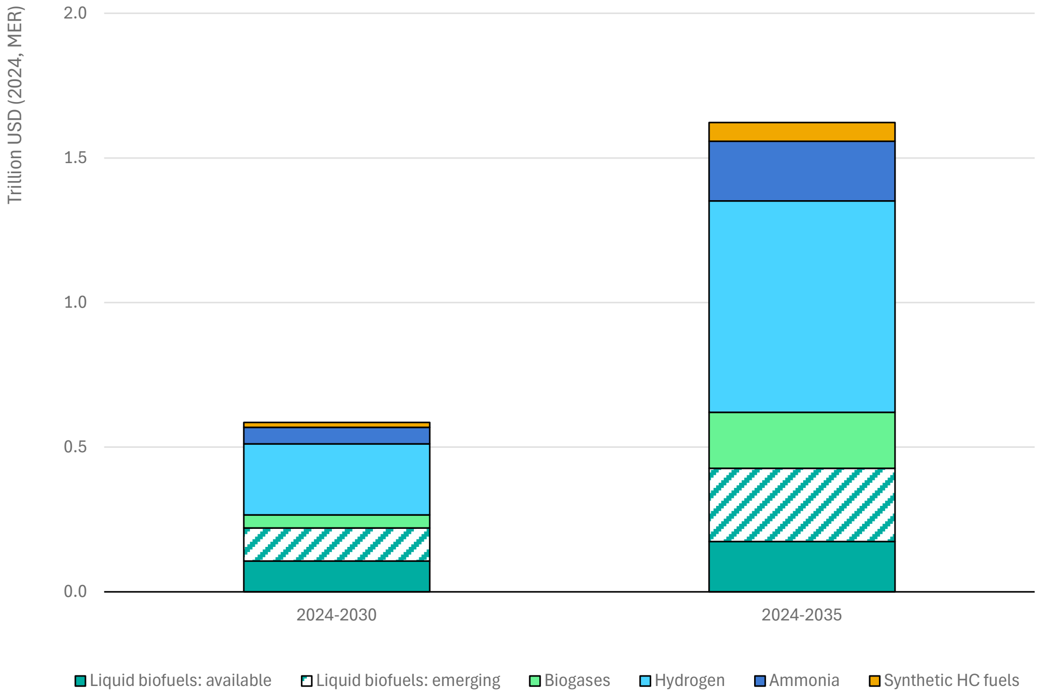
Economic development

Sustainable liquid and gaseous fuels are increasingly becoming engines for sustainable economic development, as investments in the sector grow with backing from public and private capital. Investments span full value chains – from feedstock production and fuel conversion to storage and distribution – and play a key role in driving regional economic development and competitiveness.

Investments in sustainable liquid and gaseous fuels grew 20% between 2023 and 2024. For liquid biofuels, such as ethanol and biodiesel, investments were driven by policies in the United States and Brazil, in part due to strong liquid biofuel mandates and financial support, such as the United States' Investment and Production Tax Credits and funding from Brazil's National Bank for Economic and Social Development (BNDES). Similarly, investments in biogas were driven by strong policy signals from the European Union's REPowerEU Plan, which created important investment opportunities, while investments in hydrogen projects rose 60% from 2023, with regions such as Australia, Europe and North America providing financial support.

As demand for these fuels continues to rise, investment in sustainable liquid and gaseous fuels is expected to increase. In the accelerated case (see Chapter 5) cumulative investments between 2024 and 2035 reach USD 1.5 trillion. By 2035, investments in hydrogen are projected to account for nearly half of all investments, driven by rapidly growing demand in industry. Liquid biofuels follow, representing about a quarter of new investments, as demand rises across road, marine, and aviation transport. Biogas and hydrogen-based fuels make up the remaining share helping meet demand in both transport and industry.

Figure 4.4 Cumulative investments in sustainable liquid and gaseous fuels in the accelerated case, 2024-2030 and 2024-2035



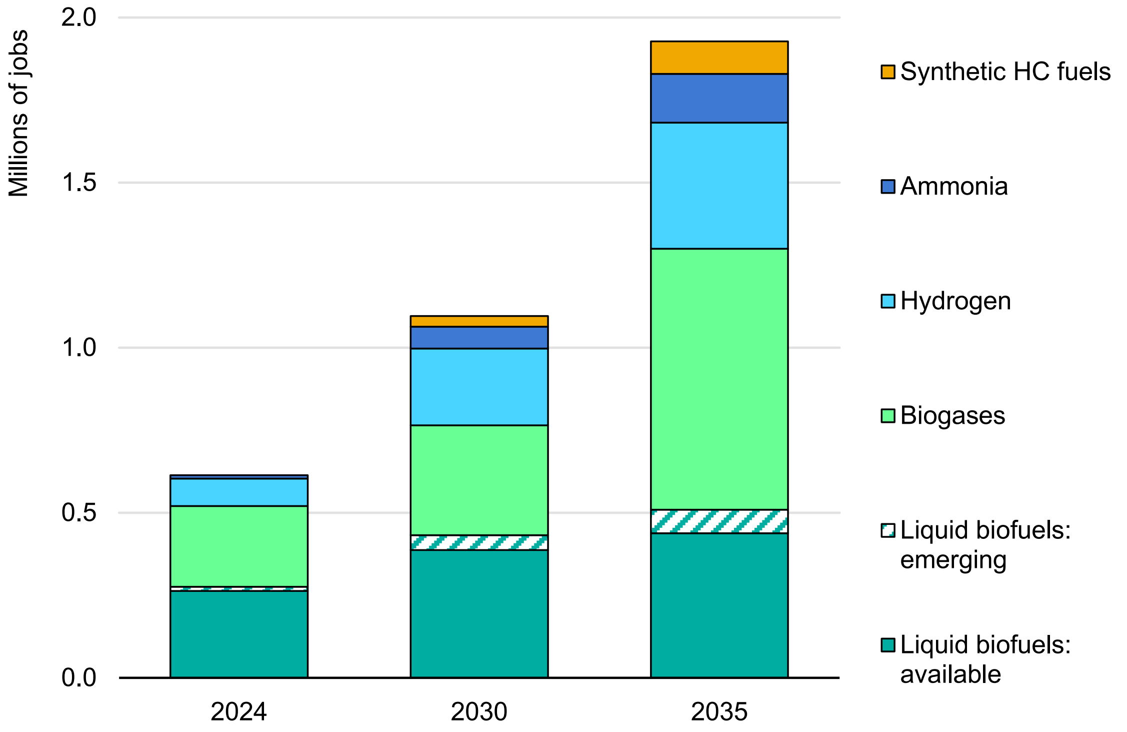
Notes: MER = market exchange rate; HC = hydrocarbon. Investments represent the capital costs of projects with announced capacities, based on their planned capacities and operational dates. "Liquid biofuels: available" refer to technology readiness level (TRL) 9 and "liquid biofuels: emerging" to TRL 7 or 8.

Sources: IEA (2025), World Energy Investment; IEA (2025), CCUS Projects Explorer; IEA (2025), Hydrogen Production and Infrastructure Projects Database; and recent announcements.

Investment in sustainable liquid and gaseous fuels also creates new employment opportunities, from research and engineering to manufacturing and operations. Their production often relies on decentralised supply chains and distributed production infrastructure, which generates direct and indirect employment in the regions where these fuels are produced and used. These opportunities are especially important in rural and underserved communities, where projects can build local capacity and support youth employment.

