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Bain & Company

Fuelling the Future: How Business, Finance and Policy can Accelerate the Clean Fuels Market

WHITE PAPER

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The global energy system is changing fast, driven by mounting energy security and climate risks, alongside accelerating innovation and investment in energy. Yet changes are uneven, and shifting geopolitics and economic pressures have reinforced the importance of reliable, affordable and clean energy as the basis for competitiveness and shared prosperity.

Against this backdrop, clean fuels are a practical lever for many regions and sectors to adapt and create economic opportunities. Clean fuel markets are not new. In many countries, they already support industries and jobs, cut emissions, reduce reliance on fossil fuels and help protect household energy costs. However, ambitions to scale up further have raised important concerns around potential competition for scarce land and resources. The sector's complex market dynamics make it essential to improve the understanding of where, and how, clean fuels can generate economic and societal value.

At the same time, despite growing ambitions, too few projects reach final investment. Even where project economics are viable, market risks and capital intensity differ from traditional energy assets, making it tough to ramp up investments. Progress requires new forms of collaboration and innovation among farmers, traders, producers, financiers and end-users, supported by durable policies and firm demand signals.

In response, the World Economic Forum, with the support of Bain & Company, has convened high-ambition businesses, financiers, policy-makers and civil society through the Future of Clean Fuels initiative to create better awareness around the market, its trade-offs and solutions that can scale it up in the right way. Encouragingly, our research finds that leaders who embrace partnerships and innovative ways to mitigate risk can realize financial returns.

This report complements that work. It highlights the important role of expanding clean fuels in our future energy system and associated key market dynamics; and it offers solutions for business leaders and policy-makers to overcome barriers hindering credible projects from materializing. It builds on expert stakeholder consultations, as well as techno-economic analysis.

We thank the members of the Future of Clean Fuels community for their insights and valuable contributions and look forward to advancing the clean fuels transition together.

Executive summary

Clean fuels are key to the energy future, yet progress is slow. Turning ambition into projects needs joint action by governments, producers, distributors and customers.

Amid rising global energy demand and evolving geopolitical dynamics, clean fuels are a key pillar for a more secure, affordable and sustainable energy system. Liquid and gaseous fuels supply 56% of energy use today and are especially important in transport and industry. Even as electrification grows fast, they will remain vital, supplying 40-55% of energy demand in 2050 across scenarios.

Clean fuels – mainly liquid or gaseous fuels, ranging from biofuels to hydrogen derivatives and lower-carbon fossil fuels – can offer multiple sources of economic and societal value. They diversify energy supply and reduce exposure to volatile fossil fuel markets by using widely available resources such as organic waste and renewable power. Biofuels production has enabled several net fossil fuel-importing countries to reduce import dependence by 5-15%.

Clean fuels also stimulate industries and jobs, especially in rural areas, with two to three times the job intensity of conventional fuels. They can reduce lifecycle greenhouse gas emissions and support productive land use – provided well-designed policies protect land, biodiversity and water resources against adverse impacts and competition between sectors.

Ambitions to realize this potential are growing, as demonstrated by the "Belém 4x" pledge to quadruple sustainable fuel production and use by 2035, put forward by Italy, Japan, India and Brazil ahead of COP30 and now endorsed by more than 25 countries.

The case for clean fuels is strong, but a reality check is needed to turn ambitions into investable projects. At least $100 billion in annual investments are needed by 2030 to deliver on global clean fuel ambitions. Current investments are ~$25 billion per year, or just above 1% of total investment for clean energy. At this rate, with only 10% of announced new capacity for 2030 past investment decision, the market will fall short of its targets.

Substantial capital is available to close this gap, but companies struggle to realize adequate returns. Uncertain and incongruent policies, weak coordination among feedstock suppliers, fuel producers and customers, and an absence of firm demand are driving up costs and risks. Yet the direction is clear: latent demand is growing, technologies are maturing and significant profit opportunities exist.

Scaling-up the market in the next decade calls for a dual focus. First, existing commercial pathways need expanding; second, greater innovation is required in early-stage pathways. Ramping up commercial fuels such as biogas, bioethanol and biodiesel – alongside measures that lower emissions from existing fossil fuels – can contribute to near-term emissions reductions, with the right incentives and safeguards. These fuels can be deployed with lower capital investment into established value chains as blend-in or drop-in solutions, serving as stepping stones to the future fuel mix.

However, rapid commercialization of new feedstocks and technologies is needed to ease supply constraints, reduce fuel emissions intensity and meet demand targets within the next 5-10 years. Despite the higher cost of clean fuels, blending strategies (virtual or physical) can limit the impacts on consumer pricing as markets mature and costs come down, while pursuing a portfolio of pathways.

Joint action to deploy proven solutions has untapped potential to accelerate the market. Despite the challenges, pioneering examples demonstrate that proven approaches are successfully unlocking adequate returns to support investment. Common to these solutions is their approach to reducing risk and providing the right enabling environment to coordinate investments. Three insights emerge from these success stories:

– Performance-based policies rewarding verified emissions reductions and other benefits have successfully embedded societal value in investment decisions. For example, in Brazil, tradeable credits, along with low-interest loans and tax incentives, have stimulated demand in support of energy security and industrial development. The success of such policies depends on interoperable standards and predictable market instruments to create revenue certainty where there is a credible path to competitiveness.

– Public-private mechanisms, such as double-sided auctions or book-and-claim, pool risks and connect producers and customers where markets are sub-scale.

– Businesses partnering across the value chain can signal demand and potential supply, while rethinking how to contract, finance and allocate capital. This approach is proving successful in unlocking projects by bridging the gap between the market risks and infrastructure-type investment that characterizes clean fuel projects.

1 Clean fuels: Unlocking value from the new energy system

Clean fuels offer opportunities for economic and social development, and improved energy security, as energy systems evolve at different speeds across regions.

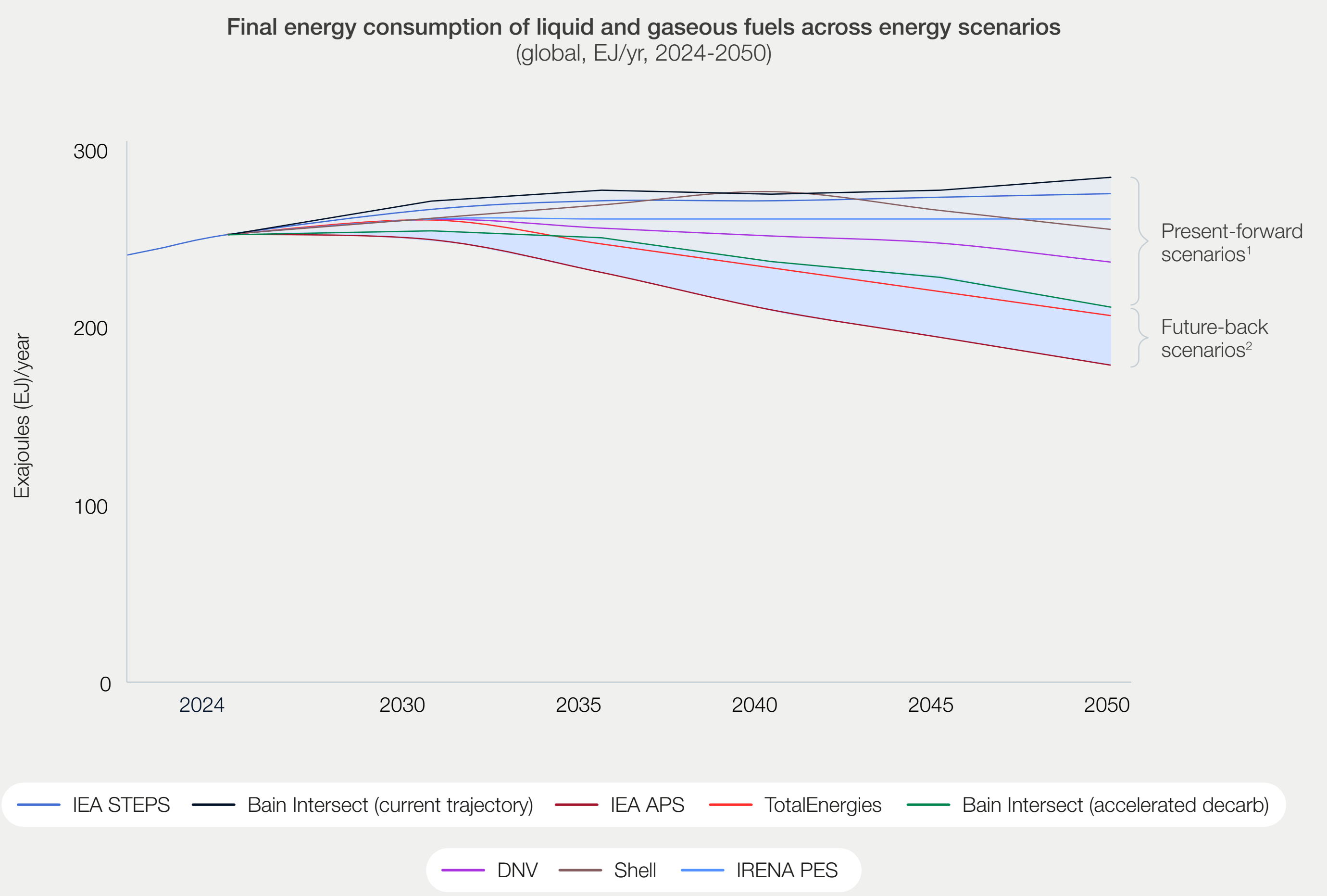
1.1 The role of clean fuels in energy's future

> Clean fuels can help reduce emissions near-term, by using existing assets and established value chains that currently rely on unabated fossil fuels.

Liquid and gaseous fuels are vital to the global economy, supplying 56% of global final energy use today[1] (~250 exajoules, EJ)[2,3] and attracting ~$1 trillion of investment each year.[4] Global energy demand is expected to continue to rise, driven by growth in both economies and populations. While electrification is central to most energy scenarios, some transport and industrial energy demands cannot be substituted effectively with electricity. Additionally, clean fuels can help reduce emissions near-term, by using existing assets and established value chains that currently rely on unabated fossil fuels.

Across most scenarios, liquid and gaseous fuels will remain a significant share of the world's energy supply for decades (see Figure 1), with 2050 estimates ranging from 175-285 EJ (40-55% of total supply),[5] equal to roughly four to five times current US demand.[6]

FIGURE 1 **Fuels will remain an important share of the energy mix under most transition scenarios**



Notes: 1. "Present-forward" scenarios are based on current policies and announced measures (partial or full realization), plus technology evolution **2.** "Future-back" scenarios represent greater acceleration in decarbonization (including direct electrification and energy efficiency improvements), assuming full and timely delivery of pledges, with reinforcing momentum across policy, investment and technology. All scenarios include fossil and clean liquid and gaseous fuels. EJ = exajoules; one exajoule (EJ) is 10^{18} joules. STEPS = IEA's stated policies scenario, APS = IEA's announced pledges scenario, PES = IRENA's planned energy scenario.

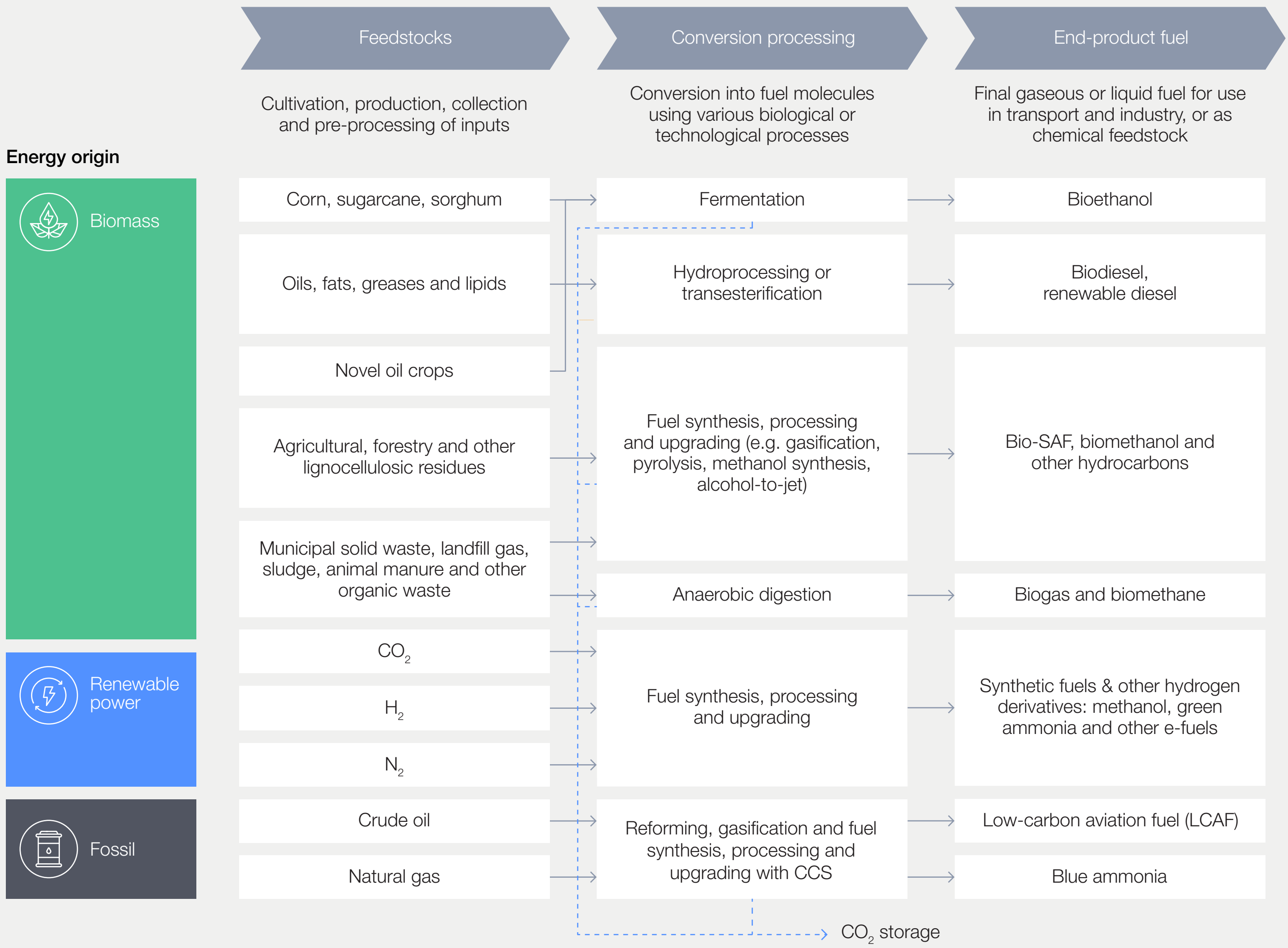
Sources: International Energy Agency (IEA), International Renewable Energy Agency (IRENA), DNV, Shell, TotalEnergies, Bain & Company Intersect.[7]

Clean fuels span multiple production pathways, representing different combinations of feedstocks, conversion technologies and end-product fuels (see Figure 2). This report considers a broad definition of clean fuels that includes liquid biofuels, biogases, lower-carbon fossil fuels, synthetic fuels and other hydrogen derivatives, acknowledging the roles all will play in the coming decades (see Box 1).

