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19 November 2025

Biofueling Transport

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Biofuels Overview: Opportunity

Key messages
Biofuels Overview: Opportunity

Biofuels are an essential in the global journey toward net zero:

- In the 2050 Net Zero scenario, biofuel could lower global emission by up to ~1 GT.
- Demand is growing at ~3% annually, with biofuels acting as a bridge in road transport's shift to EVs. Long-term growth is expected in power, industry, aviation, and maritime.

In transport, biofuel consumption is growing at 4% annually, accounting for about 4% of total energy use in the sector.

- **Bioethanol and biodiesel** account for ~90% of biofuel's share, with hydrotreated vegetable oil (HVO) and sustainable aviation fuel (SAF) taking off as demand grows.
- While **biofuels serve as a bridge** in road transport's move to EVs, **SAF drives growth**, due to the increased blending target set by the European Union, CORSIA,[1] and the WEF CST.[2]

The U.S. is the largest biofuels player, followed by Brazil and the EU, **with a total market size of ~$100 billion and 8% annual growth.** Its market has been driven by significant investments in ethanol and renewable diesel infrastructure.

Drop-in advanced biofuels offer greater abatement potential than conventional biofuels but face challenges such as limited feedstock availability and high CapEx.

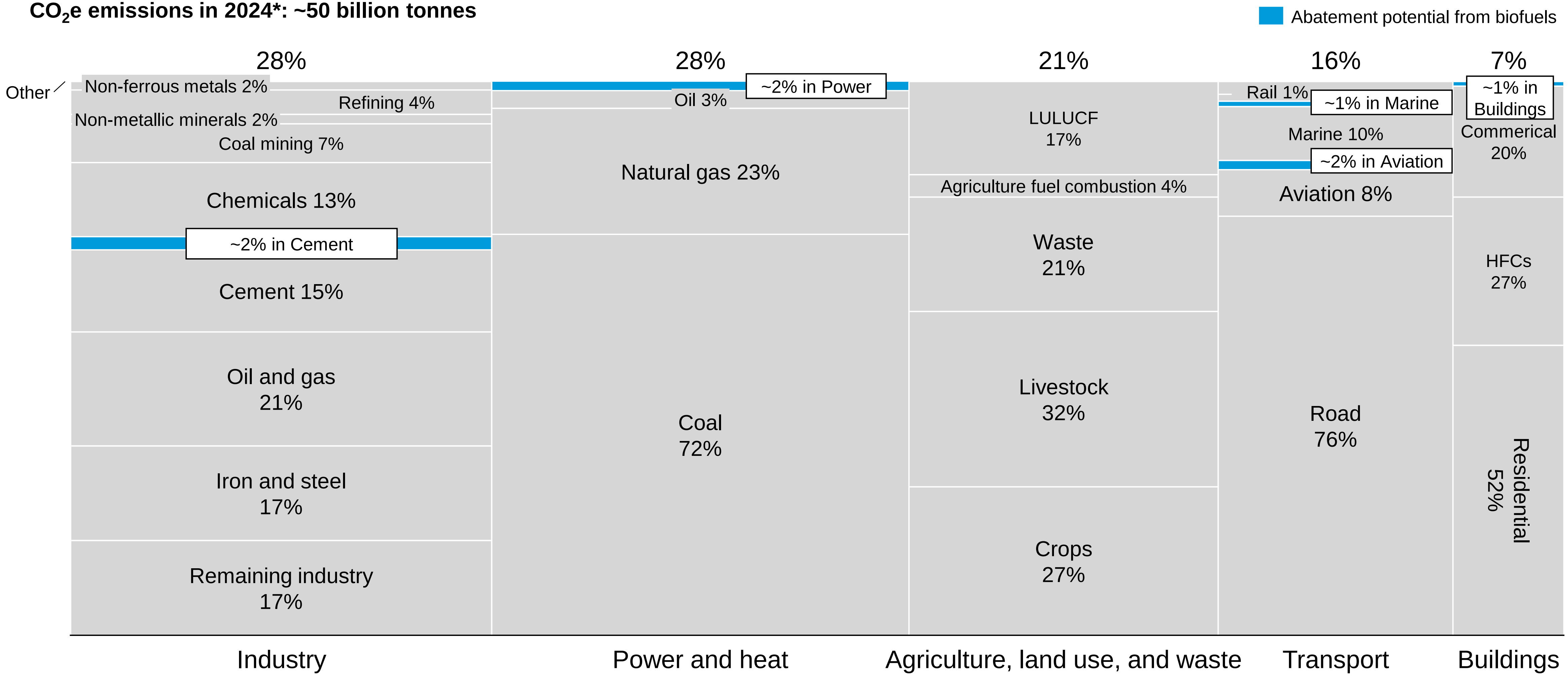
The key levers to accelerate biofuel growth toward net zero are:

- **Technology:** Support R&D to lower CapEx, scale advanced conversion processes, and diversify feedstocks.
- **Policy and regulation:** Ensure long-term policy certainty and internalize carbon costs to enhance cost competitiveness.
- **Finance:** Expand public-private partnerships across the value chain, leveraging green bonds to mobilize investment.

1) Carbon Offsetting and Reduction Scheme for International Aviation, 2) World Economic Forum Clean Skies for Tomorrow, 3) Thousand barrel of oil equivalent per day.
Sources: DOE, Biofuel Basics (2025); EIA, Biofuels Explained (2024); Bhaskar et al., Advances in Thermochemical Conversion of Biomass (2015); Renewal and Sustainable Energy Reviews, Biofuel production (2017).
Credit: Birru Lucha, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

In the 2050 Net Zero scenario, biofuel could lower global emissions by up to ~1 GT

CO_2e emissions in 2024*: ~50 billion tonnes



*2024 emissions based on projections.
Sources: Rhodium Group, The ClimateDeck (2024); BloombergNEF, New Energy Outlook (2025); IRENA, Transport (2025); IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector (2023).
Credit: Birru Lucha, Theo Moers, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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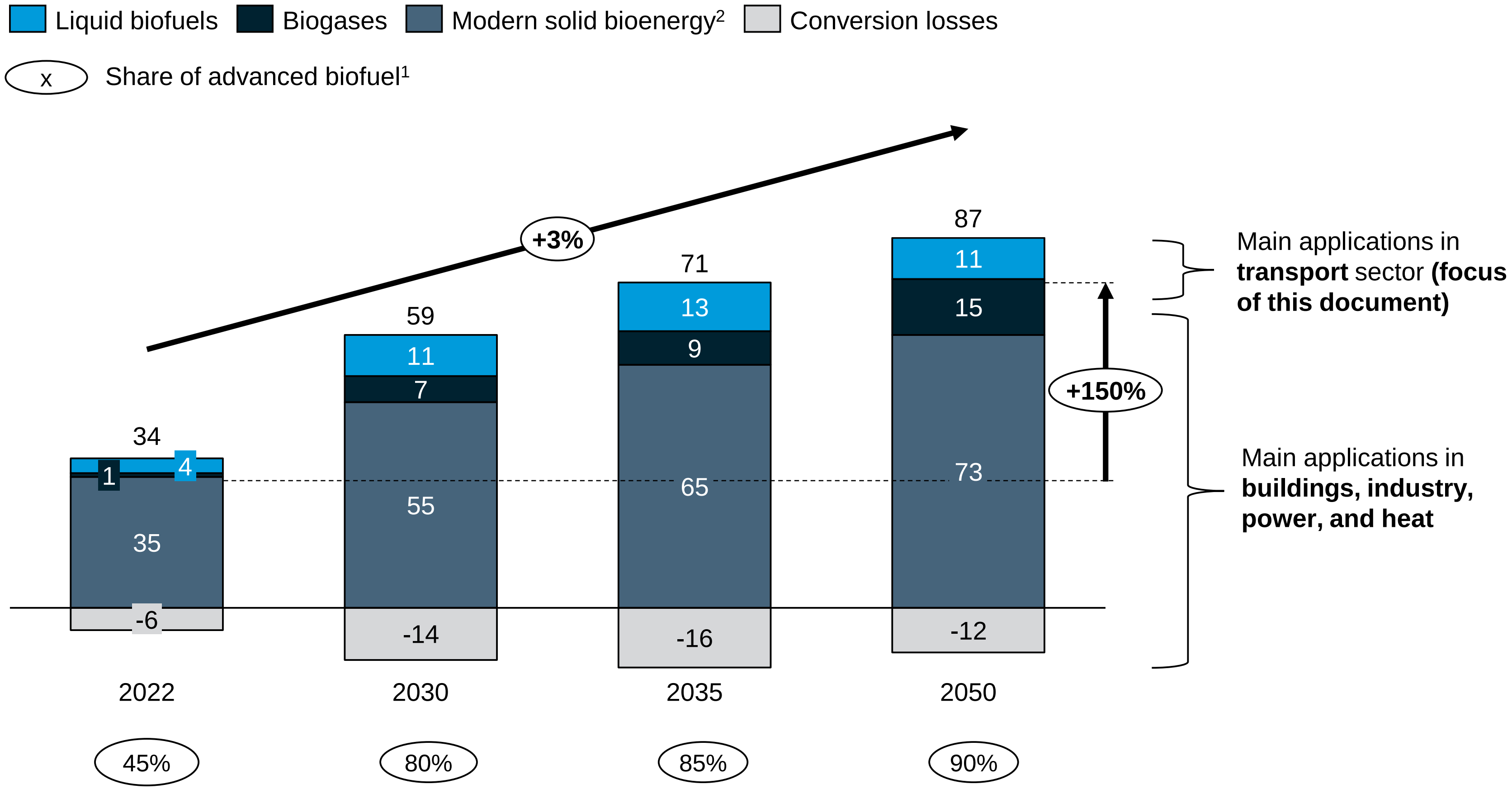
Biofuel supplies are expected to grow up to 2.5x by 2050, with solid bioenergy taking the majority share