In the accelerated case, expansion of sustainable liquid and gaseous fuels is expected to more than triple the number of direct jobs by 2035 – reaching nearly 2 million jobs. Employment in liquid and gaseous biofuels will account for nearly two-thirds of this growth, with more than 1 million new positions across multiple stages of their supply chains – from feedstock collection and transportation to conversion, distribution and end use. Investments in hydrogen, ammonia and synthetic hydrocarbon fuels make up the remaining third, with most jobs created during the construction of new projects and significant potential for regions of the world with growing renewable electricity resources.

Figure 4.5 Jobs in sustainable liquid and gaseous fuels in the accelerated case, 2024, 2030 and 2035



Notes: HC = hydrocarbon. Jobs in liquid biofuels and biogases include direct employment in construction of new facilities, feedstock collection, and biofuel production and distribution. Jobs in hydrogen, ammonia, and synthetic HC fuels include direct employment in construction of new facilities, manufacturing of hydrogen production equipment, and production and distribution of hydrogen, ammonia, and synthetic HC fuels. Indirect jobs are not included.

Further opportunities to increase direct and indirect employment may emerge alongside rising investments as governments seek to support labour markets during energy transitions through targeted training, retraining and upskilling. For example, Australia's New Energy Apprenticeship Program offers financial support to apprentices developing skills in the construction, maintenance and operation of clean energy technologies, including sustainable fuels, and Canada's Sustainable Jobs Training Fund provides financial support for sustainable energy projects, including low-emissions fuels, that help workers acquire or upgrade skills needed for changing energy labour markets.

Box 4.3 Low-emissions hydrogen employment opportunities in Namibia

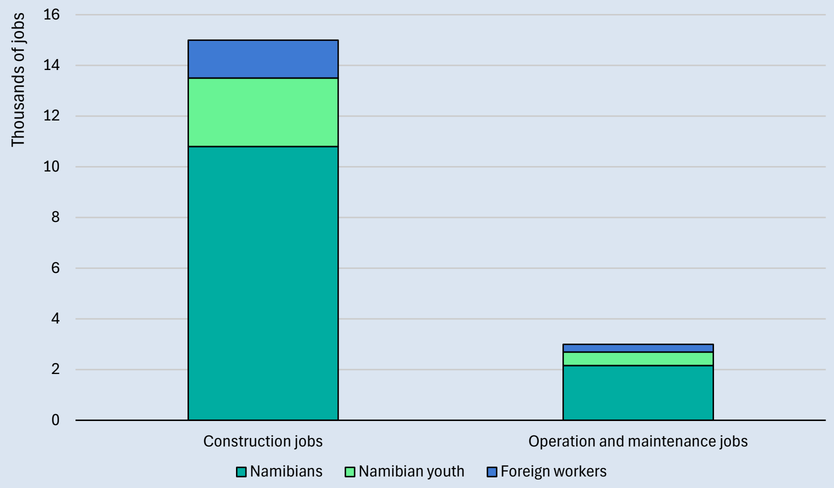
The Hyphen Hydrogen Energy project is the first large-scale renewable hydrogen facility under development in Namibia – and the largest in sub-Saharan Africa. Valued at approximately USD 10 billion, the project's capital investment is nearly equivalent to Namibia's entire GDP in 2021 (USD 12.2 billion). Pending a final investment decision, the facility aims to produce 0.35 Mt of hydrogen or 2 Mt of ammonia annually by 2030.

Beyond its energy contribution, the project has the potential to significantly advance socio-economic development in Namibia. Construction is expected to create employment for up to 15 000 people, with around 3 000 permanent jobs during operation – of which 90% could be filled by Namibians. In addition, local procurement could account for 30% of the project's total expenditures, supporting domestic enterprise development.

To enable these outcomes, Hyphen and the Government of Namibia launched a Socio-Economic Development (SED) Framework in 2023 as part of a broader Feasibility and Implementation Agreement. This framework outlines a structured methodology for setting and refining targets related to employment, local procurement, skills development and enterprise and supplier participation.

As part of this process, Hyphen has carried out a comprehensive skills audit and gap analysis to inform targeted training and capacity-building initiatives. The findings will support ongoing consultations with the government to define final socio-economic targets in line with the SED Framework.

Estimated jobs to be created by the Hyphen project in Namibia



Source: Based on data from Hyphen (2023), Socio-Economic Development Framework.

Chapter 5. Sectoral milestones for sustainable liquid and gaseous fuels to 2030 and 2035

Highlights

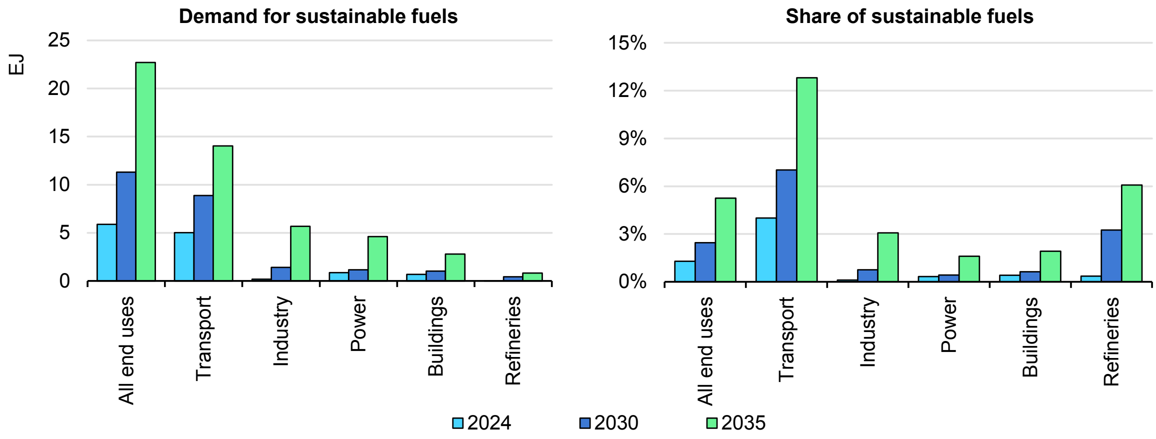
- Global demand for **sustainable liquid and gaseous fuels** expands quickly in the **accelerated case**, which assumes that by 2030 planned policies are legislated, actions are taken to remove market barriers and production capacity is added to meet new demand. For 2030-2035, the accelerated case also factors in countries' announced policies to achieve their energy and climate targets.
- Compared to today's consumption, global demand for **sustainable liquid and gaseous fuels almost doubles to 13 EJ by 2030** and **quadruples to 28 EJ by 2035** in the accelerated case; contributing to decarbonisation, diversification, energy security and economic development opportunities.
- The rise in **sustainable fuel use between 2024 and 2030 is strongly driven by biofuels**, which account for more than 70% of the increase. Towards 2035 the need to expand and diversify biomass feedstock supplies and to commercialise new technologies becomes increasingly evident.
- The use of **low-emissions hydrogen and hydrogen-based fuels expands strongly after 2030**, owing to higher demand from industry, shipping and aviation, contributing to around half of the rise in sustainable fuel consumption during 2030-2035.
- **Transport still accounts for the majority of sustainable fuel use in 2035** with a share of 50% globally. In the accelerated case, sustainable fuels cover 10% of all road transport, 15% of aviation and 35% of global shipping fuel demand by 2035.
- **The use of sustainable fuels for industry and power generation expand considerably after 2030**, each being responsible for around one-quarter of the increase in sustainable fuel use between 2030 and 2035, largely in the form of biogases, low-emissions hydrogen, and ammonia.
- Use as **chemical feedstock** is a major driver of low-emissions hydrogen and derived fuels, especially in the chemical, refining and steel subsectors.