These fuels are a critical tool to reduce emissions in fuel-reliant sectors such as transport and industry, where energy density, storability, chemical properties and infrastructure compatibility make molecules the most competitive or only option. Molecules are particularly relevant for applications such as aviation, shipping, parts of road transport and certain industrial processes that require high heat or molecules as chemical feedstocks. Clean fuels also enable refineries to adapt to the shifting demand mix and sustain asset utilization by making use of existing energy infrastructure.

This report focuses primarily on energy use in transport and industry. Other notable applications, such as the use of solid biomass and biogases in the power sector and district heating, along with the deployment of these molecules as chemical feedstocks, are not discussed in detail.

FIGURE 2 **Summary of main clean fuel production pathways**



Notes: Non-exhaustive overview of clean fuel pathways. CCS = carbon capture and storage, SAF = sustainable aviation fuel.

Source: Bain & Company.

BOX 1

Fuel pathways and applications in focus for this report

This report examines supply pathways for liquid and gaseous fuels with potential to be produced and used in ways that materially reduce lifecycle greenhouse gas (GHG) emissions, measured in CO_2-equivalent per megajoule on a full lifecycle basis.

Most of the pathways considered have the potential to cut emissions by at least half compared with conventional fossil fuels, without introducing adverse non-GHG impacts, although not all projects will be able to deliver these intensity reductions in the near-term.

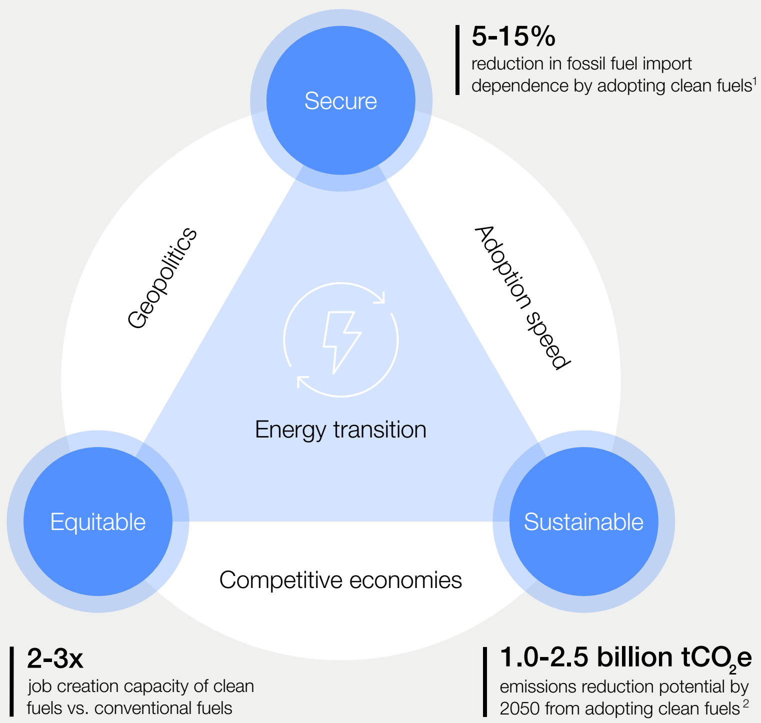
The analysis also explores the role of certain lower-carbon fossil fuels in enabling near-term emissions reductions at lower abatement cost when combined with processes such as carbon capture and storage and methane leakage minimization, while recognizing that the emissions reduction potential of such pathways is limited and unable to deliver "last mile" emissions reduction.

1.2 Unlocking societal value – global opportunities and regional realities

Clean fuels will, in most cases, remain more expensive to produce than fossil fuels over the short to medium term and are unlikely to reach cost parity on a pre-subsidy cost-per-energy-unit basis. However, when their wider societal value is incorporated, including energy security, economic and environmental benefits, they can become competitive on a system level. Clean fuels can strengthen security of supply, reduce energy import costs, support equitable economic growth and jobs, and improve sustainability, contributing towards a more affordable, resilient and lower-emission energy system (see Figure 3). Different regions will put different weight on each of these objectives, responding to adoption speed of new technologies, changing geopolitical dynamics and economic competitiveness, which will impact the role of clean fuels over time.

FIGURE 3

Clean fuels offer multiple sources of societal value



Notes: 1. Realized potential in selected net fossil fuel-importing countries. **2.** Based on mid-range energy transition scenarios. For full methodology on GHG emission reduction potential, see Appendix.

Sources: World Economic Forum, Bain & Company analysis.[8]

Secure

Liquid biofuels have lowered transport fuel import dependence by 5-15% across several net fossil fuel-importing countries.

About 75% of fossil fuel production comes from a few regions (US, Middle East and Russia) which comprise less than 40% of global demand.[9] This geographic concentration creates structural imbalances in the energy system, which can leave import-dependent economies exposed to supply disruptions, price volatility and geopolitical risk. Meanwhile, clean fuels are produced from resources that are more widely distributed across regions. By using organic waste, cover crops, agricultural residues and excess renewable electricity, regions can improve their self-sufficiency and diversify their energy supply, supporting more stable and competitive economies.

Evidence shows that liquid biofuels have lowered transport fuel import dependence by between 5% and 15% across several net fossil fuel-importing countries. In countries including Indonesia, India, Brazil and Malaysia, their expanding use has had even larger impacts.[10] Flexibility across feedstocks, infrastructure compatibility and storability can further enhance system resilience.

Equitable

Every $1 million invested in bio-based or synthetic fuel production typically generates 10-30 jobs, compared to 5-10 jobs created by conventional fuels.

Clean fuels offer industrial growth and job opportunities. Their blending/drop-in compatibility can enable emissions reductions while making use of existing assets to lower transition costs and mitigate impacts on energy prices. For example, meeting the EU's ambitious SAF mandates for 2030 could add up to 15% in fuel cost,[11] but this translates to a more modest 3-5% increase in average ticket prices.[12]

Moreover, clean fuels can stimulate domestic industrial value chains and job creation, particularly in rural areas by creating new income streams for farmers. For example, every $1 million invested in bio-based or synthetic fuel production typically generates 10-30 jobs, compared to 5-10 jobs created by conventional fuels. This is driven primarily by higher job intensity in upstream feedstock production and processing.[13]

Sustainable

Some clean fuel pathways have potential to reduce emissions by at least 50% – rising to more than 90% or even net-negative in optimal set-ups, when combined with carbon capture.

Clean fuels have the potential to reduce CO_2 emissions by 1.0-2.5 billion tonnes (Gt) per year by 2050, based on mid-range transition scenarios.[14] They can materially reduce lifecycle GHG emissions, through blending or as substitute for fossil fuels. Some pathways have the potential to reduce emissions by at least 50% – rising to more than 90% or even net-negative in optimal set-ups, when combined with carbon capture for certain bio-based processes (see Figure 10).

Some fuels can also reduce sulphur dioxide and particulate emissions, improving air quality and health outcomes.[15] In addition, clean fuels can advance circularity by valorizing[16] organic waste streams and incentivizing improved soil and waste management practices that mitigate methane emissions and land erosion, while supporting productive land use.[17] Realizing these benefits requires robust and transparent safeguards, such as lifecycle carbon accounting with incentives for continuous improvement. This will help support a technology-open approach, based on abatement cost potential and adherence to strict non-emissions criteria, which is necessary to avoid adverse impacts from deforestation, competition with food production, loss of biodiversity or water stress.

Regional realities

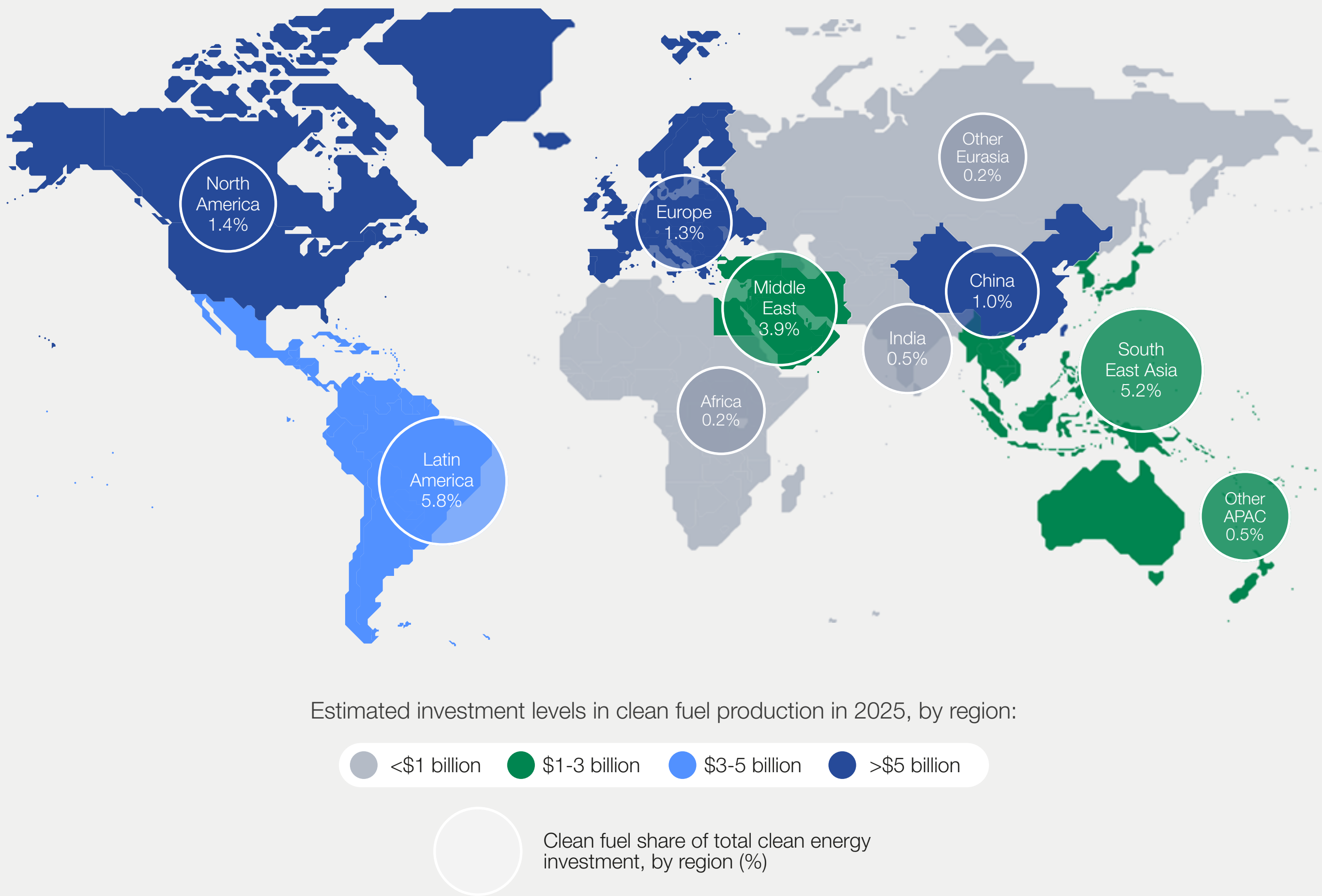
> Many regions dependent on fossil fuel imports view clean fuels as a strategic lever to diversify energy supply and reduce exposure to price volatility.

The scale and importance of these societal benefits will differ by region, shaped by local resource endowments, the cost of alternatives, infrastructure readiness and policy priorities. No single pathway will dominate everywhere. Applying a regional lens is therefore essential to evaluate competitiveness and guide investment towards the most competitive and high-impact options.

Regions with abundant, low-cost renewable electricity or sustainable biomass are naturally positioned as supply hubs, exporting to global markets and creating new commercial opportunities. Many regions dependent on fossil fuel imports view clean fuels as a strategic lever to diversify energy supply and reduce exposure to price volatility. Regional strategies are emerging – as reflected in current investment levels (see Figure 4).