Global biofuels supply projection in the Net Zero scenario (excl. traditional biomass), *EJ*



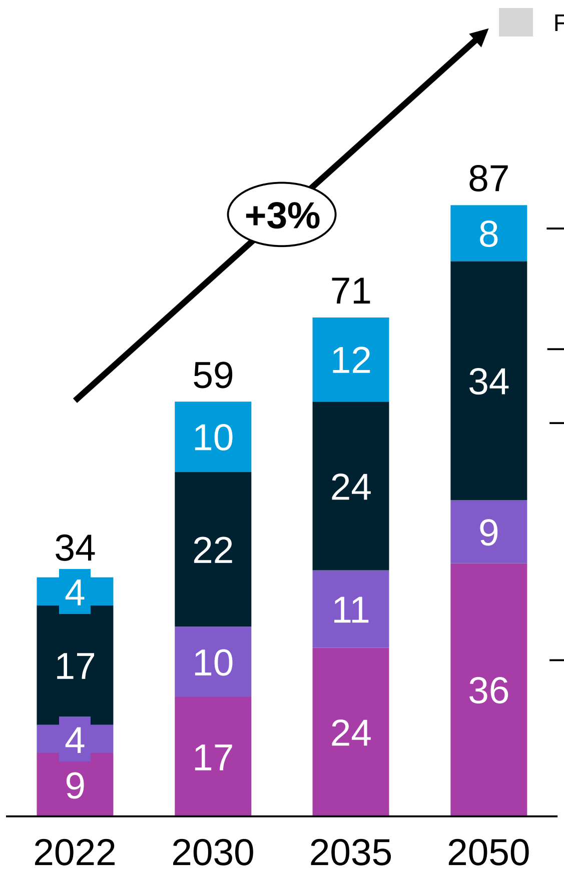
Observations

- **Modern solid bioenergy** holds a major share in biofuel supply, with demand mainly from **industry** (e.g., pulp and paper, sugar and ethanol, and cement industries) using feedstock from onsite waste.
- **Biogas** demand is increasing across sectors, especially in industry, buildings, and power generation.
- **Liquid biofuel** growth is driven by the transport sector, with most future growth expected from aviation and maritime to help achieve net-zero targets.
- **Advanced feedstock supply will grow considerably, to a 90% share in 2050** as advanced conversion technology is developed and commercialized.

1) Advanced biofuels are sustainable fuels produced from non-food crop feedstocks, including HVO, HEFA, alcohol-to-jet, and bio Fischer-Tropsch. 2) Includes charcoal, fuelwood, dung, agricultural residues, wood waste, and other solid biogenic wastes — except the traditional use of biomass.
Sources: IEA, Net Zero Roadmap (2023); IEA, Renewable fuels (2024).
Credit: Augusto Agazzi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Biofuels rapidly expanding in heavy trucking, with long-term growth in power, industry, aviation, and maritime

Global biofuels demand projection in NZE scenario, *EJ*



Transport: Biofuel use will decline post-2035 due to electrification in road transport, especially for passenger cars, though aviation will still have a significant share of biofuels. Shipping will mainly be dominated by ammonia as the primary low-emission fuel uses.

Industry: Solid bioenergy-based[1] fuels will replace fossil fuels (fuel oil and natural gas) to run high-temperature processing units.

Buildings: Will mainly use biomethane and modern solid bioenergy-based fuel.[1]

Note: Buildings' demand for biofuel excludes traditional biomass.

Power: The share of bioenergy to power sector for biomethane and modern solid bioenergy will increase.[1] Countries with the biggest bioenergy-based power generation are **Brazil, China, the U.S., and Canada.**

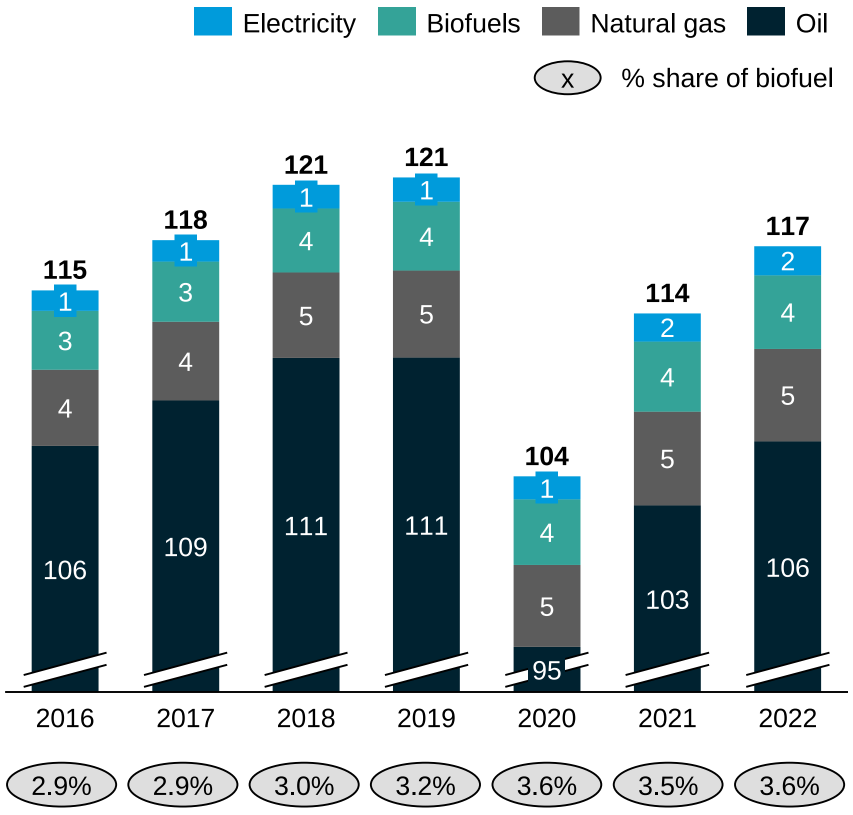
Observations

- **Power generation will account for a major share of biofuel production toward net-zero emissions, mainly from biomethane and advanced fuels from biomass feedstock**, which will comprise ~60% of total bioenergy.
- **Hard to abate industries (e.g., cement) will gradually shift to bioenergy**, in addition to increasing efficiency and expanding electrification and carbon capture efforts.
- **Transport: Biofuel growth** in the transport sector is significantly **influenced by the expansion of electric vehicles** in road transport and the **cost competitiveness of hydrogen.**
  - **Road transport:** Biofuels remain the dominant pathway for avoiding oil demand in the diesel segments. EVs outpace biofuels in the gasoline segment, leading to the potential decline of biofuel post-2035.
  - **Aviation:** Biofuel and hydrogen-based (synfuel) sustainable aviation fuel will have the majority share. Synfuel share is expected to pick up by 2035, as the technology is maturing.
  - **Shipping:** Biodiesel currently holds a small share in the bunker market but is expected to reach ~20% by 2050, with hydrogen and ammonia accounting for the remainder.

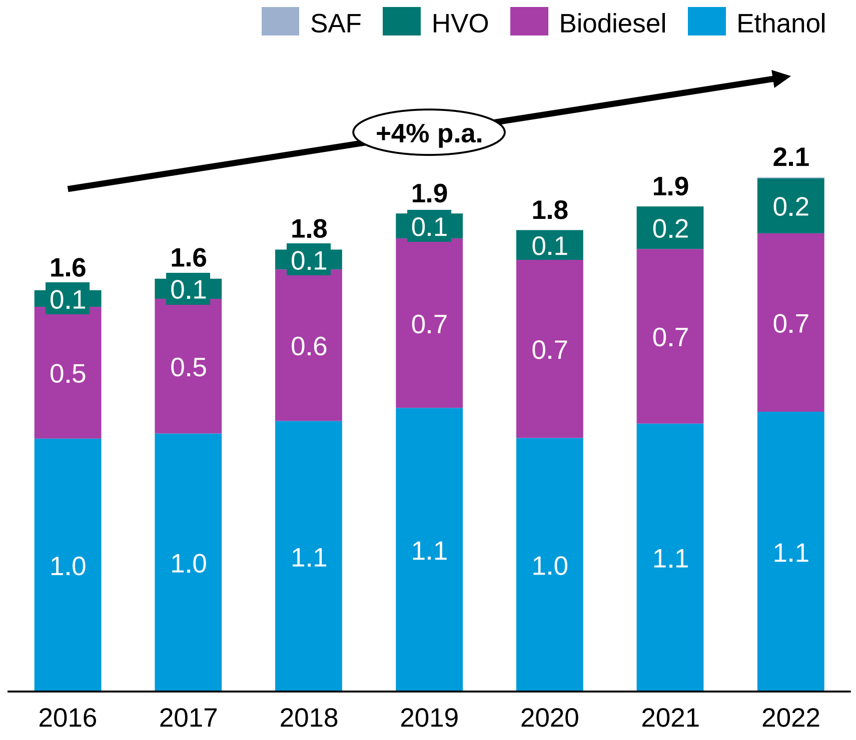
1) Includes charcoal, fuelwood, dung, agricultural residues, wood waste, and other solid biogenic wastes — except the traditional use of biomass.
Sources: IEA, Net Zero Roadmap (2023); IEA, Transport biofuels (2023); Boston University, What Countries Have the Greatest Bioenergy Power Capacity? (2023).
Credit: Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

In transport sector, biofuel consumption accounts for ~4% of global energy consumption, with 4% growth annually

Global energy consumption in transport, by fuel, *EJ*



Global biofuel consumption by type, *'000 Mboed*[1]



Observations

- **Global share of biofuel** consumption in transport sector **is still marginal** with no significant annual increase.
- Biofuel production still **focuses on bioethanol and biodiesel**, with an average 3% p.a. volume growth from 2016 to 2022.