Overview

Global demand for sustainable fuels (liquid biofuels, biogases, low-emissions hydrogen and hydrogen-based fuels)[2] reached almost 7 EJ in 2024 – double the 2010 level. More than 70% of sustainable liquid and gaseous fuels consumed today are liquid biofuels, used almost entirely in road transport. Biogases account for more than one-quarter, while low-emissions hydrogen makes up 1%.

The transport sector is responsible for three-quarters of global sustainable liquid and gaseous fuel use, followed by the power sector (14%) and buildings (9%). Liquid biofuels make up most of the sustainable fuel used in transport, while the buildings sector and electricity generation employ mainly biogases.

Figure 5.1 Global demand for sustainable liquid and gaseous fuels in selected sectors and shares of sustainable fuels in energy demands in the accelerated case, 2024-2035



Notes: Sustainable fuel use in industry includes onsite hydrogen production. In the right figure, "buildings" includes agriculture and "refineries" includes low-emissions hydrogen used in liquid biofuels production. "All end uses" encompasses the agriculture, buildings, industry and transport sectors combined. "Power" refers to the generation of electricity and heat in the electricity sector.

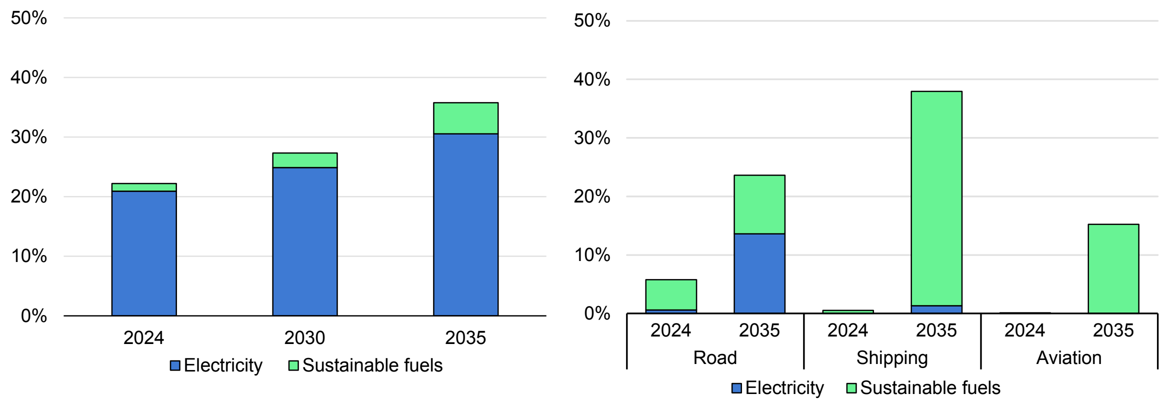
In the IEA accelerated case scenario,[3] global demand for sustainable liquid and gaseous fuels almost doubles from 2024 to 2030, to reach 13 EJ. By 2035, it doubles again to around 28 EJ – a quadrupling from 2024. With global demand of 14 EJ in 2035, the transport sector remains the main consumer, responsible for half of sustainable fuel use in 2035. In fact, sustainable fuels cover 13% of all transport sector energy needs in 2035 (compared to 4% today), with liquid biofuels

[2] See Box 1.1 Fuel pathways and sustainability criteria covered in this report.
[3] The accelerated case assumes that planned policies are legislated, actions are taken to remove market barriers and production capacity is added to meet new demand, in line with the IEA Renewables 2025 market report's accelerated-case forecast to 2030. For 2030-2035, the accelerated case also factors in countries' announced policies (up to the end of June 2025) to achieve their energy and climate targets.

continuing to dominate, alongside growing adoption of low-emissions hydrogen and hydrogen-based fuels in shipping and aviation.

The use of sustainable liquid and gaseous fuels also expands in other sectors. In industry, demand rises to around 5 EJ in 2035 from basically zero today, particularly owing to the use of low-emissions hydrogen in the chemical industry and in the iron and steel sector. The power sector becomes the third-largest consumer by 2035 at almost 5 EJ, with the use of biogases expanding and low-emissions hydrogen and ammonia also gaining ground.

Figure 5.2 Shares of sustainable liquid and gaseous fuels and electricity in global final energy demand (left) and in selected sectors (right) in the accelerated case, 2024-2035



Note: "Sustainable fuels" includes fuel inputs for the onsite production of low-emissions hydrogen in industry.

In the buildings sector, sustainable liquid and gaseous fuel use, mainly in the form of biogases, reaches almost 3 EJ – more than four times the 2024 level but still less than 2% of total energy consumed in the buildings sector globally. Meanwhile, refineries use around 1 EJ in 2035, a moderate amount compared to other sectors, but its share (6%) is still the second-highest after transport, reflecting immediate opportunities to substitute low-emissions hydrogen for the unabated fossil-based hydrogen that is currently being used.

Overall, by 2035 in the accelerated case, sustainable liquid and gaseous fuels cover 5% of global final energy demand (i.e. the combined energy demand of agriculture, buildings, industry and transport), a significant increase from the 1% share in 2024. For comparison, the share of electricity grows from 21% today to 30% in 2035, driven in advanced economies by the adoption of electric vehicles and power demand from data centres. In emerging markets and developing economies, this rise stems from increasing ownership of household appliances and greater electricity demand for cooling.

Despite the strong trend towards electrification, sometimes direct electrification options can be overly technically complicated or too costly. For example, the weight and energy density of batteries limits electricity use for long-distance transport by airplane or ship – two transport modes that currently account for 20% of all transport energy demand. Moreover, in some countries and local contexts, electrification can be delayed because grid infrastructure needs to be strengthened and/or expanded, such as for electric vehicle charging stations.

Sustainable liquid and gaseous fuels play a complementary role in improving energy security and reducing emissions. In the case of drop-in fuels, diversification and emission reductions can be achieved rapidly, thanks to the use of existing infrastructure.

Transport

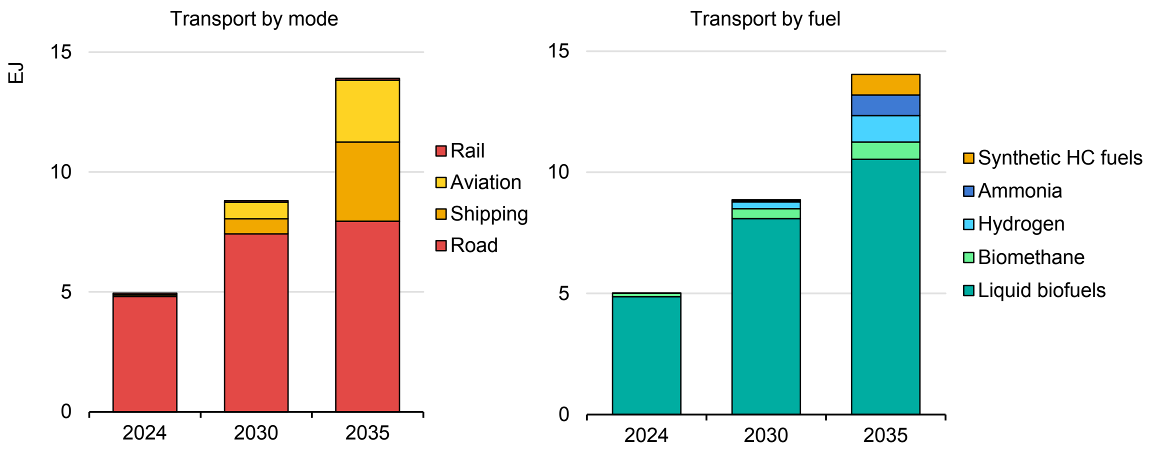
Global transport sector energy demand grew 11% between 2015 and 2024 to 125 EJ, making it the third-largest end-use sector after industry and buildings. Sustainable fuels currently cover 5 EJ or 4% of global transport energy demand, mainly owing to liquid biofuel use in road transport.