FIGURE 4 **Estimated investment levels in clean fuel production capacity in 2025, by region**

The role of clean fuels and relevant pathways will differ by region, depending on local strengths, resources and demand dynamics, including cost of alternatives.



Notes: Investment includes biogases, bio-SAF, biodiesel and renewable diesel, bioethanol, low-emission hydrogen-based fuels and CCUS to reduce fossil fuel carbon intensity. Only includes investment in clean fuel production, excluding enabling infrastructure (e.g. pipelines, fuel terminals, storage).

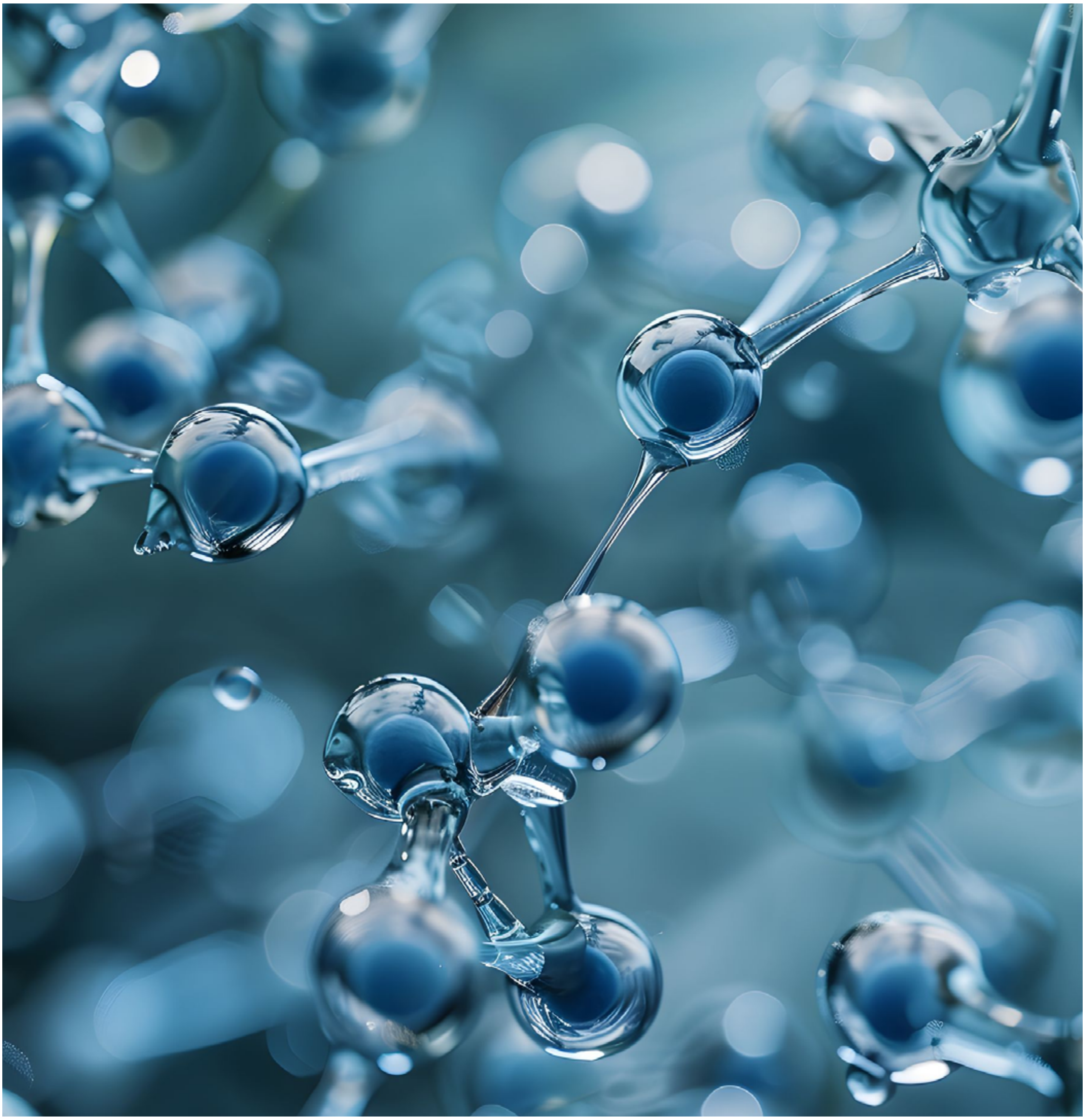
Source: IEA World Energy Investment 2025.[18]

Europe, South Korea and Japan are examples of regions developing as key demand centres through ambitious targets for biofuels and clean hydrogen derivatives to reduce reliance on fossil fuel imports.[19,20,21] Regions such as North America, South America and the Middle East are leveraging natural resource advantages to expand production for both domestic use and exports.

Given clean fuels and feedstocks will be traded internationally, interoperable certification and standards are essential for credibility, fungibility and effective markets. Recent examples of possible fraud concerns from waste oil imports to Europe underscore the need for robust, transparent systems that can travel effectively across borders.

2 Clean fuels landscape: scaling-up to the future

Creating larger markets for clean fuels requires a portfolio approach to different pathways, advancing commercial fuels and innovation in next-gen feedstocks and technologies.



2.1 Clean fuel market and techno-economic dynamics

The clean fuel market is complex, given regional realities and multiple production pathways. The scale, role and viability of each pathway are determined by techno-economic characteristics and market demand. This chapter presents a summary of how these characteristics vary by pathway and the market implications.

Market dynamics can be analysed through the following four lenses (see Figure 5):

- **Demand:** this defines how a fuel is purchased, where it can be used and how it competes with alternatives, including different abatement strategies.
- **Readiness and scalability:** these determine how quickly supply can materialize and the ultimate supply potential given sustainable feedstock and resource availability.
- **Competitiveness:** all pathways need to demonstrate a realistic route to commercial viability, based on current or future cost potential to attract investments.
- **Sustainability:** only fuels that deliver verifiable lifecycle emission reductions and meet non-GHG safeguards will secure policy support, market access and demand.

FIGURE 5 **Clean fuel market dynamics and characteristics of different pathways**

Sustainability
- GHG emissions intensity
- Pollution, land use and other environmental impacts

Demand
- Cost of alternatives
- Customer purchasing dynamics

Competitiveness
- Fuel cost competitiveness
- Abatement cost potential at scale

Readiness & scalability
- Technology and supply chain maturity
- Practical supply scale potential

Source: Bain & Company.

Demand

In Brazil, biofuels supply **30%** of domestic energy demand, catalysed by policies launched to reduce dependence on fossil fuels in response to oil price shocks in the 1970s.

The clean fuels market is already well-established, supplying around 7 EJ (1.3% of global energy consumption), mainly as bioethanol and biodiesel blends in road transport and biogas use in industry, power and heat. Of this, 80% (5.5 EJ) is used in sectors with continued reliance on fuel-based solutions such as aviation, shipping, road transport and industry.[22]

Current uptake is policy-led in most settings, responding to a range of economic, social and environmental objectives. In Brazil, for example, biofuels supply 30% of domestic energy demand,[23] catalysed by a series of policies first launched to reduce dependence on fossil fuel imports in response to oil price shocks in the 1970s.

In the US, biomethane demand has grown, particularly in the heavy-duty vehicle market,[24] supported by different state-level initiatives and federal mandates, such as California's Low Carbon Fuel Standard[25] and the Environmental Protection Agency's Renewable Fuel Standard.[26] Similar combinations of trade, industrial and climate policy are emerging elsewhere catalysing clean fuel demand.

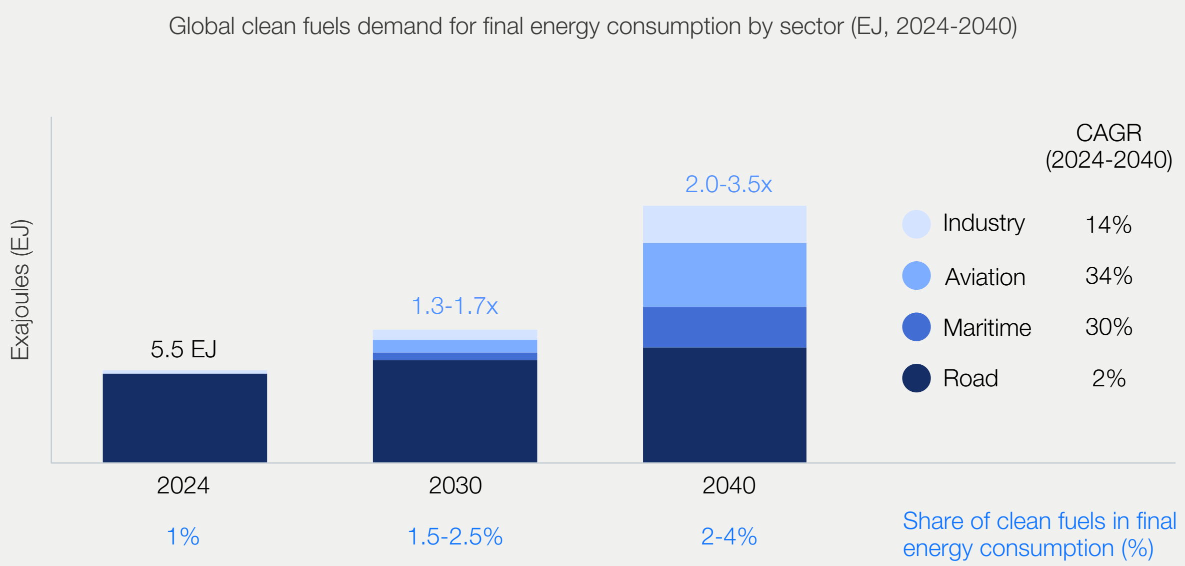
IEA estimates that if all existing announced policies and targets are implemented and market barriers removed, demand for clean fuels could quadruple by 2035.

Future demand will vary by region and by sector, shaped largely by policy priorities and the costs of clean fuels compared to alternatives. For example, in the European Union, aviation and maritime demand is set to rise under blending mandates such as ReFuelEU aviation[27] and FuelEU maritime.[28] Moreover, in December 2025 the European Commission presented the Automotive Package granting greater flexibility in meeting CO_2 reduction targets for road transport, allowing for the use of clean fuels.[29]

Efforts to coordinate global demand through international negotiation have seen mixed success; for example, the International Maritime Organization's vote in October 2025 to postpone adoption of its net-zero framework by a year[30] may delay maritime clean fuel uptake and increase the importance of cost competitiveness and blend-in potential for near-term market access.

Despite low demand certainty driving higher risk and cost, underlying demand for clean fuels is rising. Demand may grow 2-3.5 times by 2040, with near-term growth driven by road blends and longer-term expansion driven by harder-to-abate applications in aviation, shipping and heavy industry (see Figure 6).[31] The International Energy Agency (IEA) recently estimated that in an accelerated scenario – where all announced policies and targets are achieved and market barriers removed – demand could quadruple by 2035,[32] consistent with the "Belém 4x" pledge, a joint commitment by Italy, Japan, India, Brazil and over 25 other countries to quadruple sustainable fuel production and use by 2035.[33]

FIGURE 6 **Clean fuel demand is expected to increase significantly**



Notes: Only includes liquid and gaseous clean fuels; excludes power sector and district heating demand; excludes demand for fuels as chemical feedstocks. CAGR = compounded annual growth rate.

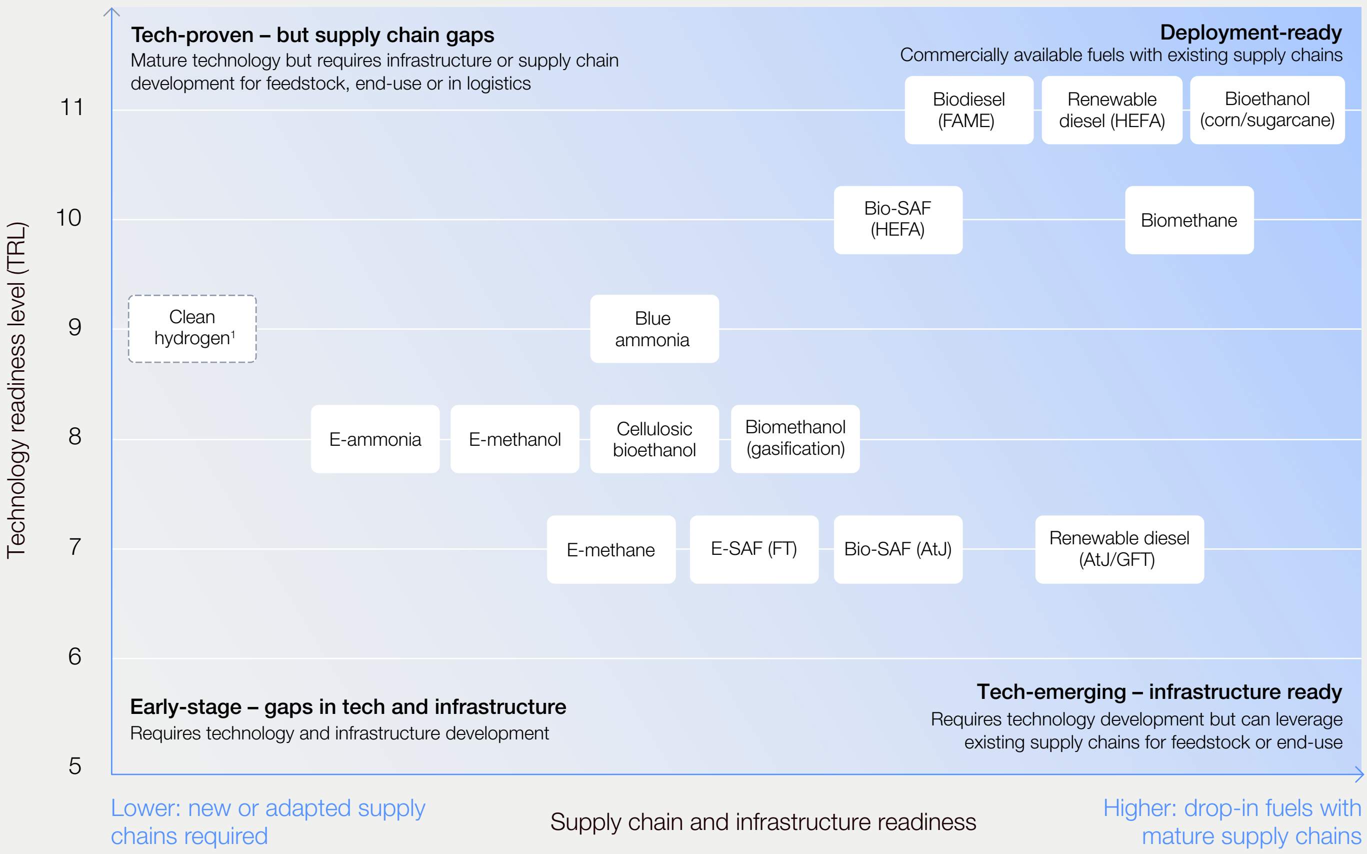
Sources: Bain & Company analysis assessing feasible clean fuel demand growth based on current trajectory, published scenarios and Bain & Company supply and demand models.[34]

Readiness and scalability

Readiness reflects both how mature the feedstock-to-fuel conversion technology is and how developed the supply chain is from feedstock sourcing to distribution and end-use integration. Figure 7 maps key pathways against these dimensions. Most pathways can be blended or used as drop-in fuels in existing engines and infrastructure. Some exceptions, such as ammonia and methanol for use in shipping require engine retrofits or modified terminal, storage and handling equipment.