Note: Total may not sum exactly due to rounding
1) Million barrels of oil equivalent per day.
Sources: IEA, Transport (2023); IEA, Biofuels (2023); IEA, Global biofuel demand, historical, main and accelerated case, 2016-2028 (2023).
Credit: Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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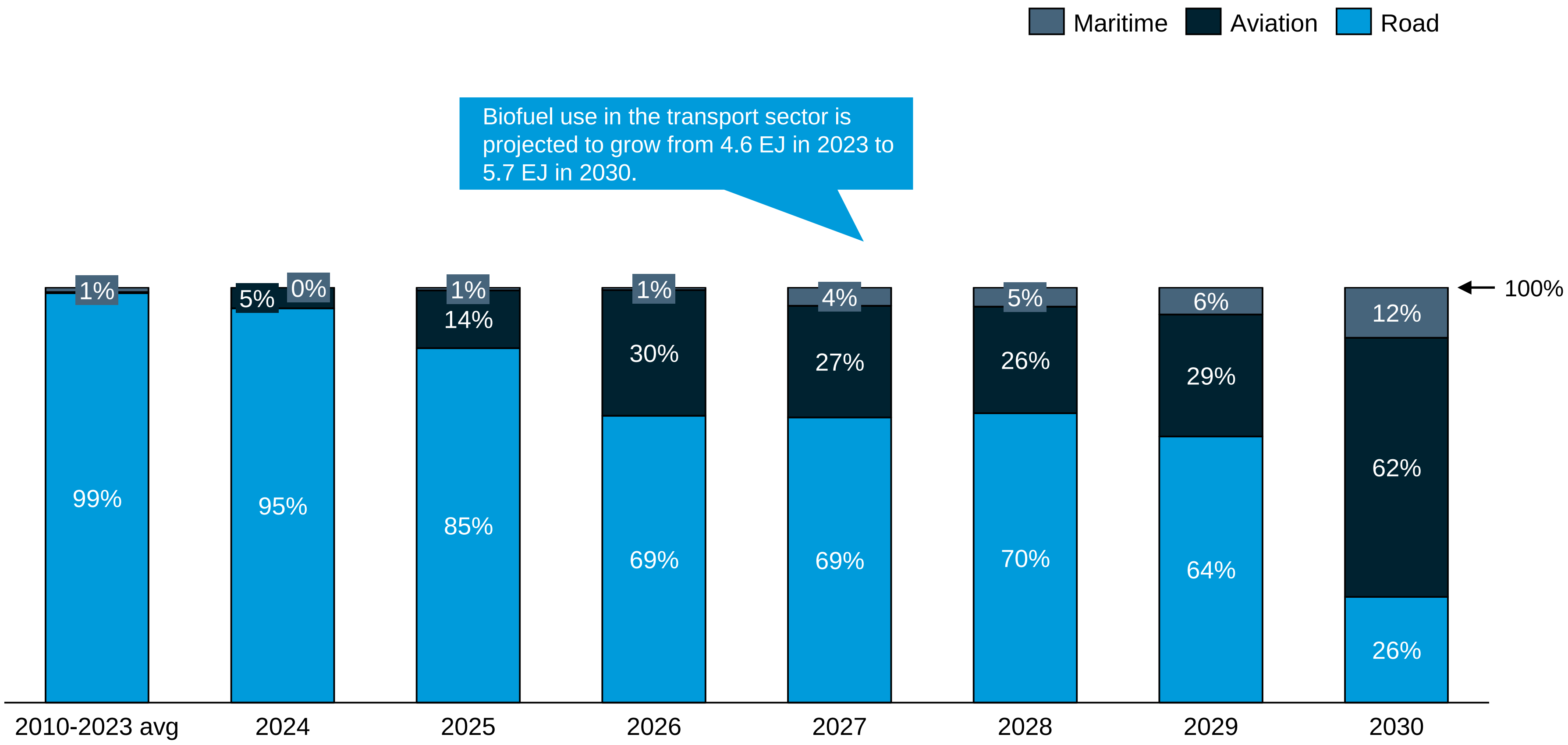
Biofuels' share in road transport will decline as EV adoption rises, while SAF drives growth

Share of liquid biofuels across transport sector, *%*



Observations

- **The declining share of liquid biofuel in road transport is driven by improved efficiency and EV adoption**, with the EU and U.S. seeing a peak before 2030.
- **Sustainable aviation fuel consumption has started to materialize in 2022**, with significant expansion anticipated from increased blending targets set by the EU, CORSIA,[1] and WEF CST.[2]
- In **shipping, biodiesel demand is growing as a short- and medium-term solution**, while other low-carbon fuels are progressing (e.g., hydrogen/ ammonia).

1) Carbon Offsetting and Reduction Scheme for International Aviation. 2) World Economic Forum Clean Skies for Tomorrow. 3) Thousand barrel of oil equivalent per day.
Source: IEA, Renewable fuels (2024).
Credit: Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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Across transport, biofuels will fill in where batteries cannot; key focus will likely be in long-haul aviation and shipping

■ Future potentials
✓ Projected long-term winner

		Biofuel	Hydrogen	E-fuel	BEV	Ammonia[1]	Observations
Road transport	Passenger vehicles	■			■ ✓		Passenger vehicles will favor **battery electric vehicles due to lower GHG emissions, rapid tech advancements, and higher economic scale** than biofuel.
	Heavy vehicles	■	■	■	■ ✓		Heavy vehicles require **higher energy density,** which can be attained only via biofuel and hydrogen.
Aviation	Short to medium haul (<7 hours)	■	■ ✓	■	■ ✓		For the short haul, **battery electric vehicle (BEV) and hydrogen could play a role** but require time to commercialize.
	Long haul (>7 hours)	■ ✓	■	■ ✓			**Higher energy density is required for long-haul flights**, making biofuels the only viable option in the market and e-fuel (PtL) the option for longer term.
Maritime	Short sea	■	■	■	■ ✓	■	**BEV will play a role for frequent routes / short distances**. **Biofuels lack competitiveness from feedstock constraints** and long-term cost-effective alternatives such as Ammonia.
	Deep sea (intercontinental routes)	■ ✓	■	■		■ ✓	**Ammonia will play a major role** for longer distances, while the remaining share is uncertain.

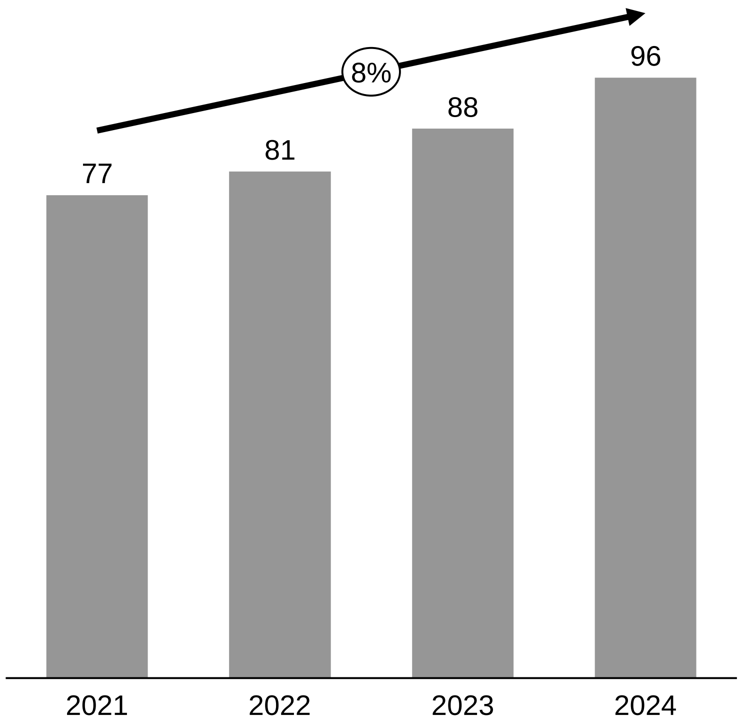
1) Derivative of hydrogen, expected to become cost-effective maritime option long-term from scale