In the accelerated case, sustainable fuel use in transport almost triples to 14 EJ by 2035, representing 13% of global transport energy demand in that year. For comparison, the electricity share similarly reaches 12% by 2035, compared with just 2% today.

Road transport already has today a sustainable fuel share of 5% or around 5 EJ in absolute terms, representing 96% of all transport sector sustainable fuel use and 70% of overall energy sector use. In the accelerated case, sustainable fuel demand in road transport grows 65% to 8 EJ by 2035, with trucks accounting for 60% of this growth in consumption. Overall, sustainable fuels cover 10% of all road transport demand, and road transport remains the largest consumer of sustainable fuels among all transport modes.

Outside of road transport, sustainable fuels play only a marginal role today. In shipping, for instance, oil covers 99% of fuel demand, but this could change. In the accelerated case, the IMO Net Zero Framework and revised GHG strategy target minimum annual GHG emissions reductions of 20% by 2030 and 70% by 2040 compared to 2008 emissions levels. To achieve these cuts, more than 3 EJ of sustainable fuels are used by 2035 in the accelerated case, to meet 35% of global shipping fuel demand, with roughly 45% coming from biofuels and 55% from low-emissions hydrogen or hydrogen-based fuels.

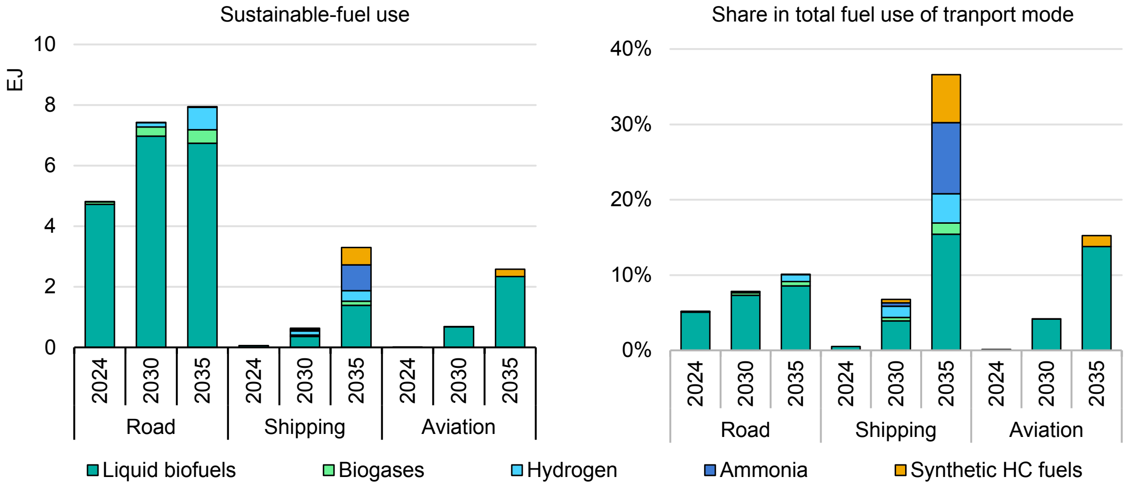
Figure 5.3 Use of sustainable liquid and gaseous fuels in the transport sector by mode and by fuel in the accelerated case, 2024-2035



Note: HC = hydrocarbon.

Aviation is the transport mode with the highest energy demand growth in recent years, with a rise of 17% from 2015 to 2024 compared to 10% for road transport and 5% for shipping. The current 0.1% share of sustainable aviation fuels (SAFs) in total aviation fuel consumption is low, with small amounts of biojet fuel being used in Europe. Several countries have put policies and regulations in place to increase SAF use, such as SAF mandates in the European Union and the United Kingdom, and GHG emissions reduction targets for aviation in Brazil's Fuel of the Future law. In the accelerated case, the global SAF share climbs to 15% by 2035, or 2.6 EJ in absolute terms, with around 90% being biojet fuel and the remainder synthetic kerosene.

Figure 5.4 Sustainable liquid and gaseous fuel use by fuel type for selected transport modes in the accelerated case, 2024-2035



Note: HC = hydrocarbon.

Across transport modes, biofuels dominate growth in the use of sustainable liquid and gaseous fuels until 2030 and further efforts are needed to expand and diversify feedstock supplies and commercialise new processing technologies. Low-emissions hydrogen-based fuels grow from 2030-2035 as they become more cost-competitive relative to biofuel pathways, and as infrastructure and end-use technologies needed for their adoption become more widespread.

Industry

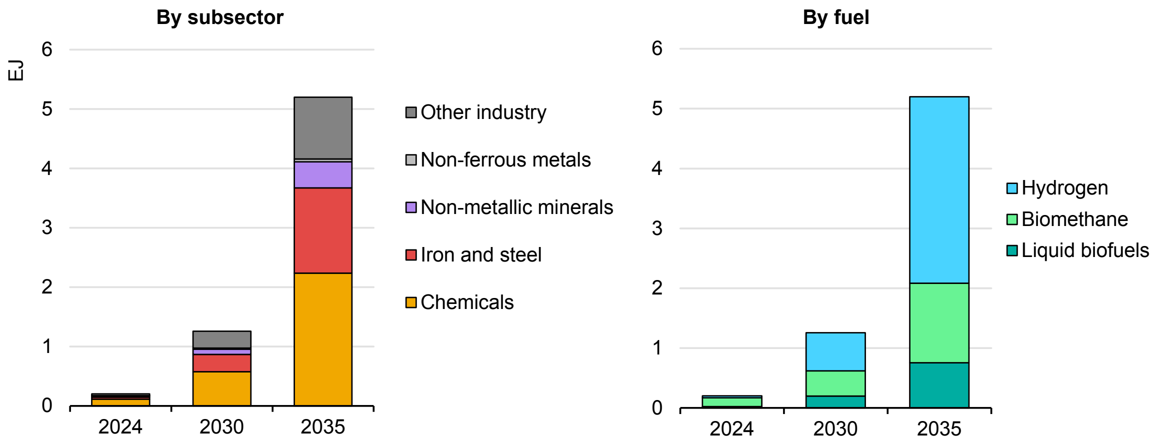
The industry sector was the largest end-use sector in terms of energy use in 2024, consuming around 175 EJ globally (38% of total final energy consumption). While fossil fuels dominate consumption at a two-thirds share, not all this fossil fuel was actually used for energy purposes: one-quarter was employed for feedstock in the chemical industry or as a reducing agent in steel production. In addition, electricity currently covers almost one-quarter of all industry sector energy needs, being used for example in electrical motors and for heating and cooling needs, while sustainable liquid and gaseous fuels make up only 0.1% of the energy consumed, mainly in the form of biomethane.[4]

Meanwhile, hydrogen is already being used in the chemical sector – mainly to produce ammonia and methanol – and makes up 5% of overall energy demand in the industry sector and 17% in the chemical subsector. The chemical industry is responsible for half of global energy sector hydrogen demand (around 12 EJ), but

[4] Solid bioenergy, which is outside the scope of this report, accounts for 7% of global industrial energy consumption today, with pulp and paper production and the food industry representing half of this demand.

this hydrogen is produced almost completely from unabated fossil fuels, mainly natural gas (except in China, where coal is also used). Thus, using low-emissions hydrogen could not only reduce emissions but could help countries that have good renewable resources and that currently rely on imports of chemicals and fertiliser (or of natural gas to make them) to reduce their import dependence and gain economically.