Similarly, carbon capture-based solutions in most locations require new infrastructure for safe transport and storage, although traditional point source technology is mature. While readiness varies significantly by fuel type, location and application, the difference in near-term scale-up potential largely stems from limitations with early-stage technology or insufficient access to sustainable feedstock.

FIGURE 7 | **Overview of technology and supply chain readiness of selected clean fuel pathways**



Notes: 1. Refers to the expanded use of hydrogen as a fuel in new applications, not considering use as chemical feedstock in existing industrial applications. TRL = technology readiness level. TRL is based on NASA's TRL scale from 1 to 9, with two additional deployment levels: 10 = deployed reliably at scale, 11 = commercial in many markets. AtJ = alcohol-to-jet, FAME = fatty acid methyl ester, FT = Fischer-Tropsch, GFT = gasification and Fischer-Tropsch, HEFA = hydroprocessed esters and fatty acids, HVO = hydrotreated vegetable oil.

Source: Bain & Company.

> **Intermediate crops and novel oil crops from degraded or marginal land have significant scale-up potential but require new agricultural practices.**

Liquid biofuels

Liquid biofuels such as ethanol, FAME biodiesel and HVO/HEFA[35] renewable diesel – produced from established agriculture-based feedstocks or waste oils – are commercially mature and widely used.[36,37] However, their growth potential is limited by finite feedstock supply. Waste oils and lipids (e.g. used cooking oil, tallow) are already approaching supply limits and will likely face constraints by 2030, due to high demand given their strong emissions reduction potential, fit with mature clean fuel pathways and ability to meet EU feedstock criteria.[38,39]

Established agricultural crops have some growth potential in certain regions via yield optimization, but face restrictions and sustainability concerns if sourced from land competing with food or associated with adverse impacts. Intermediate crops and novel oil crops from degraded or marginal land have significant scale-up potential but require new agricultural practices.

Advanced pathways that utilize emerging technologies and novel feedstocks (e.g. cellulosic ethanol, gasification/Fischer Tropsch, alcohol-to-jet) broaden the resource base; however, these are at early commercial stages and must overcome the challenge of aggregating diffuse residues of varying quality and composition.

Biogas

Biogas or biomethane from anaerobic digestion is technologically mature and produced close to feedstock sources (e.g. manure, organic waste, wastewater, landfill) and can be upgraded for grid injection or local use. Scalability is largely a logistics and sustainability challenge, related to the collection and preprocessing of feedstocks at sufficient scale, while avoiding methane leakage.

Regions with established waste management systems and modern gas grids can expand volumes faster, as seen in Europe and the US. Elsewhere, progress relies on building out collection systems and upgrading infrastructure around effective use cases.

Synthetic fuels

Synthetic fuels offer large long-term scale-up potential where low-cost clean electricity is abundant and alternative high-value uses of electricity are limited, but the technology and wider supply chain is less mature. Electrolyser technology is advancing, but full systems for fuel production remain in early commercialization.

Scalability depends on access to reliable biogenic CO_2 from high-concentration sources. Direct air capture (DAC) technology can provide a feedstock of high-purity CO_2 with the flexibility to decouple the emission source from the point of capture. Currently, while first-of-a-kind DAC projects have a high cost and limited track record, technology improvements and deployment at scale are expected to drive cost reductions in subsequent projects.

Emerging interest in naturally occurring geologic hydrogen could complement synthetic fuel pathways by providing a potentially low-cost, low-emission hydrogen source if scalable extraction proves viable.[40] Infrastructure readiness varies by fuel type; for instance, e-ammonia and e-methanol require engine modifications for use, whereas e-methane, e-SAF and e-diesel have the advantage of (post-production) compatibility with existing infrastructure, such as engines, pipelines and storage.

Low-carbon fossil fuels

Other lower-carbon fossil fuel options, such as fossil fuels combined with carbon capture, can help reduce emissions in transition. The core technologies are relatively mature, but scalability depends on reliable CO_2 transport and storage systems, sustained high capture rates and rigorous methane management in gas supply chains.

These solutions can deliver near-term emission reductions, often at more limited cost – for example, low-carbon aviation fuel is estimated to deliver around 6-13% emissions reduction versus conventional jet fuel, by implementing practices such as emission management and carbon capture at refineries and use of lower-carbon electricity and hydrogen.[41] Similarly, carbon capture integrated with fossil fuel extraction by injecting captured CO_2 into mature oil and gas reservoirs, where the injected CO_2 becomes securely stored, can create potential for emission reductions and in some cases exceed the emissions associated with the fossil fuel, depending on storage efficiency and lifecycle emissions.[42] The relatively high willingness to pay for such solutions based on higher yields from existing reservoirs can support early CCS scale-up opportunities around important emission clusters.

Competitiveness

Clean fuels are typically more expensive than fossil equivalents due to capital intensity, feedstock and logistics expenses, market risks and technology immaturity. Costs vary significantly across technology pathways, feedstocks and regions.

Mature biofuels such as corn ethanol, biodiesel and HVO renewable diesel are currently the most economically viable, with potential for cost parity with fossil fuel alternatives in certain regions and with optimal production set-up (see Figure 8). Today, production costs for new HVO plants range from $20-40/GJ,[43,44] versus $17-25/GJ for diesel equivalents.[45]

Feedstock limits and more mature technologies restrict opportunities to lower costs further. In some markets, however, costs and ultimately prices can come down by reducing feedstock bottlenecks. For example, for certified used cooking oil (UCO) or tallow, a significant share of profits is captured at the feedstock stage. Vertically integrated refineries that source these feedstocks internally benefit from lower production costs by avoiding the full market margin on feedstock purchases and, as a result, can potentially capture a larger share of overall value when selling the final fuel.

Emerging pathways, such as advanced biofuels and synthetic e-fuels, are significantly more expensive (see Figure 9). Costs will come down with scale, increased process efficiency and standardization, lower financing costs and more competitive markets. Yet in most cases, due to inherently higher operating expenses, their costs are estimated to remain higher than fossil fuels in most situations, in the near to medium term. Policy incentives that capture both positive and negative societal impacts are needed to allow cleaner fuels to compete effectively based on their abatement profile.

Refineries rarely produce a single product;[46] processes such as HEFA yield a mix of fuel types, with ratios shaped by plant design, feedstocks and market choices. Businesses must balance production costs with maximizing the yield of the highest value products, considering the full product slate rather than a single fuel. Optimizing for the most profitable mix is key to viable and scalable clean fuel projects and can make even more expensive fuels relevant to support a profitable business case.

Blending strategies – physical mixing or virtual blending through credits – are critical to drive early market adoption and emissions reductions, while mitigating the impact on consumer energy prices. Ensuring competitive energy costs over time also requires well-designed policy incentives that balance supply and demand, preventing bottlenecks and price volatility.

FIGURE 8 **Global average production cost ranges – mature clean fuels**

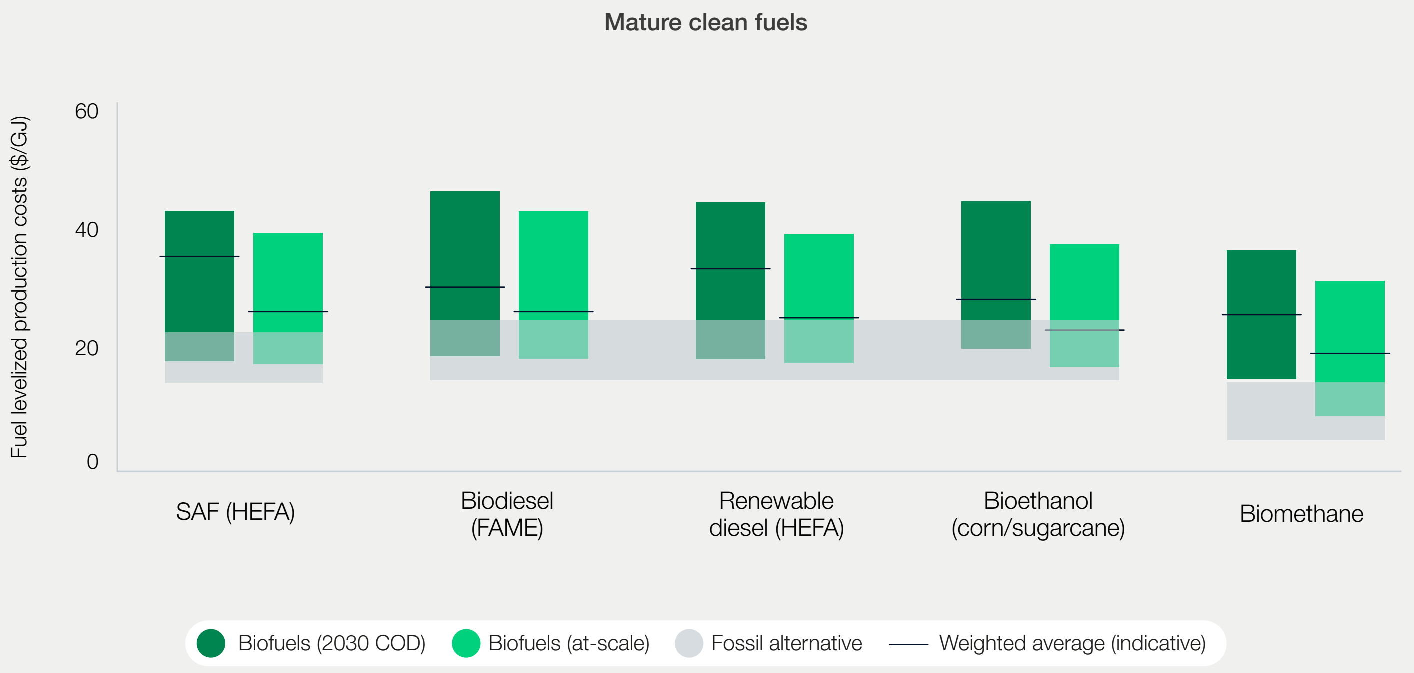
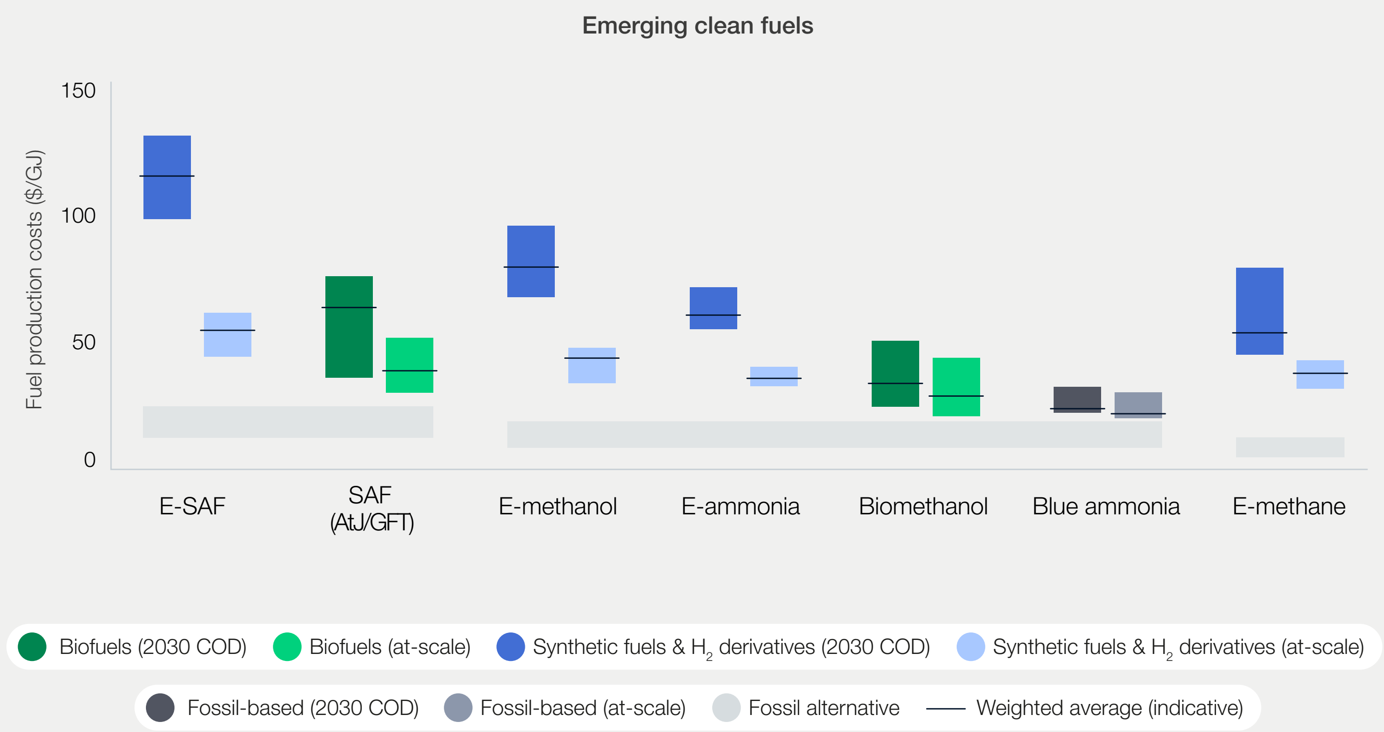


FIGURE 9 **Global average production cost ranges – emerging clean fuels**



Notes for Figures 8 & 9: "At-scale" refers to forecasted levelized production costs[47] at nth-of-a-kind plants. COD = commercial operation date. For full methodology, see Appendix.