Source: IEA, Net Zero Roadmap (2023). IEA, Lowering Hinders for Maritime Biofuels (2025)

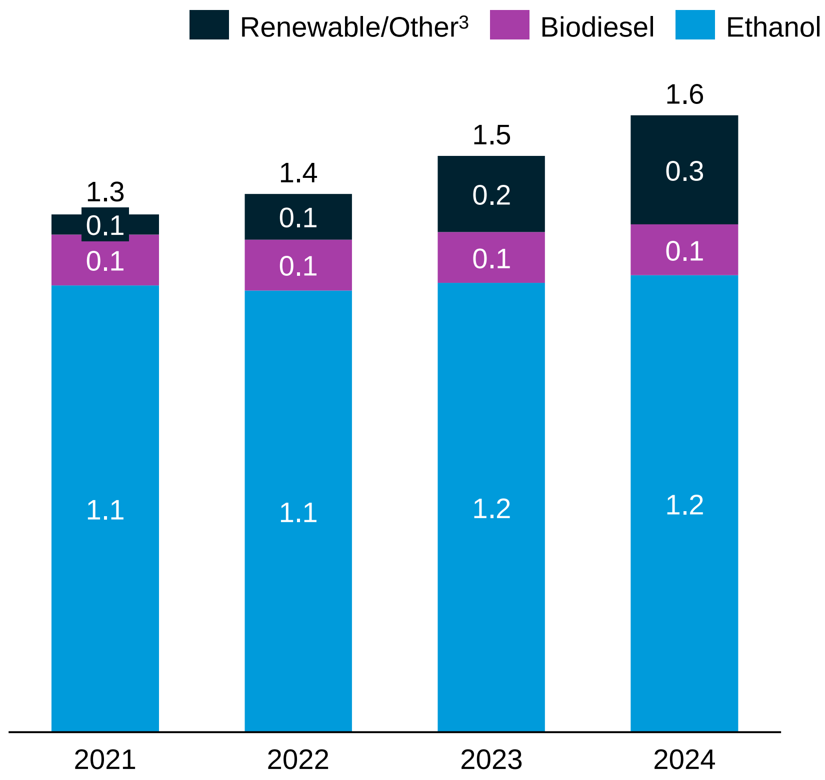
Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

The U.S. biofuel market has grown ~8% annually, primarily driven by increased production of renewable and other biofuels

U.S. retail biofuel market size[1], *$B*



U.S. biofuel production capacity, *'000 Mboed*[2]



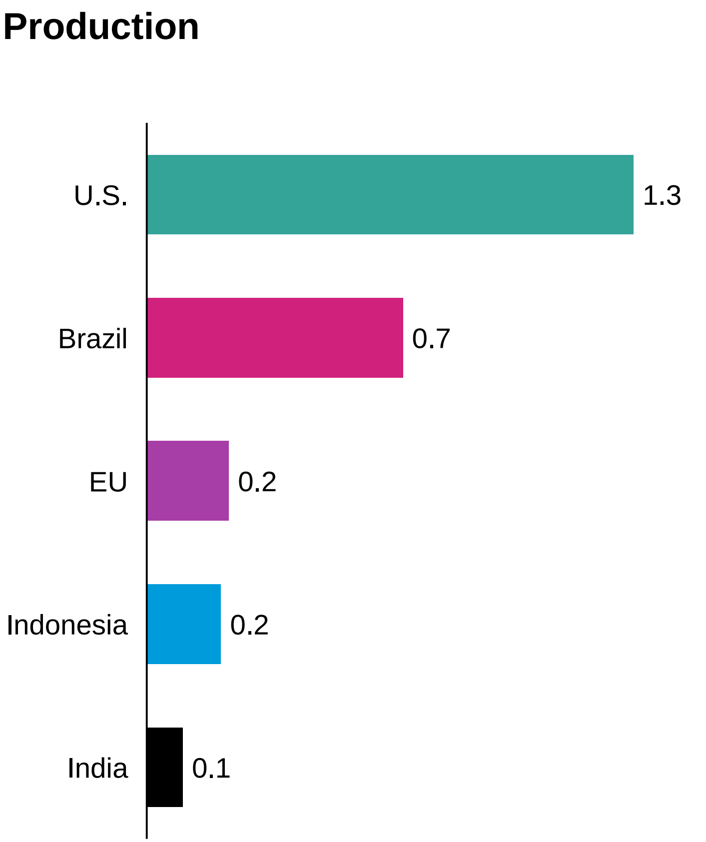
Observations

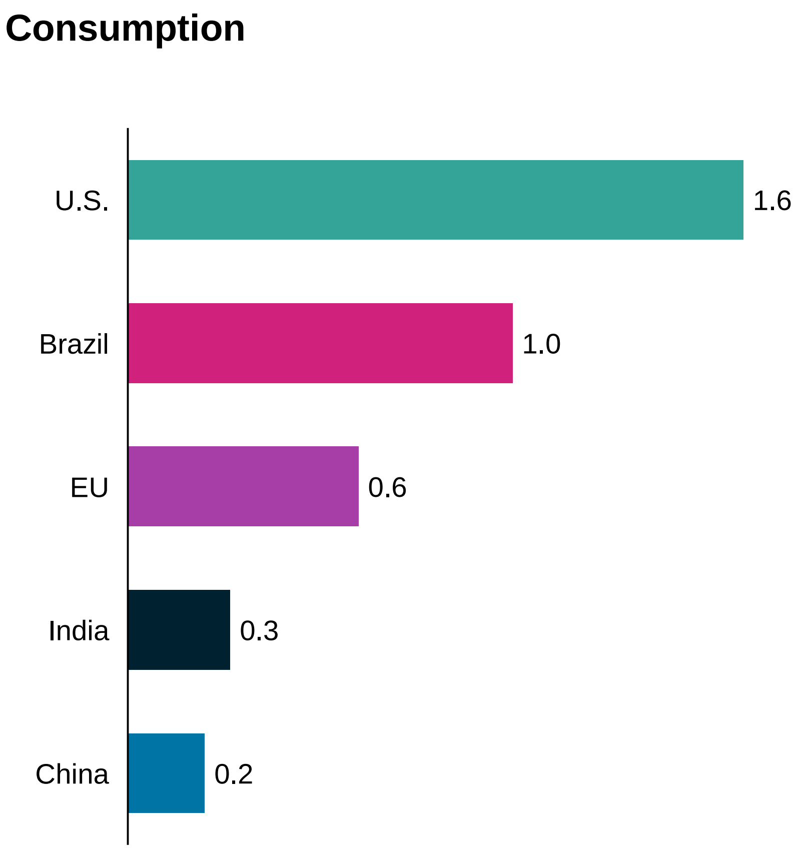
- **Renewable/other:** Production capacity shows a **sharp increase (2020-24 CAGR: ~80%).** A strong policy tailwind and positive demand outlook likely supported the growth (e.g., blenders tax credit).
- **Biodiesel:** Production capacity has **decreased (2020-24 CAGR: -4.5%).** Many biodiesel plants are being converted to produce advanced biofuels (SAF) or renewable diesel, which offer better policy incentives and economics.
- **Ethanol:** Production capacity has stayed relatively flat (2020-24 CAGR: 0.90%) but still accounts for the largest portion of the total biofuel market.

Note: Total may not sum exactly due to rounding.
1) Market size was calculated using retail product prices of mixed fuels (without the consideration of percentage biofuels); pure biofuel market size to be lower than the suggested figures.
2) Million barrels of oil equivalent per day.
3) Renewable/Other refers to renewable fuels (e.g., HVO, HEFA, etc.), excluding fuel ethanol and biodiesel.
Sources: EIA, U.S. Fuel Ethanol Plant Production Capacity (2024); EIA, U.S. Biodiesel Plant Production Capacity (2024); EIA, U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity (2024).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

U.S. is the largest producer and consumer of biofuels, followed by Brazil and the European Union

Biofuels production and consumption by top 5 countries globally, *Mboed*[1]





Observations

- **U.S.: Largest producer** and **consumer of biofuels**, with significant investments in ethanol and renewable diesel infrastructure.
- **Brazil:** Pioneer in ethanol use, with high blending ratios and a mature biofuel market.
- **EU:** Focused on biodiesel production and consumption, with strong sustainability criteria.
- **Indonesia:** Aggressively expanding biodiesel mandates, aiming for B40 (40% biodiesel blend).
- **India:** Accelerating ethanol blending programs, targeting E20 (20% ethanol blend) by 2025.
- **China:** Exploring alternative markets for biodiesel due to recent EU tariffs, with a shift toward marine fuels and sustainable aviation fuel.