Figure 5.5 Use of sustainable liquid and gaseous fuels in industry by subsector and fuel in the accelerated case, 2024-2035



In the accelerated case, sustainable liquid and gaseous fuel use in industry grows strongly, reaching more than 1 EJ by 2030 and quadrupling to 5 EJ by 2035, representing 3% of industrial energy demand in 2035. Biomethane accounts for one-quarter of all sustainable fuel use in industry in 2035. Being compatible with existing infrastructure and industrial technologies, it can be a near-term option to replace natural gas.

In the chemical subsector, low-emissions hydrogen replaces hydrogen from unabated fossil fuels to cover roughly 20% of chemical industry hydrogen demand by 2035. The use of low-emissions hydrogen also expands to the iron and steel subsector, meeting around 60% of all hydrogen needs by 2035. Plus, several projects that intend to use low-emissions hydrogen for direct reduction of iron (DRI) are under development: eight with an electrolyser capacity at or above 100 MW have reached a final investment decision, with the largest being built by Stegra in Sweden (electrolyser capacity of 800 MW).

Also in the chemical industry, liquid biofuels can be used as a feedstock to replace oil. In fact, feedstock uses of liquid biofuels account for around 15% of the sustainable liquid and gaseous fuels used in industry in 2035 in the accelerated case. Overall, sustainable liquid and gaseous fuels cover 4% of chemical industry energy needs by 2035 in the accelerated case (up from just 0.2% today). In the cement industry the share reaches 2%, while in iron and steel 7% is achieved.

Refineries

Refineries are currently the other large consumer of hydrogen besides industry, using it for the cracking of oil and the sulphur treatment of oil products. At consumption of 5 EJ, refineries are responsible for around 45% of global hydrogen demand in the energy sector. Roughly 35% of energy consumed globally in refineries is for hydrogen production but, like in the chemical sector, almost all of this hydrogen is produced from unabated fossil fuels. In the accelerated case, however, 15% of all hydrogen consumed in refineries is low-emissions by 2035, with more than a quarter of this consumption being based on already announced projects for low-emissions hydrogen production. Consequently, the sustainable fuel share of refinery energy consumption rises to around 6%.

Buildings

With demand of 127 EJ, the buildings sector was the second-largest end-use sector in 2024, slightly ahead of transport. Sustainable liquid and gaseous fuels currently cover 0.45 EJ (0.35%) of energy demand in the global buildings sector, mainly linked to the use of biogas for cooking. In China, for example, biogas from household-level biodigesters meets around 12% of energy demand for cooking.[5] In the accelerated case, the use of sustainable liquid and gaseous fuels in buildings almost quintuples in absolute terms to 2 EJ by 2035 but still represents less than 2% of buildings sector energy demand. Sustainable fuel use remains concentrated on biogases, used in cooking and for space and water heating.

Power sector

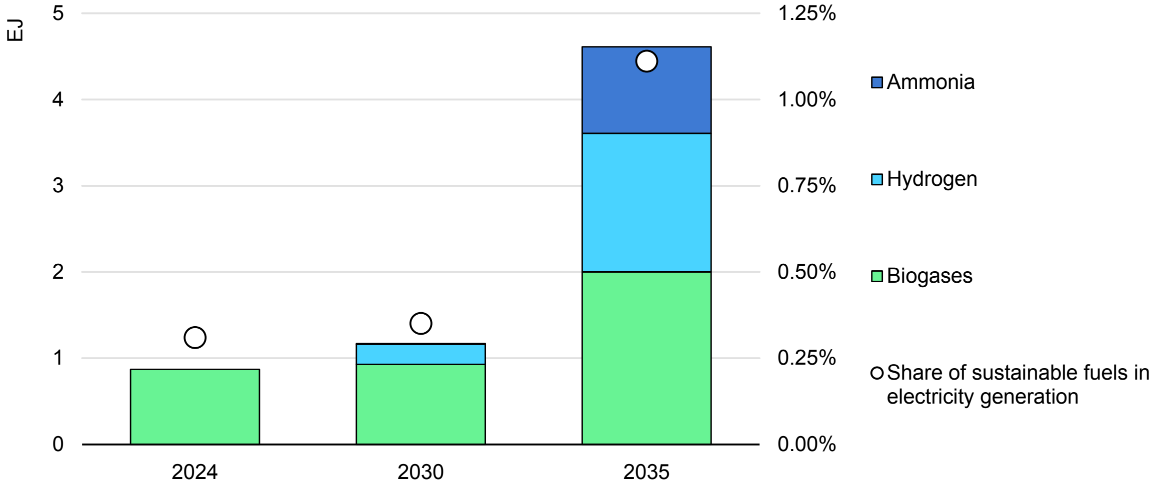
Of the roughly 265 EJ of energy consumed globally by the power sector in 2024, 70% was fossil fuel-based. Around 1 EJ of sustainable liquid and gaseous fuels was used, with biogases accounting for almost all of it.[6] In the accelerated case, the use of biogases more than doubles by 2035. In fact, total installed electricity generation capacity fuelled by biogases expands from 27 GW in 2024 to almost 90 GW in 2035.

While the share of biogases in electricity generation remains small at less than 1% in 2035, these plants provide additional benefits. Smaller biogas power plants, for instance those with internal combustion engines, are frequently situated close to

[5] Modern solid bioenergy, which is outside the scope of this report, accounts for 3% of energy demand in buildings, with around 60% used for space heating and 30% for cooking.
[6] Modern solid bioenergy is also used in the power sector, especially for combined heat and power production.

feedstock sources such as farms, landfill sites and wastewater treatment facilities and often serve as decentralised electricity and heat generation options with minimal transmission losses. Additionally, biomethane can be blended into the natural gas used in open- or combined-cycle gas turbines, providing flexibility to the electricity system to support the integration of variable renewables such as solar PV and wind.

Figure 5.6 Sustainable liquid and gaseous fuel use in electricity generation by fuel type in the accelerated case, 2024-2035



Low-emissions hydrogen and ammonia are other sustainable fuel options for the power sector. Although they are not currently being used,[7] installed hydrogen- and ammonia-fired capacity reaches 170 GW by 2035 in the accelerated case, covering around 1% of global electricity generation. In the near term, using low-emissions hydrogen and ammonia can reduce emissions from existing plants while also providing electricity system flexibility. In the longer term, power plants running entirely on hydrogen or ammonia and equipped with storage could balance seasonal electricity demand and supply variations.

Hydrogen can also be blended into the natural gas used in gas turbines. In fact, 100%-hydrogen firing was demonstrated in 2023 in an 80-MW gas turbine in Korea, and gas turbine manufacturers aim to have 100%-hydrogen modern gas turbines (i.e. that use a dry low-nitrogen-oxide combustion system) commercially available by 2030.

[7] Hydrogen is already being used as fuel in the sector, with a share of less than 0.2% in the global generation mix. However, it is not used as pure gas but rather in mixed gases that contain hydrogen from steel production, refineries or petrochemical plants.

Similarly, the direct use of 100% ammonia was demonstrated in a 2-MW gas turbine in 2022. Gas turbine manufacturers are therefore working on developing ammonia combustion system retrofits for existing gas turbines, to allow 100% ammonia firing. Cofiring in coal power plants, which is another option for using ammonia in the power sector, is particularly important in this transitional decade in countries that have large shares of coal in the power mix. Trials in Japan, China and Indonesia have demonstrated it successfully.