Sources: Forecasts are from Bain & Company analysis using feedstock price forecasts from Euromonitor and proprietary capex/opex data, supplemented by 2024 industry interviews.

Sustainability

> Most clean fuel pathways discussed have the potential to reduce emissions by at least 50% compared to conventional fuels – and in some optimal set-ups, achieving up to 90%.

Full lifecycle carbon intensity (CI) varies significantly by and within pathways, as well as between projects using similar feedstocks and technologies. Feedstock type, crop yield and agricultural practices, emissions leakage, conversion efficiency and energy inputs are key drivers of emissions – each with different weights depending on the pathway.

Under well-designed policies, most clean fuel pathways discussed have the potential to reduce emissions by at least 50% compared to conventional fuels – and in some optimal set-ups, achieving up to 90% emission reductions or even net-negative emissions (see Figure 10). For example, emissions from biomethane vary from an average of 30-40gCO_2e/MJ (~50-60% reduction versus natural gas) to net-negative by capturing biomethane from animal manure, which would otherwise be emitted during natural decomposition as methane (a significantly more potent GHG than the CO_2 emitted after biomethane combustion).[48]

Biofuel production can also be paired with carbon capture to reduce emissions. Similarly, synthetic fuels and other hydrogen derivatives have the potential to deliver 90%+ emissions reductions, provided renewable electricity is used in their manufacture and wider supply chain emissions are minimized.

FIGURE 10 **Lifecycle GHG emissions intensity ranges, selected clean fuel pathways**

Notes: CI = carbon intensity. Assumes synthetic fuels are produced using renewable electricity and CO_2. Ranges reflect default values assigned to specific fuel types by regulatory frameworks, and certified project data for different pathways. Columns show accurate values against the y-axis, but values in captions are rounded for ease of comparison.

Sources: see endnote.[49]

Beyond the GHG impacts of clean fuels, it is important to account for broader sustainability concerns, such as competition for land use, impact on water systems, and broader health and safety outcomes. Rigorous monitoring, reporting and verification (MRV) are needed to ensure that clean fuels deliver positive environmental and societal outcomes.[50]

Transparent, robust MRV and certification systems adaptable to different regional and project contexts are essential to verify emissions reductions, compare outcomes and guide investment. However, current MRV methodologies vary widely across jurisdictions, undermining interoperability and trust.

2.2 Implications for scaling-up the market in the next decade

Since most clean fuels are – and will remain – costlier than conventional fossil fuels, scaling-up the market will require stable, well-designed policies.

Clean fuel demand is set to rise significantly over the next decade, but today's mature technologies and feedstocks alone cannot meet this demand.[51,52] Accelerating growth depends on stimulating demand and overcoming supply constraints in parallel, which will enable the expansion of multiple complementary technologies and feedstocks. Since most clean fuels are – and will remain – costlier than conventional fossil fuels, scaling-up the market will require stable, well-designed policies.

Feedstock access is a key chokepoint to expanding supply. Competitive growth requires widening the sustainable resource base, advancing emerging conversion routes and promoting practices that lower lifecycle carbon intensity. The blending/drop-in nature of many pathways enables rapid deployment without major new infrastructure in most situations, helping limit price impacts as markets mature.

Commercial options such as biomethane, ethanol, biodiesel and renewable diesel can also enable the next wave of pathways. For example, as gasoline demand declines in the US, "ethanol overhang"[53] can be redirected to alcohol-to-jet production – one of the most promising pathways to decarbonize aviation long-term.

The optimal mix of clean fuels will vary by region, sector and time frame, reflecting resource availability, local policy priorities and total system cost compared to alternative energy supply options and abatement strategies. Progress requires a dual track approach: continue scaling-up commercial blend-in fuels, while boosting investments in innovation and first-of-a-kind projects and feedstocks that can accelerate competitively and sustainably.

3

Turning ambitions into projects: key solutions to unlock investment

Ambition is outpacing investment; several public and private sector solutions are proving effective to unlock credible projects.

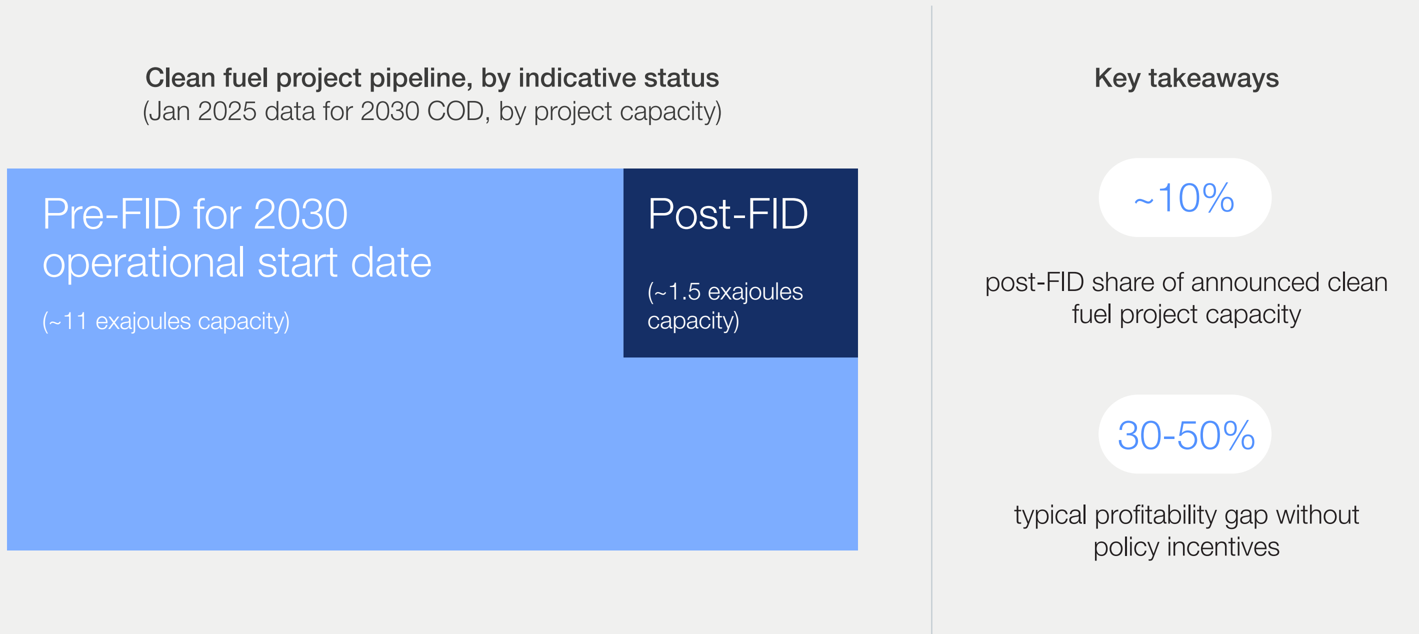
3.1 Investment barriers to project progress

> **Meeting the demand for clean fuels implicit in current national and corporate pledges would require a fourfold increase to roughly $100 billion per year by 2030.**

Momentum is improving but remains insufficient. Annual investment in clean fuel production capacity has risen by ~30% from 2024 to 2025 and is expected to reach ~$25 billion by the end of 2025. Yet this is still a fraction of what is required.[54] Meeting the demand for clean fuels implicit in current national and corporate pledges would require a fourfold increase to roughly $100 billion per year by 2030.[55]

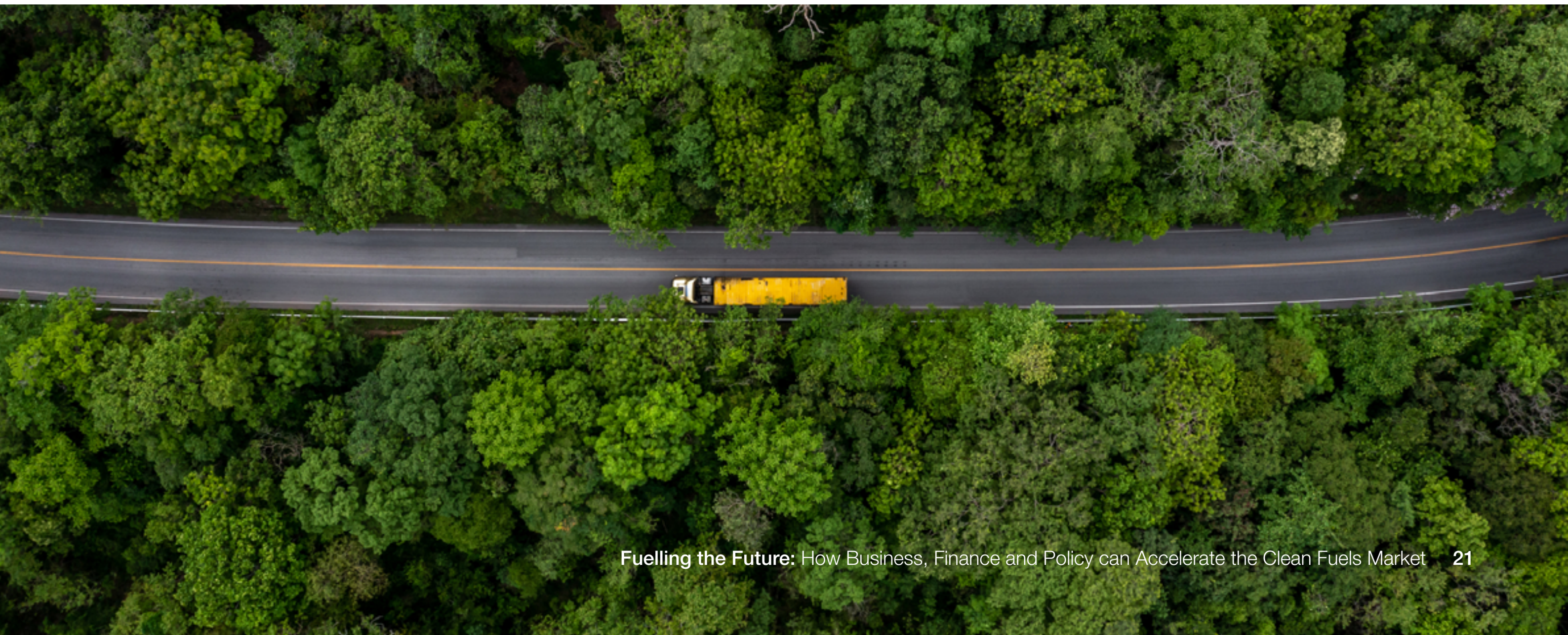
The clean fuels project pipeline is expanding, with at least 12.5 EJ of new capacity targeting operation by the end of the decade; but only around 10% of projects have reached FID (see Figure 11).[56] Given the typical two- to five-year construction period after FID, the share of operating capacity is unlikely to grow rapidly. Understanding the barriers preventing projects from advancing is critical to designing the solutions needed to overcome them and accelerate market growth.

FIGURE 11 **Clean fuel pipeline: 90% of projects to 2030 are still pre-FID**



Notes: Includes projects targeted for energy use across e-fuel and key biofuels (e.g. SAF, renewable diesel) with start dates between 2025 and 2030, excluding operational projects. Post-FID includes projects that have secured FID or are in construction.

Source: Bain & Company.



Clean fuel faces unique challenges

Clean fuel investments face a unique set of challenges compared with traditional energy capital projects. Their value chains are complex and interdependent, often spanning multiple feedstocks, conversion technologies, logistics networks and end-use markets. Progress in one part of the chain often depends on another part maturing at a similar pace. For example, scaling-up biomass feedstocks requires coordination between refiners, farmers and waste aggregators.

Beyond these structural challenges, their financial risk profiles also differ significantly. Clean fuel projects are typically capital-intensive, expose investors to technology and market development risk, and rely on policy frameworks that are still evolving, do not provide sufficient incentives or lack stability. Even modest changes in perceived risk can significantly improve project economics and investability. For example, de-risking a bio-SAF project to reduce the total cost of financing by three percentage-points – from 15% to 12% – can reduce the levelized production cost by up to ~15% per barrel of jet fuel.[57]

Policies and market rules have not yet caught up with this complexity, where fragmented standards, inconsistent certification systems and uncertainty around policies add friction.