1) Million barrels of oil equivalent per day.
Source: REN21, Renewables 2024 Global Status Report Collection (2024).
Credit: Augusto Agazzi, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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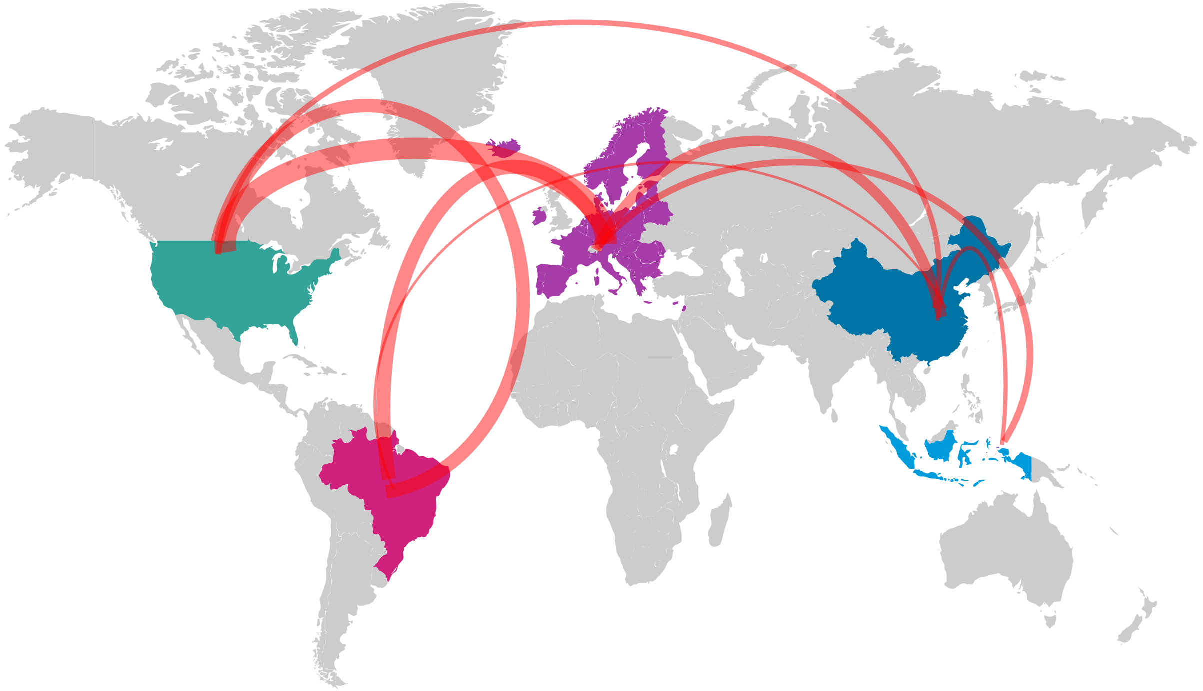
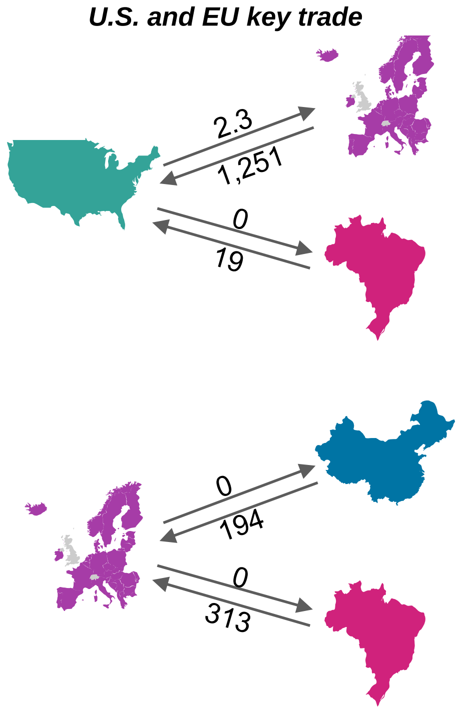
U.S. and EU are expected to become net importers of biofuel feedstock through 2050

Biofuels trade map, 2025 (U.S., EU, Brazil, China, Indonesia), *$M*





Observations

- The U.S. and EU are expected to become **net importers** of feedstocks and potentially finished products given increasingly high mandates in their policy.
- Developing countries such as China, India, SEA, and Brazil will continue to become **net exporters** of raw feedstocks.
  - However, increasing domestic consumption can hamper supply from exporting countries (e.g., Indonesia has an export cap of CPO to ensure domestic supply).
- Africa has the **potential to emerge as a feedstock supplier.**
  - Northern Africa has an abundance of Gen 1 and Gen 2 crops (e.g., sugar crops, oilseed crops).

Source: UN, Trade Map (2025).
Credit: Augusto Agazzi, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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Biofuels are categorized based on feedstock

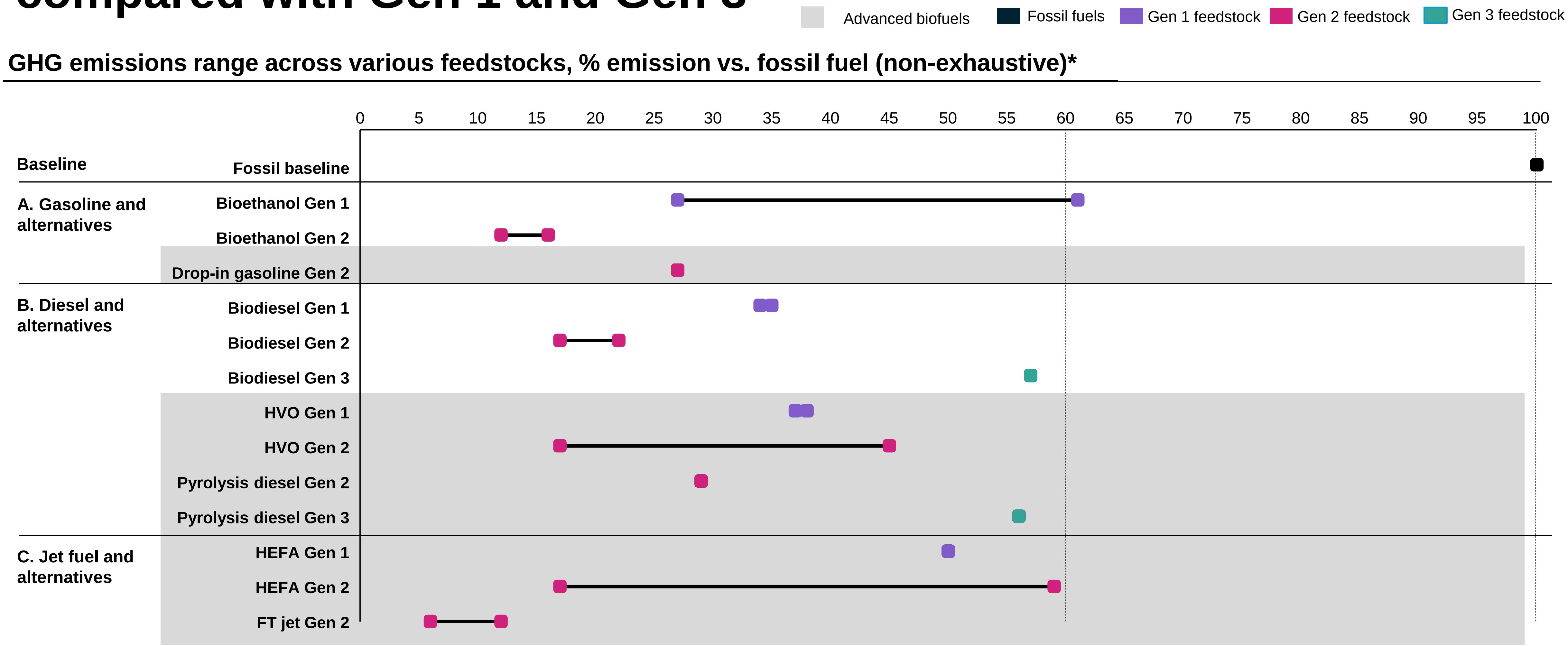
Focus of deck (Generation 1 and Generation 2)

Biofuel type	Generation 1	Generation 2	Generation 3	Generation 4
Feedstock	• **Sugar-based crops:** Corn, sugarcane, sugar beets, wheat, barley • **Oil-based crops:** Soy, oilseed rape, jatropha, palm and other vegetable oils	• **Lignocellulosic waste materials:** Corn and wheat straw, sugarcane bagasse, sugar beet pulp, cassava peels, switchgrass (hard and soft wood) • **Other non-food yields:** Forest waste, food crop waste, used cooking oils, industrial and municipal waste	• **Microalgal biomass:** Various forms of cultivation, including open pond, hybrid system, closed modular photobioreactor, heterotrophic fermentation, and integrated cultivation	• **Microorganisms:** Enhancing metabolic processes and carbon capture capacity of feedstocks, leveraging techniques like microengineering and carbon capture and storage
Products	• Biodiesel, and ethanol	• Biodiesel, ethanol, biogas, drop-in fuels, and mixed alcohol	• Biodiesel, ethanol, biogas, drop-in fuels, and mixed alcohol	• Biodiesel, ethanol, and drop-in fuels
Advantages	• **Enhances energy security** locally • Reduces CO2 marginally **depending on crop** utilized	• Removes problematic **food vs. fuel competition** • Increases **land efficiency, reduces waste**, and puts less pressure on biodiversity	• Produces a wide range of outputs and generates **10x as much** as traditional feedstock • **Easily cultivated**, has low land usage, and can grow on marginal land • **Absorbs large amounts of CO2** during growth	• Produces fuels with **significantly lower carbon intensity**, reducing greenhouse gas emissions • Generates **higher yielding organisms** through genetic modification
Disadvantages	• **Competes with local food production** (environmental and economic consequences) • Most products (except drop-in fuels) **require blending with fossil fuel**, limiting emission reduction impact	• Requires **energy-intensive processes** • On-net **could increase energy use** based on lifecycle analysis, making it generally not competitive vs. fossil fuel	• Requires **many resources** (water, nitrogen, phosphorous) to grow • Produces **less-stable biofuels** (highly unsaturated)	• Requires **a capital-intensive process** and **significant further research** • Sparks **ethical debates** on utilizing genetic engineering for energy and agriculture
Feedstock scalability	• Highly scalable	• Limited (vs. Gen 1) and fragmented based on geography, but solid commercial footing	• Limited, still at the early-stage commercial scale	• Significantly limited, exists mostly on research scale