Overall, almost 5 EJ of biogases, low-emissions hydrogen and ammonia combined are used in the power sector in 2035 in the accelerated case, making this future power sector the third-largest consumer of sustainable liquid and gaseous fuels after transport and industry.

Setting possible targets to 2030 and 2035

Based on a sectoral analysis in the accelerated case, a fourfold increase in the global use of sustainable fuels is ambitious but achievable by 2035. It incorporates existing plans for demand creation from the IMO, ICAO, and announced national policy goals. If fully implemented, it would mark a major step towards implementation of the COP28 commitment to transition away from fossil fuels. Furthermore, turning this ambition into reality would support the COP30's call to boost implementation of the goals derived from the results of the Global Stocktake, notably the key objectives of transitioning away from fossil fuels in a just, orderly and equitable manner, and accelerating the deployment of zero- and low-emissions technologies in hard-to-abate sectors.

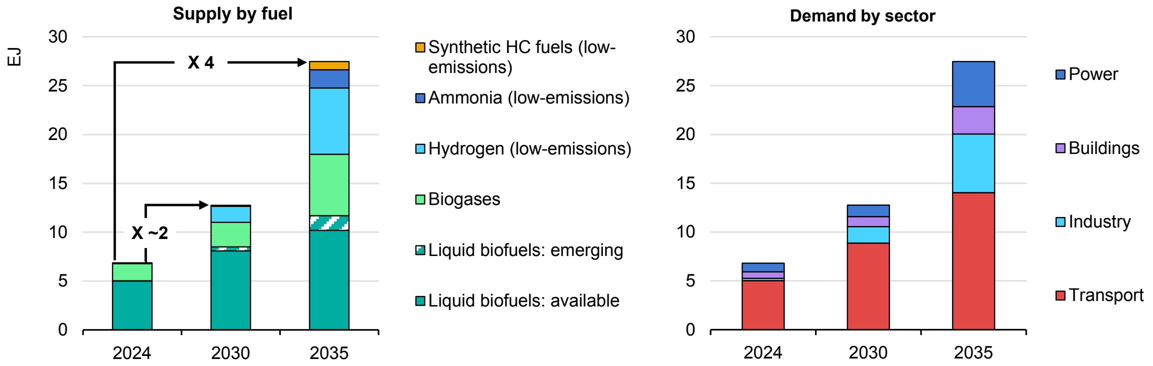
A collective global target to increase the use of sustainable liquid and gaseous fuels by at least a factor of four in a decade would send a strong signal to investors and industry, help accelerate supply chain development, reduce costs and embed higher ambition in national strategies. Beyond decarbonisation, it would also enhance energy security, diversify supplies and create new economic opportunities.

It is useful to take a holistic view of sustainable fuel development, as sectoral demand patterns change over time. Concurrently, it is also important to recognise the varying contributions of different fuel pathways in meeting demand. In the transport sector, road demand accounts for almost 45% of the increase up to 2030. While consumption in this subsector begins to slow down thereafter with the uptake of electric vehicles, it continues to rise in shipping and aviation.

As such, demand from the transport sector continues to spur growth in sustainable fuel use, with a share of still 50% globally by 2035. Industry and electricity sector consumption expand considerably after 2030, driven mainly by the chemical and steel subsectors, and by the need for greater power system flexibility.

The portfolio of sustainable fuels evolves to accommodate these demand pattern changes. Liquid and gaseous biofuels, which currently make up almost all sustainable fuel use, remain important throughout the decade, accounting for two-thirds of total sustainable fuel use in 2035. Meanwhile, low-emissions hydrogen and hydrogen-based fuels – which today furnish only around 1% of all sustainable fuels used – gain ground to reach almost 2 EJ by 2030, then expand more than fivefold by 2035. In fact, during 2030-2035, low-emissions hydrogen and hydrogen-based fuels are responsible for about half of the rise in sustainable fuel consumption.

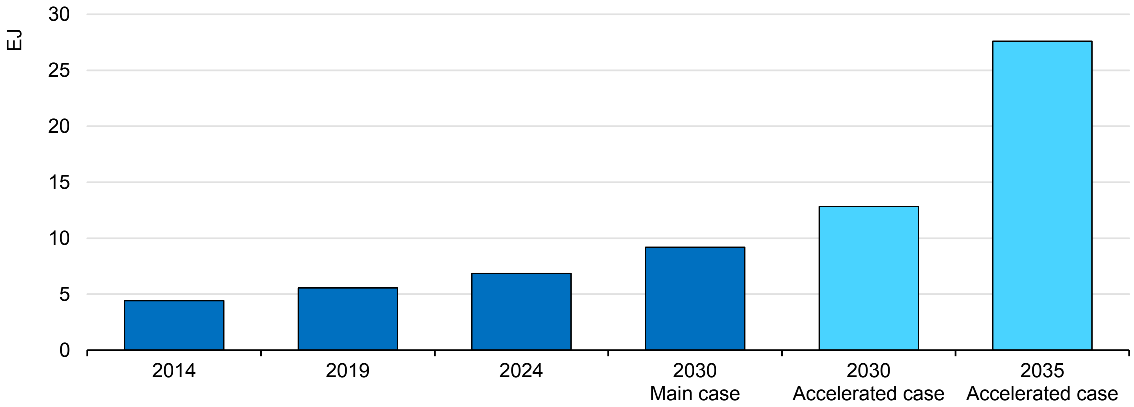
Figure 5.7 Sustainable fuel supply by fuel and demand by sector in the accelerated case, 2024-2035



Notes: HC = hydrocarbon. “Industry” includes onsite production of low-emissions hydrogen, ammonia and methanol as well as low-emissions hydrogen use in refineries. "Liquid biofuels: available" refer to technology readiness level (TRL) 9 and "liquid biofuels: emerging" to TRL 7 or 8. “Buildings” includes agriculture. “Power” refers to the generation of electricity and heat in the power sector.

It should be noted that results from the accelerated case represent global averages. Depending on country and regional circumstances, national shares, mixes and volumes can be very different. This diversity allows governments to design strategies and roadmaps that leverage their national strengths. By tailoring approaches to domestic resource endowments, infrastructure conditions and sectoral characteristics, countries can maximise the use of their comparative advantages. Such differentiation not only strengthens the cost-effectiveness and feasibility of global sustainable fuel deployment but also ensures that national strategies remain aligned with broader energy security, diversification decarbonisation, social and economic objectives.

Figure 5.8 Global sustainable fuel use, historical, main case and accelerated case, 2014-2035



Turning this ambition into reality would represent a step-change in sustainable fuel use and supply, which have been growing steadily but slowly for a long time. It would be a key move towards achieving economies of scale, and thus the necessary cost reductions. This could in turn open the way to even more ambitious sustainable fuel targets, reflecting evolving energy and climate objectives both nationally and globally.

While realising this growth does not call for breakthroughs in technologies or feedstocks, attracting timely investment at scale to build up the necessary sustainable fuel production and infrastructure will require the full and careful implementation of announced policies and the removal of market barriers. Chapter 6 therefore details relevant priority areas for action; policy solutions; primary current challenges; and examples of best practices.

Chapter 6. Conclusions and priorities for action

The policy environment for sustainable fuels is highly complex, encompassing a wide range of technology pathways that differ significantly from each other in costs, technology readiness, infrastructure requirements and development challenges. Biofuels are currently the most developed and cost-effective fossil fuel alternative, with ethanol and biodiesel reaching cost parity in some markets. However, policy action is needed to expand and diversify sustainable biomass feedstock supplies, commercialise new processing technologies and improve comparability of carbon accounting methodologies to aid large-scale deployment.