Taken together, these factors explain why many credible projects remain stuck between feasibility and FID. The barriers identified can be grouped into four broad categories: project economics and finance, supply chain, customer demand, and policy and standards (see Figure 11). Their impact varies by pathway. For example, mature fuels such as HEFA are often constrained by supply chain bottlenecks, while emerging technologies face greater exposure to technical and cost risks.

TABLE 1 **Stuck between feasibility and FID: six barriers hampering project progress**

Project economics and finance	**1. High costs and technology risks:** High capital intensity, limited economies of scale, conversion inefficiencies and early-stage technology risks lead to higher initial costs and project delivery risk. **2. Inadequate financing, high price premiums and de-risking mechanisms:** Few instruments can cater to clean fuel risk dynamics or bridge the gap between venture-like risk and infrastructure-type projects.
Supply chain	**3. Uncertain feedstock and uncoordinated supply chains:** Fragmented feedstock, production and logistics create bottlenecks and timing mismatches (e.g. scaling-up waste collection in line with production ramp-up).
Customer demand	**4. Misaligned contracts, high price premiums and nascent market structures:** Differences between producers and customers on contract terms (e.g. price, volume, tenure), combined with lack of established platforms to standardize and benchmark agreements, lead to delays.
Policy and standards	**5. Policy instability and fragmentation:** Lack of stability and credibility in future policies requires balancing ambitions with realistic and competitive implementation. **6. Incongruent standards and certifications:** Disparate definitions and certification standards (e.g. on LCA) and limited mutual recognition hinder interoperability across jurisdictions and trade.

Note: LCA = lifecycle assessment.

3.2 Three levers to unlock investment

Innovative mechanisms and coordinated action are essential to overcome market barriers and mitigate investment risks. Encouragingly, proof points already exist – including current projects that demonstrate effective ways to improve revenue visibility, pool and distribute risk, and internalize the societal value of clean fuels in line with regional energy goals. The public and private sectors have distinct but complementary roles in helping unlock these solutions.

Based on engagement with private and public stakeholders from the Future of Clean Fuels community and broader industry stakeholders, this report has identified nine solution areas across three major levers: policy, public-private collaboration and business (see Figure 12):

1. **Policy measures:** Policy sets the rules of the game. Predictable, durable and performance-based frameworks let clean fuels compete in a technology-neutral way and convert societal value (e.g. lower emissions, stronger security, improved economic competitiveness) into price signals. Countries will weight these goals differently given regional priorities and contexts. To enhance trade in fuels and feedstocks, interoperable standards and certifications across borders are essential.

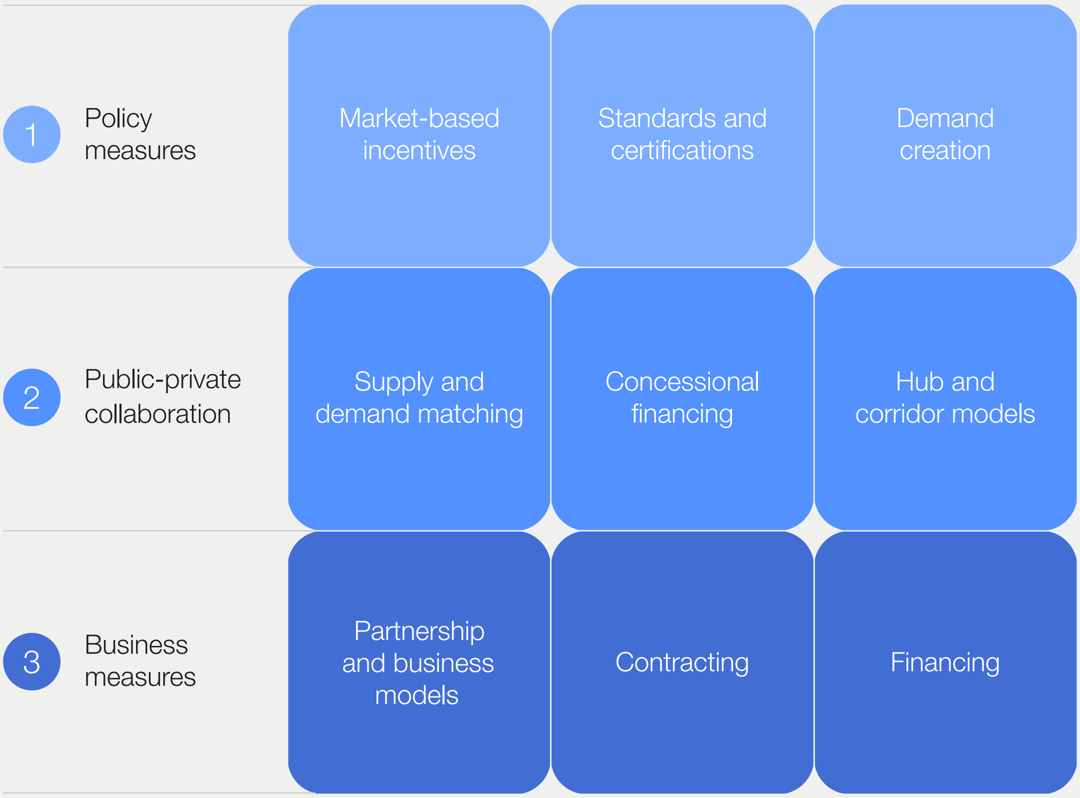
2. **Public-private collaboration:** Collaboration coordinates market-making action; it connects supply and demand, pools and shares risk, and unlocks the shared infrastructure essential for supporting early-stage projects.

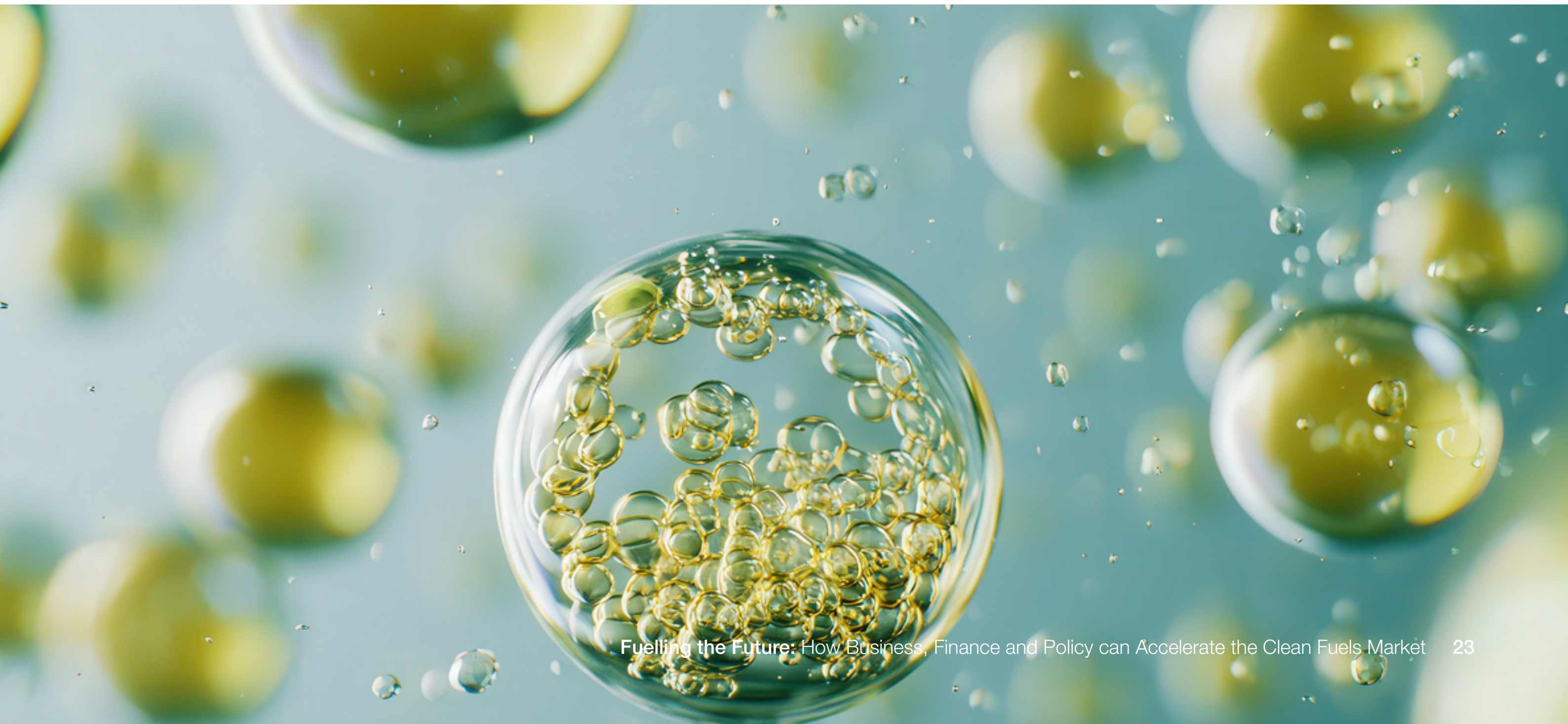
3. **Business measures:** Businesses mobilize project delivery – by leveraging innovation, capital, capabilities and risk-taking to scale up both mature and emerging clean fuel pathways.

Formation of strategic partnerships across the value chain allows the private sector to align incentives, pool risk and develop immature value chains cooperatively to accelerate growth.

This chapter highlights case studies of successful projects that show how leaders from across the world are combining these solutions to attract viable clean fuel investment at scale.

FIGURE 12 **Nine solutions to unlock investment through three levers: policy measures, public-private collaboration and business measures**





Lever 1

Policy measures

Policy measures are crucial to catalyse strategic clean fuel investment by rewarding system value and ensuring fair, performance-based competition. Businesses stress the criticality of policy stability, emphasizing that even moderate but consistent policies can unlock investment, while shifting rules erode confidence and stall capital. Given the 20-30-year lifetimes of most plants, long-term policy predictability is vital to sustain viable business cases.

Given the 20-30-year lifetimes of most plants, long-term policy predictability is vital to sustain viable business cases.

Market-based incentives

Market-based incentives narrow the price gap between clean and fossil fuels by internalizing system value in market prices. Carbon pricing penalizes fuels proportional to their emissions, while tax credits reward clean producers via fiscal support. Contracts for difference (CfDs) complement these tools, providing revenue certainty through a guaranteed fixed strike price and compensating producers when market prices fall, reducing investor risk and unlocking capital.

Incentives that price in local benefits, such as tax rebates for projects demonstrating community value like job creation, can further incentivize investment and ensure that clean fuel development delivers shared economic and societal gains. Targeted direct incentives, for example with capex or development subsidies, also help kick-start and crowd private capital into emerging technologies, where there is a plausible path to competitiveness.

Standards and certifications

Effective, transparent and stable certification systems and taxonomies are essential for investor confidence, ensuring clean fuel projects qualify for incentives, comply with regulation and deliver verified environmental benefits. International alignment and interoperability enable trade and efficient supply-demand matching, allowing advantaged producers to compete in high-demand markets. Consistent LCAs underpin performance-based tools such as credit issuance and trading, while shared standards translate environmental integrity into economic value, rewarding real performance and supporting global scale.

Demand creation

Demand-creation mechanisms, such as mandates and public procurement, secure offtake to improve revenue predictability, reduce investor risk and enhance project bankability. Blending mandates set minimum clean fuel shares in the fuel pool, establishing stable demand for long-term investment. Performance-based mandates reward verified carbon intensity, allowing the most sustainable options to compete to deliver abatement in the most affordable way. Public procurement uses government purchasing power to create early demand and attract private capital.

Together, these tools can build visibility, confidence and scale, unlocking early clean fuel projects ahead of organic market demand growth when deployed in the right way. Parallels could be drawn with natural gas markets for pipeline gas and LNG, where long-term contracts have played a key role in underpinning large investments to build markets. There are also similarities with renewable electricity, where auctions, power purchase agreements and feed-in tariffs played a key role in early scaling-up of markets and investments.

CASE STUDY 1

Brazil

Background and objectives

Brazil has one of the world's largest biomass resources and, through decades of industrial policy, has become a biofuels leader. The country has implemented a unified energy-climate-industrial policy to strengthen energy security and reduce oil imports, cut transport emissions and boost competitiveness and jobs.

Key policy pillars

– **Fuels of the Future Bill:** Adopted in 2024,[58] this establishes a comprehensive framework to promote low-carbon, renewable and advanced fuels across Brazil's transport and energy mix. The law builds on earlier initiatives such as RenovaBio and expands support to aviation fuels, green diesel, biomethane, carbon capture and storage (CCS) and stronger blending mandates. Brazil combines demand-creation measures with market and financial instruments:

– **Demand-creation mandates:** Ethanol (30% blending in gasoline), biodiesel (15%), SAF (1% emissions reduction target from 2027 scaling-up to 10% by 2037) and biomethane (1% in natural gas) blending.

– **Market instruments:** Tradeable CBIO credits (a Brazilian carbon credit) for certified GHG reductions, biomethane guarantees of origin, Brazilian Development Bank (BNDES) low-interest loans, Rota 2030 tax incentives and new credit lines for biogas and biomethane.

Impact

– ~30% of national energy comes from bioenergy.

– ~1 million direct and indirect biofuel jobs.

– ~65 Mt CO_2e avoided emissions annually.

Exportable lessons

– **Coordinate policy levers:** Align energy, climate and industrial policies to secure broad acceptance, increasing stability and investor confidence. This provides a coherent framework for sustained investment and market growth.