1) Fatty acid methyl esters. 2) Liquid bio-hydrocarbons that are functionally equivalent to petroleum fuels and fully compatible with existing petroleum infrastructure.
Sources: Molecules, Second-Generation Biomass as Feedstock for Bioethanol Production (2024); ScienceDirect, Biofuels (2024); NRDC, Cultivating Clean Energy (2009).
Credit: Sean Lee, Birru Lucha, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Gen 2 biofuels have greater emission reduction potential compared with Gen 1 and Gen 3

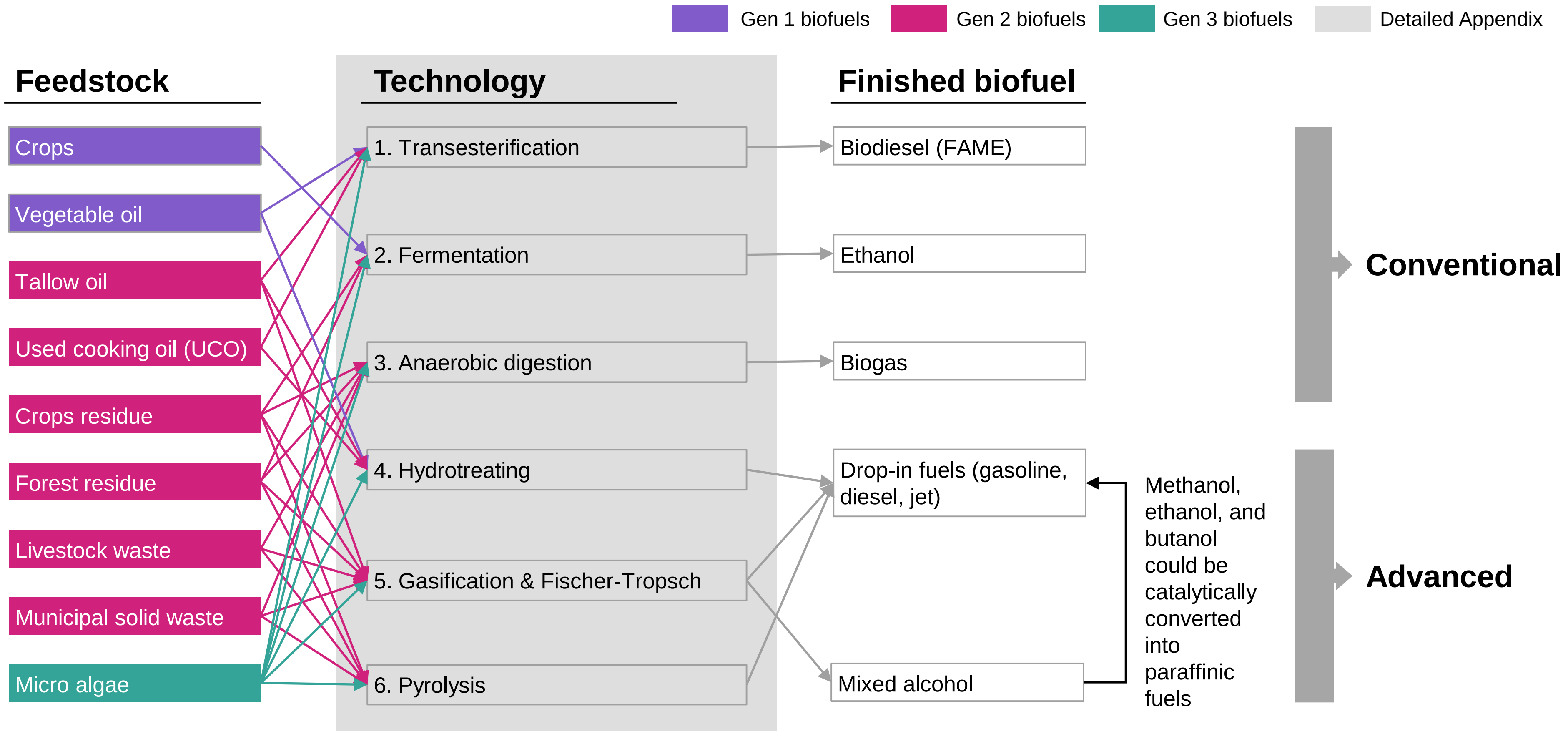
GHG emissions range across various feedstocks, % emission vs. fossil fuel (non-exhaustive)*



*Discrepancies between the high and low ranges can be explained due to specific feedstock used, as shown in the Appendix.
Sources: IEA, Bioenergy (2020); Argonne National Laboratory, GREET WTW calculator (2022).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Conventional biofuels require blending, whereas advanced fuel could be used as direct fossil fuel replacement based on product

Biofuel technology pathways with various feedstock and end products



Observations

- **Conventional biofuel** feedstocks are mainly derived from crops (or their derivatives), but products' usage is **subject to blending limitations.**
- **Advanced biofuels** are mainly produced from Gen 2 and Gen 3 feedstocks; products could be used as **direct replacements of fossil fuel**, compatible with existing engines and fossil fuel infrastructure.

Note: Conventional biofuels refer to Gen 1, crop-based pathways. Advanced biofuels refer here to Gen 2 and Gen 3 pathways produced from waste, residues, or algal feedstocks. Policy definitions of "advanced biofuels" may differ across jurisdictions.

Sources: McKinsey, Sustainable Fuels Outlook (2023); IRENA, Innovation Outlook: Advanced Liquid Biofuel (2016); Frontiers in Energy Research, Conversion of Algal Biomass into Renewable Fuel (2022).

Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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Across various technologies, conventional biofuels are more mature, while advanced biofuels are beginning to scale up

○ R&D/pilot scale ◐ Ready for commercialization ● Mature and commercialized

Biofuel technology comparison across key pathways (non-exhaustive)

	1. Transesterification	2. Fermentation	3. Anaerobic digestion	4. Hydrotreating (HVO & HEFA)	5. Gasification & Fischer-Tropsch	6. Pyrolysis
Technology maturity	●	●	●	●	◐	○
Advantage	Proven technology for Gen 1	Proven technology for Gen 1	Wide range of waste applicable for feedstock	Proven technology for Gen 1 Processing facility could repurpose old refining plant	Wide range of waste applicable for feedstock Proven technology with large-scale plant for fossil feedstock	Wide range of waste applicable for feedstock Bio-oil (output of pyrolysis) can be upgraded through standard refining process
Dis-advantage[1]	Limited feedstock available for Gen 2	Gen 2 processing is more energy-intensive with lower yield (higher OpEx)	Risk to methane and ammonia leakage	Limited feedstock availability for Gen 2 More energy-intensive vs. fossil diesel, higher OpEx	Complex syngas pre-treatment process leads to high CapEx and OpEx Existing fossil feedstock plant is not applicable for biomass feedstock	High CapEx Energy-intensive (high OpEx) Bio-oil has unstable characteristic, is difficult to store and process
Main players	**U.S., EU, Indonesia, and India** (~70% of global capacity)	**U.S. and Brazil** (>80% of global capacity)	**EU** (50% of global production), **U.S., China, and India**	**EU** (Finland, Sweden, France, and Italy)	**EU** (UK, Finland, Germany)	**EU** (Sweden, Norway, Netherlands, Finland, Denmark), **U.S., Canada**