Low-emissions hydrogen can substitute for unabated fossil-based hydrogen in industry and underpins emerging applications. While falling renewable electricity prices contribute to its appeal, progress is hindered by insufficient demand-side policies and the high capital requirements for transport, distribution and storage infrastructure. Hydrogen-based fuels such as ammonia, methanol and synthetic hydrocarbons add to the diversity of potential emissions reductions options. They typically require less new infrastructure than hydrogen but are around 50% more expensive to produce. Moreover, their scalability is constrained by access to low-cost sources of CO_2 feedstocks, with the exception of ammonia that is inherently carbon-free.

If fully legislated and implemented, current and proposed national and international policies would put sustainable fuel use on a path to nearly double from the 2024 level by 2030, and quadruple by 2035. As no single sustainable fuel or feedstock can meet the full scale and diversity of global fuel demand, progress must occur on multiple fronts to increase sustainable fuel uptake in established markets and also expand demand potential and mobilise the resource base in new markets. New technologies that can convert a broader range of feedstock stream into sustainable fuels will need to be commercialised, including pathways involving electrolytic hydrogen and its derivatives. At the international and domestic level, the IEA recommends six priority actions to accelerate sustainable fuel use:

Priority 1: Establish roadmaps, targets and support policies

Challenge: Despite growing interest in sustainable fuels, long-term visibility remains limited. Many countries lack clear targets or support policies such as binding mandates and financial incentives to guide market development. Without defined timelines or quantified goals, investors face uncertainty, and supply chain actors hesitate to commit resources. The absence of co-ordinated national strategies often leads to fragmented efforts and slows progress towards meaningful deployment at scale.

Policy response: Governments should establish clear, time-bound targets for sustainable liquid and gaseous fuel deployment, ideally aligning them with broader energy and climate goals taking into account local demand structure, existing infrastructure, resource availability and industrial hubs. These targets should be underpinned by national roadmaps that detail specific milestones and priority sectors (e.g. road, aviation, shipping and industry). Relevant enabling actions could include binding mandates, financial and predictable regulatory support, infrastructure development, value chain integration and feedstock supply improvement. Roadmaps should be developed in close consultation with industry representatives, regional actors and civil society to ensure broad buy-in and implementation. They should be updated regularly based on technology progress, market signals and lifecycle GHG performance.

Selected policy examples:

Brazil's Fuel of the Future Law established new blending targets for ethanol and biodiesel and established programmes for renewable diesel, SAF and biomethane, building on its existing performance-based requirements (RenovaBio) and financial support for sustainable fuels in the road, aviation and industry sectors.

As part of Japan's energy transition, its Seventh Strategic Energy Plan lays out a co-ordinated and integrated approach to increase the use of hydrogen, hydrogen-based fuels and biofuels in road transport, aviation and industry, sending strong policy signals for investors.

Priority 2: Increase demand predictability

Challenge: Despite broad policy coverage, especially in developed economies, global deployment of sustainable liquid and gaseous fuels remains too slow, with the persistent cost premium over fossil alternatives being the primary barrier to wider adoption. Without clear and durable demand signals or price certainty, producers struggle to achieve economies of scale, while private investors hesitate to commit capital. This lack of confidence delays market formation and infrastructure investment, underscoring the need for policies that both bridge the cost gap and provide predictable conditions for producers and consumers.

Policy response: Accelerating the deployment of sustainable fuels requires a mix of ambitious, stable and enforceable policies, such as mandates and performance standards, along with proactive public procurement. Sector-wide mandates and performance standards should be technology-open, allowing any sustainable fuel pathway to compete to provide the most affordable fuel at the lowest emissions. This can be achieved by rewarding fuels in proportion to their lifecycle GHG emissions savings, and directing investment towards the most cost-effective pathways. To balance ambition with feasibility, mandates and performance-based standards can include comprehensive compliance trading systems, cost floors and ceilings and be underpinned by safety valves that limit excessive compliance costs if fuel supplies fall short.

At the same time, governments can create early and reliable demand through public procurement policies – for example by requiring minimum sustainable fuel shares in public transport fleets, military and emergency services, and government-contracted aviation and shipping. To further support demand for sustainable liquid and gaseous fuels, administrations can also work to gradually phase out fossil fuel subsidies in a just, orderly and equitable manner.

Long-term offtake agreements, contracts for difference and advance market commitments can help reduce revenue risks and unlock private investment. Procurement frameworks should incorporate lifecycle GHG criteria and sustainability safeguards to ensure environmental integrity while supporting domestic industry development.

Selected policy examples:

The EU's ReFuelEU Aviation and FuelEU Maritime regulations set progressively increasing requirements through 2050, providing clear long-term market signals for sustainable fuels in aviation and shipping. Fuel volumes used to comply with these sectoral mandates can also be counted by member states towards RED III transport targets, which apply only until 2030

The US Renewable Fuel Standard obliges refiners and importers to blend minimum volumes of renewable fuels each year, with compliance supported by a tradable credit system (RINs). Targets are set on a short, multi-year basis, providing certainty over the near term.

Italy's competitive auction-based financial scheme provides contracts for differences, as well as capital grants, for new biogas projects to ensure stable demand and competitive market prices for new projects.

Priority 3: Cooperate in developing transparent and robust carbon accounting methodologies

Challenge: The credibility and comparability of sustainable fuels hinge on robust carbon accounting methodologies and globally accepted rules. Yet, thresholds and the scope of emissions vary widely across jurisdictions and fuel pathways.

This fragmentation creates investment uncertainty, hinders new economic development and trade opportunities, and complicates the development of common sustainability criteria. It also risks undermining public trust if fuels marketed as "sustainable" fail to deliver meaningful climate benefits or have unintended negative impacts.

Policy response: Robust and mutually agreed carbon accounting methodologies are needed to improve comparability, interoperability in the longer term, and to track progress and enable policies rewarding better performances over time. Governments and international regulatory bodies should adopt transparent, science-based carbon accounting frameworks that cover the fuel's full lifecycle, and strive for enhanced interoperability of methodologies through international cooperation, or via bilateral or multilateral agreements. Carbon accounting frameworks should align with international best practices and be applicable to all fuel types and sectors to ensure a level playing field, avoid double-counting, and guarantee data transparency and verifiability to build integrity into reporting. The IEA labelling system proposed in this report (see Fig 4.3) is a tool for comparing lifecycle GHG performance across different fuel families (liquid and gaseous biofuels, hydrogen, hydrogen-based fuels) and pathways and for tracking progress over time in a transparent and consistent way.

Standardised methodologies and verification procedures are essential for tracking progress, enabling cross-border trade and integrating sustainable fuels into compliance markets. Accounting systems should be updated regularly and supported by independent monitoring, reporting and verification mechanisms. Alignment among different sectoral frameworks (e.g. aviation, maritime and road) should also be prioritised to ensure producers have equitable access to different sustainable fuel markets, further supporting production and deployment.

Selected policy examples:

In 2016 ICAO adopted CORSIA, and in 2019 introduced its lifecycle emissions methodology, which underpins emissions reporting and offsetting for more than 130 participating countries by 2026. In 2023, the IMO adopted lifecycle assessment guidelines for marine fuels to support implementation of its proposed Net-Zero Framework. Both institutions have established transparent accounting approaches for global fuel use, though some methodological differences mean their outcomes are not yet directly comparable.