– **De-risk investment:** Pair performance-based incentives such as tradeable credits with concessional finance to lower capital costs and reward verified emissions reductions.

Source: Brazil's Ministry of Energy and Mines.

CASE STUDY 2

California

Background and objectives

California is the US's second largest transport fuel market. A large vehicle fleet, major refining base and heavy freight make transportation the state's largest source of emissions. The state prioritizes clean fuel to reduce emissions, diversify fuel supply, strengthen energy security, create quality jobs and promote next-generation fuel development.

Key policy pillars

- **Market-based incentives:** California's Low-Carbon Fuel Standard (LCFS) enforces increasingly tight carbon-intensity targets for fuel suppliers. Compliance requires supplying lower-CI fuels or retiring tradeable credits, rewarding verified lifecycle reductions.
- **Policy coordination ("stacking"):** LCFS is designed to stack with other federal tools (e.g. Renewable Fuel Standard; Inflation Reduction Act 45Z/45V tax credits), strengthening project economics across investments and operations.

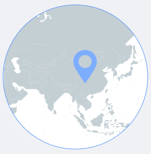
Impact

- >95% of total US renewable diesel consumption occurs in California.
- >$20 billion equivalent in LCFS credits issued to date.
- ~25% reduction in California's surface transport emissions since 2007.

Exportable lessons

- **Diversify incentives:** Pair upfront fiscal tools (e.g. tax credits) with performance-based credits (e.g. LCFS) to create multi-stage revenue and bankability.
- **Coordinate across levels:** Align state and federal frameworks to ensure that support endures through political or financial shifts.
- **Reward performance:** Tie credits to lifecycle CI metrics to incentivize continuous innovation and improvement.

Sources: Bureau of Transportation Statistics, US Energy Information Administration (EIA), California Air Resources Board (CARB).[59]



CASE STUDY 3

China

Background and objectives

China has incorporated clean fuels into its broader energy security and industrial competitiveness strategy. The Administrative Measures for the Special Management Measures for Central Budgetary Investment in Energy Conservation and Carbon Reduction (October 2025) aim to standardize and strengthen central funding for carbon reduction initiatives. For the first time, sustainable aviation fuel (SAF) and green methanol are explicitly eligible for national financial support, transitioning from scattered local pilots to a coordinated, multi-mechanism framework designed to mobilize investment and accelerate progress towards China's dual-carbon goals – to reach absolute peak CO_2 emissions before 2030 and to achieve net-zero emissions by 2060.

Key policy pillars

– **China's nationwide funding framework** covers six project categories, including low-, zero- and negative-carbon demonstration projects, such as SAF, green methanol, CCUS and zero-emissions transport corridors.

– **Central investment** may cover up to 20% of approved project costs, with higher ratios (60–80%) for foundational infrastructure depending on region. Mechanisms include direct investment, capital injections and subsidies administered by the National Development and Reform Commission (NDRC) and provincial authorities.

– **Preferential and provincial finance** is also available for clean fuel projects, including: access to concessional loans from policy banks (e.g. China Development Bank, Exim), interest-subsidy programmes, provincial guarantees and green funds, as well as green bonds and credit quotas. Combined, these lower project weighted average cost of capital (WACC) and complement central budget support.

Impact

– Establishes the first coordinated national investment framework for clean fuels.

– Expected to catalyse first-of-a-kind large-scale SAF and methanol projects, bridging financing gaps.

– Enhances policy alignment towards the goals of 2030 peak emissions and 2060 carbon neutrality.

Exportable lessons

– **Central investment as catalyst:** Even modest public co-funding can de-risk early clean fuel ventures and crowd-in private capital.

– **Policy clarity drives confidence:** Clear eligibility and forward-looking scope improve accountability and attract long-term investors.

– **Strategic signalling matters:** Naming SAF and green methanol explicitly sends powerful market signals that accelerate industrial learning and scale-up.

Sources: World Economic Forum, NDRC.[60]

Lever 2

Public-private collaboration

Public-private collaboration mechanisms help unlock viable clean fuel business cases by coordinating complementary public and private capabilities to de-risk, mobilize finance and accelerate deployment. They are particularly valuable in the early-market phase, helping demonstrate commercial feasibility, pool risks and establish shared infrastructure before private investment and organic demand can scale up independently.

Supply and demand matching

Supply-demand matching mechanisms improve market coordination by aligning producers and buyers to provide the revenue visibility and certainty required to attract investment and scale up clean fuel markets. Demand-pooling platforms, such as the World Economic Forum's First Movers Coalition, aggregate commitments from multiple buyers to create larger, credible volumes and reduce transaction costs.

Book-and-claim systems expand market access by decoupling environmental attributes from physical delivery, allowing buyers to claim verified emissions reductions while sourcing fuels produced elsewhere. This can be particularly important for aviation and shipping, for instance where crossing national borders and continents is core to operations.

Double-sided auctions provide producers with long-term revenue certainty and buyers with flexibility and price discovery, by linking long-term supply contracts to short-term resale through competitive bidding on both sides. Together, these tools expand market access, reduce risk and create early demand signals to unlock investment and accelerate clean fuel deployment.

Concessional financing

Concessional financing and other energy transition financing mechanisms lower the cost of capital and share risk between public and private investors, making early clean fuel projects investable, crowding-in private capital and accelerating scale-up. Blended finance structures combine public or philanthropic funding with commercial capital to improve risk-return profiles and attract institutional investors.

First-loss capital and loan guarantees further de-risk investment by absorbing initial losses or backstopping lenders against default, protecting investors and crowding-in private capital. Green bonds, transition bonds and infrastructure support, such as co-investment in transport or storage assets, reduces costs across value chains and improves overall market viability.

Together, these mechanisms lower financing barriers, mobilize private capital and support investments until sectors can sustain investment on commercial terms.

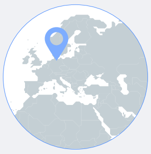
“ Hub and corridor models bring together producers, users, infrastructure providers and policy-makers to coordinate supply, demand and logistics, building confidence for investors.

Hub and corridor models

Hub and corridor models help overcome first-mover barriers: developers are reluctant to build capacity without guaranteed demand, while offtakers hesitate to commit without reliable supply or supporting infrastructure – particularly where new engines or assets are required.

By concentrating early activity within defined geographies such as industrial clusters or trade routes, hub and corridor models bring together producers, users, infrastructure providers and policy-makers to coordinate supply, demand and logistics, reducing risk and building confidence for initial investment. The World Economic Forum's Transitioning Industrial Clusters initiative is one example of such efforts.

Focused deployment accelerates learning, lowers costs through shared infrastructure and demonstrates commercial feasibility. Through public-private collaboration, these models also help align regulation, harmonize standards and create replicable blueprints for scaling-up clean fuels across regions and sectors.



CASE STUDY 4

H2Global double-sided auctions

Description

H2Global offers a double-sided auction instrument to secure low-cost green hydrogen derivative imports into Europe, funded to date by Germany's Federal Ministry for Economic Affairs and Energy (BMWK) and implemented via contracting entity, Hintco.

Solution

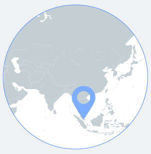
H2Global bridges contract price and duration mismatches between clean fuel producers and buyers through double-sided auctions. Hintco signs 10-year supply contracts with low-cost producers and re-auctions volumes annually to buyers, typically at prices lower than the purchase rate.

This structure provides long-term revenue certainty for producers and short-term flexibility for buyers. Public funds need only cover the price gap and resale revenues are recycled to minimize subsidies. By aligning incentives and improving price discovery, H2Global helps unlock investment and accelerate market formation.

Impact

- ~€397 million pilot award to Fertiglobe's renewable ammonia (Egypt) at ~€1,000/tonne landed.
- First resale auction in 2026 to connect supply to demand and test scale-up and subsidy needs.

Source: H2Global Foundation.[61]



CASE STUDY 5

Pentagreen Capital concessional financing

Description

A blended finance debt platform jointly owned by HSBC and Temasek, Pentagreen manages the Green Investments Partnership, a fund that mixes public, private and philanthropic capital to fund sustainable infrastructure in South East and South Asia.

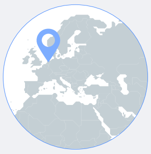
Solution

Pentagreen blends subordinated/first-loss capital, absorbing initial losses and de-risking senior lenders enough for private capital to participate in higher-risk clean fuel projects at scale. It also offers flexible debt (e.g. longer tenors, interest-only periods), to help projects clear credit tests without distorting price signals, and technical assistance (e.g. project prep/feasibility) to help them attract lower-cost private capital.

Impact

- Mobilization: $510 million first close (September 2025) from public-private-philanthropic investors; targeting ~$1 billion for green infrastructure.
- Example deals: $30 million green loan to BECIS Bioenergy, for distributed bioenergy in South East Asia and India; $80 million co-financing for solar and storage in South East Asia.

Source: Pentagreen Capital.[62]



CASE STUDY 6

Rotterdam-Singapore Green and Digital Shipping Corridor

Description

Government-led, industry-backed corridor connecting the Ports of Rotterdam and Singapore. It aligns standards, fuel supply and operations, while each port builds a multi-fuel cluster.

Solution

The Rotterdam-Singapore Green and Digital Shipping Corridor creates a defined trade route where the clean maritime value chain can align and invest with reduced first-mover risk. By aggregating demand and synchronizing fuel supply, safety and measurement standards, it builds an integrated ecosystem across both ports.

Interoperable certification ensures fuels can be bunkered and credited seamlessly at either end, maintaining fungibility for global trade. Deployment starts with mature fuels such as biofuels and methanol, expanding to ammonia and hydrogen as vessels, infrastructure and safety systems mature. With clean fuel hubs at each port, the corridor offers a replicable model for scaling-up green shipping globally.

Impact

- Rotterdam executed Europe's first green methanol terminal bunkering and the world's first barge-to-ship methanol bunkering.
- Singapore completed its first simultaneous methanol bunkering-and-cargo operation.
- Rotterdam has begun its hydrogen backbone and is developing an ammonia import and cracking terminal.
- Singapore issued methanol bunkering standards and licences and is advancing ammonia bunkering projects on Jurong Island.

Sources: Port of Rotterdam, MPA Singapore.[63]

Lever 3

Business measures

Unlocking early clean fuel projects requires private sector initiatives to reduce and share risk and coordinate across immature value chains. Businesses accelerate progress by combining capabilities and aligning incentives through partnerships, using innovative financing mechanisms, and deploying contracting models designed to reduce risk and improve project bankability.

Partnerships and business models

Partnerships and innovative business models strengthen early clean fuel projects by aligning incentives, sharing risk and pooling complementary expertise across the value chain. OEM-developer partnerships combine technology know-how with delivery capability to accelerate deployment, while investor-developer collaborations provide early capital and strengthen financial discipline.

Integrated ventures and vertical integration models enhance bankability through captive supply or offtake arrangements. Together, partnerships can help transform fragmented initiatives into coordinated value chains to align development timelines and incentives.

Contracting

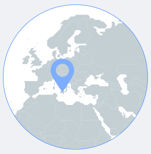
Innovative contracting mechanisms improve project bankability by improving revenue certainty and distributing risk across the value chain. Tools such as advanced market commitments, take-or-pay agreements, tolling structures and back-to-back offtake contracts create predictable cash flows through long-term purchase obligations, minimum payment guarantees, shared risks and/or reduced exposure to commodity price swings.

These arrangements are increasingly being adapted from other infrastructure sectors to clean fuels, giving developers and investors clearer visibility of future revenues and counterparty performance, essential to moving projects from feasibility to final investment decision.

Financing

New financing instruments are also mobilizing private capital for clean fuel deployment by aligning returns with sustainability outcomes and mitigating delivery risk. Green and sustainability-linked loans, transition bonds and innovative approaches to reduce risk by bringing onboard different types of investment capital are proving effective to change return profiles of projects and reduce capital cost. Similarly, mezzanine capital, credit guarantees and insurance products help de-risk construction and technology scale-up.

By improving capital efficiency and protecting lenders and equity holders against early-stage volatility, these mechanisms are helping unlock first-of-a-kind clean fuel projects and demonstrate commercial viability.



CASE STUDY 7

Enilive Gela biorefinery (Sicily)

Description

The Gela Biorefinery by Enilive (an Eni company) transformed a former petrochemical site into one of Europe's most advanced biorefineries, producing HVO, bio-LPG, bio-naphtha and SAF using proprietary Ecofining™ technology. In 2025, Gela became Italy's first SAF production site with a capacity of 400,000 tonnes per year – around one-third of projected European demand – aligning with EU decarbonization goals.

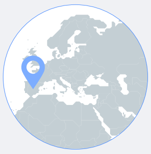
Solutions

- **Upstream partnerships and vertical integration:** Strategic collaboration with Italian UCO aggregators for domestic feedstock supply; development of international agri-hubs (e.g. Makueni, Kenya) for non-food oils, creating a diversified, secure and traceable feedstock supply.
- **Technology partnership:** Co-development of Ecofining™ technology with Honeywell UOP, compatible with retrofitted plant, for flexible biofuel production from multiple feedstocks.
- **Offtake contracts:** De-risked revenues to increase bankability by leveraging Enilive's retail stations and B2B channels, securing offtake contracts with logistics companies (Lannutti and Spinelli) and airlines.

Impact

- ~750,000 tonnes/yr feedstock processing capacity (>95% wastes/residues); ~400,000 tonnes/yr SAF capacity.
- ~1,080 jobs (94% local).
- Supply chain resilience via integrated agri-hubs and "zero-km" local UCO sourcing.
- Brownfield conversion cuts capex, timelines and permitting versus greenfield.