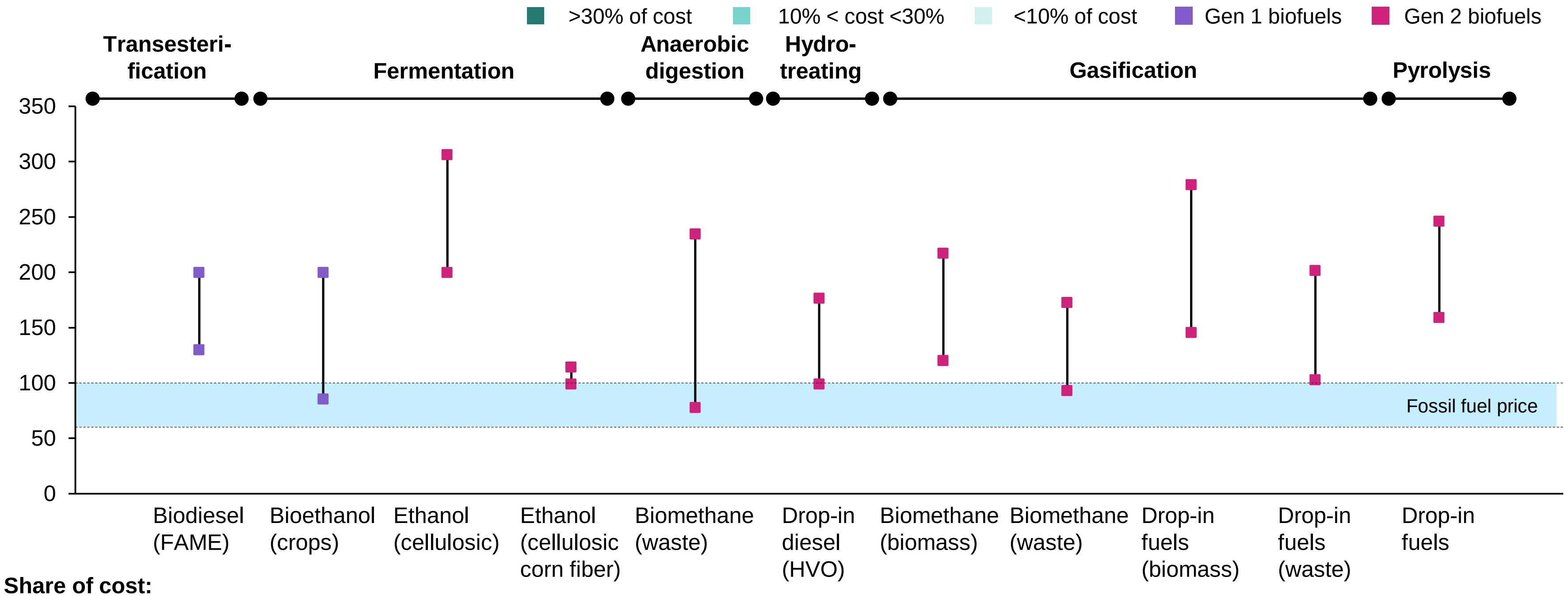
Observations

- **Conventional Gen 1 biofuels dominate,** but **growth is limited.**
- **Expansion in Gen 2 diesel (HVO) is driven by global mandates and EU initiatives** to end support for Gen 1 biodiesel.
- **HEFA plays an important role in fulfilling SAF demand**, hence exponential growth.
- **Gasification (via Fischer-Tropsch) will be commercialized post-2025**, leading to more share of drop-in fuels.

Note: 1) CapEx = capital expenditure, OpEx = operating expenditure. 2) Million barrels of oil equivalent per day.
Sources: Energies Nouvelles, Biofuels Dashboard (2023); World Biogas Association, IEA Forecasts 32% Growth in Coming Years for Biogas Sector (2024); ETIP Bioenergy, Bioenergy BtL via Fischer-Tropsch Synthesis (2021); IEA, Bioenergy installations (2025); IATA, SAF Volumes Growing but Still Missing Opportunities (2023); IEA, Net Zero Roadmap (2023).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Advanced biofuels are still expensive; technology advancement is key to being competitive with conventional biofuel

Cost comparison across biofuels products and technology in 2020 (non-exhaustive), *$/boe*



Share of cost:

	Biodiesel (FAME)	Bioethanol (crops)	Ethanol (cellulosic)	Ethanol (cellulosic corn fiber)	Biomethane (waste)	Drop-in diesel (HVO)	Biomethane (biomass)	Biomethane (waste)	Drop-in fuels (biomass)	Drop-in fuels (waste)	Drop-in fuels
CapEx, %	7%	21%	38-41%	65%	27-63%	6-16%	44-53%	66-90%	51-57%	71-91%	30-46%
Feedstock, %	78%	57%	32%	0%	(-)33-41%	66-78%	24-29%	(-)52-0%	24-35%	(-)47-0%	18-24%
OpEx, %	16%	21%	27-30%	35%	31-70%	16-18%	23-27%	34-63%	14-19%	29-57%	35-46%

Observations

- **Most of the advanced biofuels are CapEx- and energy-intensive (OpEx);** continuous R&D and economies of scale through commercial plants could drive down the cost.
- **Early market opportunities exist for Gen 2 from waste** (biogas, drop-in fuels) driven by cheaper feedstocks.
- **Gasification and Fischer-Tropsch technology has potential for earlier commercialization** vs. pyrolysis; commercial scale already exists for fossil feedstock (coal, natural gas).
- **Hydrotreating (HVO, HEFA) is dependent on feedstock cost;** further expansion could lead to price volatility.

Source: IEA, Advanced Biofuels (2020).

Credit: Augusto Agazzi, Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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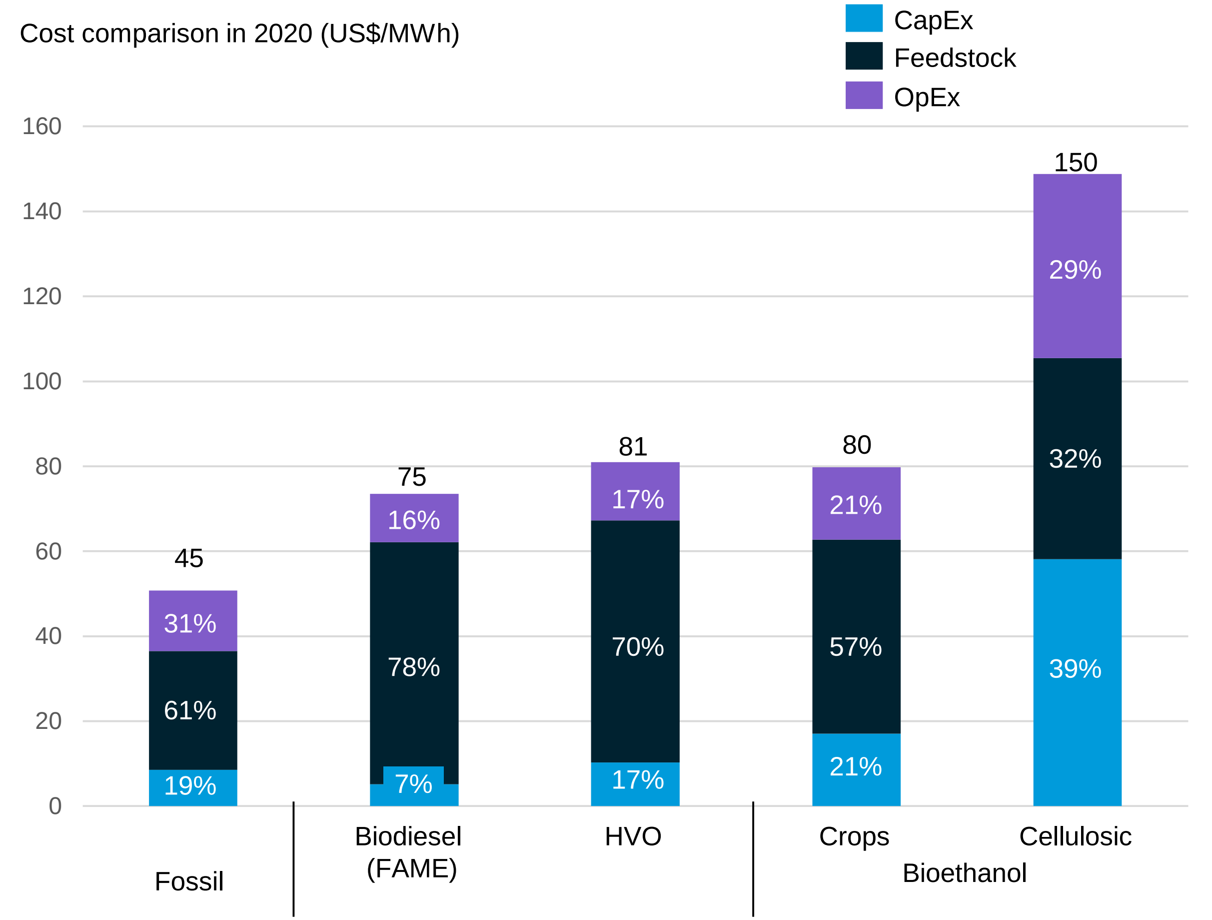
Biofuels face feedstock volatility, while fossil fuels are driven by extraction and geopolitical dynamics

Biofuels vs. fossil fuels cost breakdown



Observations

Dependency:

- **Biofuels are dependent on agricultural feedstocks**, which are volatile due to **weather, land use, and policy subsidies.**
- **Fossil fuels are more dependent on extraction technology and global geopolitics**, making them sensitive to **OPEC decisions, drilling technology, and carbon pricing.**

Subsidies:

- **Role of subsidies in both sectors: Biofuels benefit from blending mandates** and **agricultural incentives,** while **fossil fuels** get **tax breaks** and **infrastructure support.**
- **Future cost projections:** Biofuels are expected to get **cheaper with tech improvements** (Gen-2 biofuels, synthetic fuels), while fossil fuel costs may **fluctuate with geopolitical events and carbon taxes.**

Source: IEA, Advanced Biofuels (2020).
Credit: Augusto Agazzi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Biofuel advancement and growth require advanced technology, regulatory certainty, and accessible financing

Technology

- **Promote R&D programs for advanced biofuels supported by grants**
  - Advanced biofuel from FT and pyrolysis technology is still CapEx-intensive; R&D and economics of scale are required to reduce cost
- **Reduce feedstock cost by:**
  - Diversifying feedstock, including waste and low-quality feedstock system.
  - Using integrated landscape management strategies for feedstock collection and pre-treatment.
  - Increasing supply system intensification.