California's Low Carbon Fuel Standard (LCFS) sets a carbon intensity benchmark for fuels. Biofuels with carbon intensity scores below the benchmark generate credits that can be sold to producers of higher-carbon fuels, rewarding biofuel producers for reducing the carbon intensity of their fuel and incentivising innovation. The LCFS is also continually improved by data updating and the addition of new fuel pathways to continuously support sustainable fuel growth.

Priority 4: Support innovation to narrow cost gaps

Challenge: The cost of emerging sustainable fuel pathways remains significantly higher than that of fossil fuels for most applications, primarily due to their limited deployment, high capital costs and low technical readiness. Without targeted support, many emerging technologies – such as hydrogen-based fuels or fuels from lignocellulosic biomass – will struggle to become commercially viable. The risk is that only the most mature or lowest-cost options become locked in, limiting the potential to diversify feedstocks and strengthen supply resilience – ultimately constraining the environmental and economic development benefits these fuels can deliver.

Policy response: Governments should prioritise innovation support to gradually reduce the cost of sustainable fuels. They could offer grants and mandate carve-outs for pilot and demonstration facilities, helping to support and de-risk emerging technologies with high potential for GHG emissions reduction. When possible, governments could also facilitate integration with existing value chains, supply networks and fuel infrastructure to leverage current assets and competitive advantages, thereby further reducing costs.

Public-private partnerships and international collaborations can accelerate learning and knowledge diffusion to develop solutions tailored to specific domestic needs, while competitive funding instruments can reward the most promising and scalable solutions. Long-term policy visibility is essential to give innovators and investors the confidence to engage.

Selected policy examples:

Canada's Energy Innovation Program – Clean Fuels and Industrial Fuel Switching provides public funding to support pilot and demonstration projects and accelerate deployment of new fuel technologies. It is one element of Canada's broader support for sustainable fuels, alongside the Clean Fuel Regulations, the Clean Fuels Fund and the Hydrogen Strategy for Canada.

Australia's Future Made in Australia Innovation Fund will provide up to AUS 1.5 billion in grants to support precommercial innovation, demonstration and deployment of renewable energy and low-emissions technologies, including low-emissions hydrogen and sustainable liquid fuels, to advance Australia's transition to a net zero economy. Similarly, it is one element of Australia's broader support for sustainable fuels, alongside the National Hydrogen Strategy and Australia's Net Zero Plan.

Priority 5: Develop supply chains and address infrastructure and integration needs

Challenge: Accelerating sustainable fuel production requires resilient supply chains and distribution infrastructure. Biomass, waste and residue supply chains are shaped by policies in other sectors, which increases the complexity of policy development. Infrastructure bottlenecks in the transport of certain sustainable fuels as well as in the transport and sequestration of CO_2 limit cross-border flows and discourage investment in international value chains, particularly between resource-rich and fuel-importing countries.

Policy response: Policymakers should support the development of integrated, sustainable, and traceable supply chains that use and reward synergies between the energy sector, agriculture, land management and municipal waste valorisation in a holistic way. Infrastructure planning should anticipate long-term needs, including industrial hubs, transport networks, storage facilities, and dedicated pipelines and bunkering for emerging sustainable fuels. International co-operation can help match regional production strengths with global demand, while technical assistance and capacity building can make it easier for emerging and developing economies to participate in global supply chains.

Selected policy examples:

India's National Green Hydrogen Mission provides support across the entire value chain – from public funding for research, pilot, demo and hydrogen infrastructure projects to the development of codes and standards in partnership with industry, to labour market development.

Argentina's PROBIOMASA initiative aims to strengthen domestic biogas supply chains by providing funding for pilot and demonstration projects; sharing data on biomass resources to improve investment decisions; disseminating new and emerging research among different levels of government and industry; and communicating the benefits of biogas to the general public.

Priority 6: Make financing more accessible, especially in emerging and developing economies

Challenge: Sustainable fuel projects can involve many challenges, ranging from infrastructure buildout to supply chain development, finding offtake agreements and possibly upskilling the labour force to meet operational needs. Such hurdles can weaken investor confidence and delay final investment decisions. Thus, without stable financing measures, project developers are often unable to raise affordable capital delaying the deployment of sustainable fuels.

Policy response: Governments and development finance institutions should take measures to enable greater access to financing mechanisms to ensure projects receive final investment decisions and reach commercialisation. Public financing tools such as grants, loan guarantees and tax credits can support capital costs and improve investor confidence in projects, while mechanisms such as contracts for difference can ensure stable prices for fuels.

Multilateral development banks and international climate funds could also expand or set up dedicated facilities targeted to help scale investments in sustainable fuels especially in markets with immature financial systems and/or very high cost of capital. In addition to direct financing, these facilities will also need to support project preparation to develop bankable projects, include capacity building and skills development as well as the development of sustainable fuel standards.

Financing mechanisms such as low-interest debt and supporting the issuance of green bonds can help lower financing costs and raise required capital. A range of financing addressing local contexts including fuel family mix, market maturity, and country-specific investment risk will be required to scale up these fuel projects, especially in emerging and developing economies.

Selected policy examples:

The Development Bank of Southern Africa is a founding partner of the SA-H2 blended finance fund. This is a multilateral initiative to accelerate low-emissions hydrogen deployment in South Africa by providing capital to project developers at the early stages of development to reduce risk and support commercialisation.

India's scheme to enhance ethanol distillation capacity provides subsidies that cover the interest on loans used to construct, expand, or retrofit ethanol facilities, helping to de-risk financial investments in facilities that use of a wider range of feedstocks for ethanol production.

Abbreviations

ASTM	American Society for Testing and Materials
BNDES	Banco Nacional de Desenvolvimento Econômico e Social (Brazilian Development Bank)
CAPEX	Capital Expenditure
CARB	California Air Resources Board
CBG	Compressed Biogas
CBIO	Crédito de Descarbonização (Decarbonisation Credit)
CCfD	Competitive contracts for difference
CCS	Carbon Capture and Storage
CCUS	Carbon capture, utilisation and storage
CEN	European Committee for Standardization
CHP	Combined Heat and Power
CI	Carbon intensity
CO_2	Carbon dioxide
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct air capture
DRI	Direct reduction of iron
EJ	Exajoule
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
ETHOS	Energy Transformation PatHway Optimization Suite
ETP	Energy Technology Policy
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric vehicle
FAME	Fatty acid methyl esters
FFV	Flex-fuel vehicles
FOB	Free On Board
FQD	Fuel Quality Directive
GDP	Gross Domestic Product
GHG	Green House Gas
GJ	Gigajoule
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GW	Gigawatt
HEFA	Hydroprocessed esters and fatty acids
HC	Hydrocarbon
HVO	Hydrotreated vegetable oil
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
ICAO	International Civil Aviation Organization

ILUC	Indirect Land Use Change
IMO	International Maritime Organization
ISFM	Initiative for Sustainable Fuels and Mobility
LCFS	Low Carbon Fuel Standard
MJ	Megajoule
MSW	Municipal solid waste
MW	Megawatt
RED	Renewable Energy Directive (RED)
RFNBO	Renewable fuels of non-biological origin
RFS	Renewable Fuel Standard
RIN	Renewable Identification Numbers
SAF	Sustainable aviation fuel
SED	Socio-Economic Development
TCP	Technology Collaboration Programme
TRL	Technology readiness level
UK	United Kingdom
UOP	Universal Oil Products
USD	United States Dollar
WEF	World Economic Forum
ZAE	Zoneamento Agroecológico (Sugarcane Agroecological Zoning)

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