Source: Eni.[64]



CASE STUDY 8

Repsol Ecoplanta waste-to-methanol (Spain)

Description

First-of-a-kind waste-to-methanol plant which will convert non-recyclable municipal solid waste (MSW) into renewable and circular methanol. Strategically located in Repsol's industrial complex, it has synergies with other facilities and has access to the nearby port of Tarragona via pipeline. A key challenge is overcoming novel technology risks, inherent higher costs and effectively aggregating feedstock at sufficient scale.

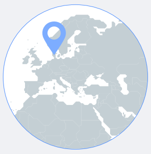
Solutions

- **Waste valorization:** Competitive alternative for waste managers that will avoid higher disposal costs of non-recyclable material in landfill.
- **Business case optimization:** Synergies with existing industrial complex leveraged to reduce capex.
- **Technology de-risking:** Partnership with Enerkem (technology provider) to ensure satisfaction on product yields, quality and cost.
- **Product optionality:** Biomethanol can be used directly in maritime sectors and, following additional processing, in road and aviation sectors; circular methanol can be used in the chemicals sector. Optionality helps de-risk and allows Repsol to flexibly target offtakers in sectors with highest willingness to pay.

Impact

- 400,000 tonnes/yr MSW processing capacity; 240,000 tonnes/yr renewable methanol capacity.
- FID approved in 2025 (>€800 million capex); COD in 2029.
- 340 direct and indirect jobs during operations and ~2,800 jobs during construction.
- 3.4 million tonnes CO_2e of emissions reductions over the first 10 years of operations.

Source: Repsol.[65]



CASE STUDY 9

European Energy and Mitsui Kassø e-methanol facility (Denmark)

Description

First-of-a-kind commercial-scale e-methanol plant developed by European Energy and Mitsui. The plant is strategically located adjacent to Europe's largest solar park (304 MW), allowing direct supply of renewable power to its electrolysers to produce green hydrogen, which is then synthesized with captured CO_2 to make e-methanol.

Solutions

- **Technology integration and power price arbitrage:** Integrates solar power, electrolysis, CCUS and methanol synthesis, producing e-methanol only when power prices fall below a set threshold to maximize profitability.
- **Cross-sector offtake contracts:** Revenues de-risked through offtake contracts signed with Maersk (maritime), The LEGO Group (plastics) and Novo Nordisk (pharmaceuticals). Ability to sell across sectors provides optionality and reduces risk.

Impact

- 304 MW solar power capacity; ~42,000 tonnes/yr e-methanol production capacity.
- Up to 97% reduction in CO_2 emissions compared to fossil methanol.

Sources: Mitsui & Co, European Energy.[66]

CASE STUDY 10

Be8 Passo Fundo ethanol plant (Brazil)

Description

Brazil's first large-scale cereal-based ethanol plant, marking a shift from traditional sugarcane and corn-based models. In addition to ethanol, the facility will supply products for food markets and integrate biomass-based co-generation, to achieve self-sufficient electricity production, with surplus energy supplied to the municipal grid.

Solutions

- **Feedstock optimization:** Leveraging locally abundant cereal feedstocks to build local, resilient supply chains.
- **Multi-product integration:** Process yields high-value products for multiple industries: ethanol (clean fuel), vital gluten (human food) and bran (animal food) to diversify revenue streams, de-risk and increase profitability.

Impact

- 220 million litres of ethanol production capacity.
- Reached FID in 2024 with R$729.7 million investment (via BNDES financing); targeting operations in 2026.
- >800 jobs created during construction, giving preference to local labour and ~175 during plant operation.

Source: Be8 Energy.[67]

CASE STUDY 11

Yara's renewable hydrogen plant (Porsgrunn, Norway)

Description

Yara Clean Ammonia's green hydrogen plant for ammonia production is Europe's largest operational facility of its kind. It shows how clean fuels can act as platform molecules supporting multiple use cases, both towards fuel and indispensable use as chemical feedstock in fertilizer production.

Solutions

– **Infrastructure integration:** New electrolytic hydrogen facility integrated with existing ammonia plant and surrounding infrastructure to improve profitability and accelerate deployment.

– **Product optionality:** Both the electrolytic hydrogen and clean ammonia can be marketed to offtakers across multiple industries, including shipping, fertilizers and power generation, depending on willingness to pay, reducing revenue risk.

Impact

– Commenced operations in 2024.

– 20,000 tonnes per annum clean ammonia production capacity.

– 41,000 tonnes of CO_2 reduction potential per year.

Source: Yara.[68]

CASE STUDY 12

Infinium Project Roadrunner (Texas, US)

Description

Commercial-scale e-fuels plant producing e-SAF, e-diesel and e-naphtha. The project represents one of the first integrated efforts in the US to combine renewable power, captured CO_2 and advanced electrolysis for commercial e-fuel production.

Solutions

– **Value chain coordination:** Integration across power, hydrogen, CO_2 and offtake partners to de-risk a nascent e-fuels market.

– **Financing structure:** Combination of equity financing from Brookfield Asset Management and Breakthrough Energy Catalyst, plus debt financing from HSBC under a project-based credit arrangement.

– **Power and technology partnerships:** 150 MW of new wind power secured via PPA with NextEra Energy Resources; 100 MW proton exchange membrane electrolysers supplied by Electric Hydrogen;[69] CO_2 feedstock from Kinetik Holdings; fabrication partnership with Titan Production Equipment.

– **Offtake certainty:** 10-year e-SAF supply agreements signed with American Airlines and International Airlines Group (IAG) to support bankability.

– **Cross-sector product optionality:** e-SAF for aviation, e-diesel for maritime and heavy-duty transport, and e-naphtha for low-carbon plastics.

Impact

– Over $275 million in equity investment secured, with additional debt financing committed.

– 23,000 tonnes per annum combined nameplate capacity of e-SAF, e-diesel and e-naphtha.

– FID in 2025; commissioning expected in 2027 (currently under construction).

– Creation of hundreds of skilled jobs in West Texas during construction and operations.

Sources: Energy Impact Partners, Infinium.[70]

CASE STUDY 13

1PointFive (a subsidiary of Oxy) STRATOS Project (Texas, US)

Description

Large-scale direct air capture (DAC) project developed by 1PointFive, a subsidiary of Occidental (Oxy). DAC is a form of carbon capture technology that pulls carbon dioxide (CO_2) directly from the atmosphere, offering a flexible way to decarbonize by decoupling the emission source from the point of capture. The captured atmospheric CO_2 can be securely stored underground to deliver carbon dioxide removal (CDR) or used to create low-carbon products, such as fuels. Low-carbon fuel pathways could include storing the CO_2 during the enhanced oil recovery (EOR) process, which repressurizes depleted oil reservoirs to optimize recovery, or using the CO_2 as a feedstock to produce synthetic transportation fuels, such as sustainable aviation fuels. Most existing STRATOS offtake agreements are for CDR credits to be delivered through saline sequestration.

Solutions

- **Strategic site selection:** Co-located with existing CO_2 pipeline infrastructure and high-quality subsurface formations suitable for sequestration, optimizing integration with transport, storage and utilization pathways while reducing capital requirements and accelerating deployment.
- **Market building:** Offtake agreements representing more than 1 million tonnes of carbon dioxide exist today for STRATOS, demonstrating important demand signals for low-carbon solutions. Public demonstration of DAC advantages and integrity helps establish carbon removal market to de-risk investments for financiers.
- **Regulatory foresight:** Early engagement and permitting to align operations with regulatory milestones and avoid costly delays.
- **Product optionality:** Captured CO_2 can be stored to generate carbon dioxide removal credits, used through a carbon capture and storage-enhanced oil recovery pathway to produce lower-carbon fossil fuels, or used for e-fuel production.

Impact

- $1.3 billion of capital investment.
- Scaling-up verifiable, cost-effective decarbonization solutions to support hard-to-abate industries, such as aviation, while leveraging existing infrastructure and value chains.
- 500,000 tonnes per annum CO_2 capture potential when fully operational.
- >1,000 jobs created during construction phase and ~120 direct jobs during operational phase.

Sources: Occidental Petroleum, 1PointFive.[71]

Call to action

Clean fuels present a high-growth market opportunity. For businesses to realize it, coordinated action across policy, finance and value chains will be key to unlocking investment and scale.

Clean fuels are an established and necessary lever for meeting growing energy demand in a sustainable manner. They can reduce GHG emissions in transport and industry, diversify energy supply and create industrial and rural jobs, harnessing resources that are more widely distributed across regions. With sound safeguards and policies ensuring they are produced and used responsibly, clean fuels can be deployed quickly through blends and drop-in use, limiting impact on consumer prices while supply chains and technologies mature to improve economics.

Ambition is rising, but real progress requires more projects to break ground than currently seen. Companies and investors struggle to commit capital due to high risks, compounded by immature value chains, incongruent policies, uncertain demand and complex market dynamics. Overcoming these barriers is not a simple task to solve. It will take policies that lower barriers and well-designed, stable incentives to create predictability for investors. It will take public and private stakeholders to collaborate on mechanisms to pool and share risks. And it will take corporates, including agribusinesses, technology providers, refiners, investors and demand sectors, to adopt innovative and collaborative approaches to de-risk investments.

Examples from real-world case studies give cause for optimism. Despite challenging economics and higher risks, these projects are demonstrating how challenges can be overcome to deliver financial return and societal value.

Regional and global platforms for collaboration can help. The World Economic Forum – through initiatives such as Future of Clean Fuels, First Movers Coalition, Airports of Tomorrow and Transitioning Industrial Clusters – convenes leaders from business, finance and government to collaborate, mobilize demand, share what works – and what doesn't. The Clean Energy Ministerial process and the work of Mission Possible Partnership also catalyse important efforts for multilateral collaboration, particularly between governments and regulatory bodies.

Ultimately, clean fuels represent a significant commercial opportunity and a route towards a more resilient, competitive and low-emissions energy system. Progress requires greater collaboration and transparency among stakeholders throughout the value chain to turn ambition into projects.

To learn more and start collaborating, visit the Forum's Future of Clean Fuels community.

Four areas for collective focus

Collaborate to shape policies for performance and predictability

Policy designs that incentivize competition between pathways to provide the most affordable fuels with the lowest emissions are critical to reward continuous improvement. Collaboration between governments and industrial counterparts can remove barriers and turn societal value into transparent price signals, by focusing on public mechanisms that are durable amid changing political priorities.

Design projects with regional priorities in mind

Solutions will differ by region, making close public-private collaboration essential. Corporate leaders can engage local and regional policy-makers early in the project development stage to ensure investments support regional priorities, strengthen project viability, build local support and secure incentives or risk-sharing mechanisms that sustain investment over time.

Build partnerships across the value chain

Few companies will have the capabilities to effectively develop projects alone. Value chain leaders can proactively form strategic partnerships and adopt models where they are willing to share risk and rewards. This requires a different, customer-orientated mindset that shapes value propositions rather than traditional commodity market-type approaches.

Engage financiers early and adopt new investment models

Early collaboration with financiers is key to de-risk and structure projects for bankability. Leading companies and investors are reducing risk in creative ways, such as seeking non-traditional funding sources and mechanisms to reduce financing costs and considering future upside potential versus alternative investments in capital allocation processes.

Appendix

Note on Figure 3

Greenhouse gas emission reduction potential by 2050 is estimated based on uptake of clean fuels as a share of total final energy consumption under mid-range energy transition scenarios, and assumed weighted average emission reduction potential of 60 to 80% compared to conventional fuel intensity, evaluated by sector (industry, road transport, shipping and aviation). Sources: see endnote.[8]

Notes on Figures 8 and 9

1. At-scale refers to estimated levelized production costs for nth-of-a-kind plants, at the point when a certain technology or project configuration is considered commercially mature with limited cost improvement potential. In contrast, first-of-a-kind plants are the first commercial deployment of new technology or a certain project configuration.

Levelized production cost (LPC) is a metric that represents the average cost per unit of output over a project's entire lifetime, calculated by dividing the total lifetime costs by the total lifetime production. It is used to compare different production technologies, by aggregating initial investment, operating costs and fuel expenses into a single, comparable unit cost.

COD refers to commercial operation date, the date at which a project becomes fully operational and begins to generate revenue.

2. Clean fuel costs include feedstock supplier margins (for non-integrated plants) but exclude producer margins.

3. Fossil-fuel comparators include Jet A, diesel/gasoline, natural gas and bunker fuel, based on observed 2024 pre-tax wholesale prices. Sources: World Bank Commodities Price Data (The Pink Sheet), US Energy Information Administration (EIA) – Petroleum & Other Liquids and the European Commission's Weekly Oil Bulletin.[72]

4. Clean-fuel cost ranges reflect regional variations in feedstock and operating conditions. Examples:

– HEFA SAF and renewable diesel (low: China sunflower oil; high: Europe advanced oil crops)

– FAME biodiesel (low: China sunflower oil; high: China palm fruit)

– Bioethanol (low: US corn; high: Europe corn)

– Biomethane (low: Middle East biowaste; high: Asia biowaste)

– E-fuels, such as e-SAF, e-methanol, e-ammonia, e-methane, green H_2 and blue ammonia (low: Middle East; high: Europe)

– Alcohol-to-jet and gasification/Fischer-Tropsch (low: US corn; high: Europe agricultural and wood residues)

– Biomethanol (low: municipal solid waste; high: Middle East biowaste)

5. Forecasts are from Bain & Company analysis using feedstock price forecasts from Euromonitor and proprietary cost and technology data from Bain & Company, supplemented by 2024 and 2025 Future of Clean Fuels community workshops and industry interviews.[73]

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Endnotes

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