Policy

- **Establish long-term regulatory certainty**
  - Countries must establish stable, long-term biofuel mandates and incentives to align their renewable energy vision.
  - Not every country can become a Norway (i.e., high adoption of EV cars).
- **Introduce carbon pricing mechanism**
  - For countries with a clear need for biofuels, implementing carbon pricing models like California's LCFS can help internalize the environmental costs of fossil fuels, thereby accelerating carbon emission reductions.
- **Incentivize biofuel beyond road transport**
  - The aviation industry will rely heavily on sustainable aviation fuel; policy needs to focus on incentivizing growth in this sector, as production cost is still relatively high.

Financial

- **Increase public-private partnership; use cases to be established**
  - Governments need to work with private companies across the biofuel value chain (e.g., R&D for Gen 3 feedstock).
- **Promote green bond financing for biofuel actors**
  - Private companies need to be incentivized to take on more mix funding to fund biofuel projects at a lower cost of capital to build infrastructure and fund R&D.

Sources: Team analysis; DOE, Integrated Strategies to Enable Lower-Cost Biofuels (2020).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Biofuels Technology

Biofuel technologies are evolving rapidly, with differentiated maturity levels and cost structures across fuel types. Feedstock availability, cost, and compatibility with existing infrastructure are major constraints to scale.

Biodiesel (FAME[1]) and bioethanol hold the most share. Growth is expected through 2035, led by the U.S., Brazil, the EU, and Indonesia, and supported by production mandates and blending requirements.

HVO[2] (renewable diesel) is growing its share; the U.S. and Europe lead with 80% of global capacity, which is expected to double by 2028, even surpassing projected demand.

- Production costs remain **above traditional diesel ($100 to $178/boe)**, mainly driven by **feedstock price volatility**, with UCO and tallow oil costing up to 10x more than palm oil.

SAF[3] production growth hinges on policy support to achieve net-zero aviation. It has the potential to scale 5x by 2030, with the **majority coming from biofuel:**

- **HEFA[4] (biojet) leads today, with ~16% CAGR projected through 2030**, yet it is feedstock-constrained.
  - Cost remains high (>$ 160/boe), and over 100 projects are in the pipeline.
  - Production is still concentrated mainly in the EU and U.S.; **Neste is the global leader** at 22 Kboepd capacity as of 2024.
- **FT-SPK's[5] technology is in the early stage** at $100 to $300/boe cost depending on the feedstock (biomass vs. waste)**; the EU leads with ~60% market share**, driven by strict energy standards.
- **Pyrolysis-derived SAF is still in the pilot stage, with the EU leading the development**; bio-oil costs are high **($150 to $270/boe)** and quality varies; compatibility with refiners is being tested.

1) Fatty acid methyl esther, 2) Hydrotreated vegetable oil, 3) Sustainable aviation fuel, 3) Hydroprocessed esters and fatty acids, 4) Fischer-Tropsch synthetic paraffinic kerosene.
Credit: Birru Lucha, Augusto Agazzi, Heonjae Lee, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

U.S. biofuels have a market size of ~$100B as of 2024; bioethanol takes the majority of share

Various biofuels for transport sector

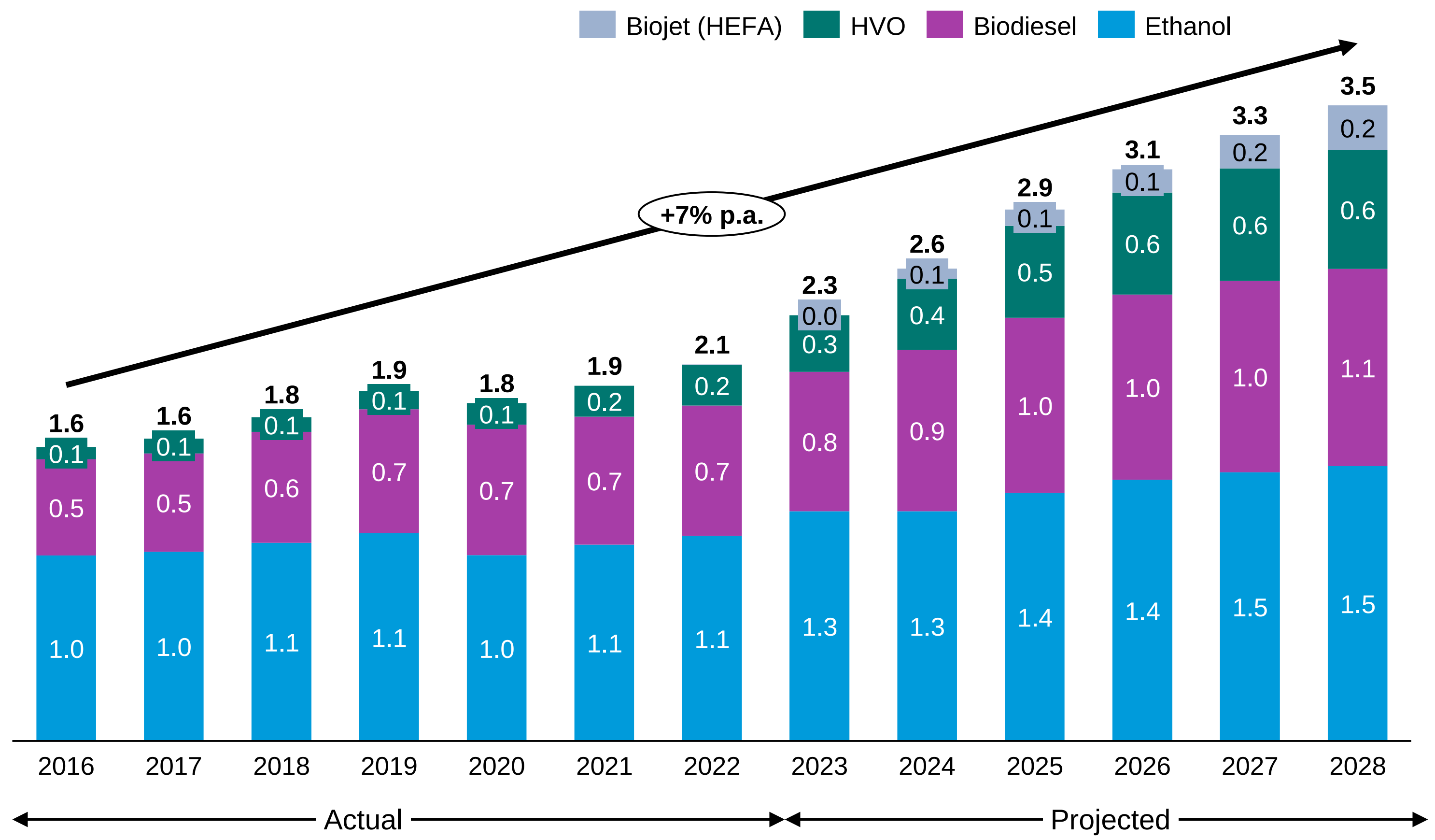
○ R&D/pilot scale ◐ Ready for commercialization ● Mature and commercialized

	1	2	3	4	5	6
Fuel products	**Biodiesel**	**Bioethanol**	**HVO[1]**	**SAF–HEFA[2]**	**SAF– FT SPK[3]**	**SAF – pyrolysis-derived**
Use in transport sector	Road, marine	Road	Road, marine	Aviation	Aviation	Aviation
Technology	Transesterification	Fermentation	Hydrotreating	Hydrotreating	Gasification & Fischer-Tropsch	Pyrolysis
Technology maturity	●	●	●	●	◐	○
Retail market size (2024)[4]	$8B	$66B	$22B			
CAGR (2020-2024)	-4.5%	~1%	~75%			
Costs (2024, $/bbl)	~4	~4	~4-7			
Profit margin (%)	~10-15%	~10-15%	<10%			

1) Hydrogenated vegetable oil. 2) Hydroprocessed esters and fatty acids. 3) Fischer-Tropsch — synthetic paraffinic kerosene.
4) Market size calculated using retail product prices of mixed fuels (without the consideration of percentage biofuels); pure biofuel market size to be lower than the suggested figures.
Sources: The Brainy Insights, Biodiesel Market Size by Feedstock (2023); Fortune Business Insights, Hydrotreated Vegetable Oil Market Size (2024); Spherical Insights, Global Bioethanol Market Size (2023); Precedence Research, SAF Market Size, Share, and Trends (2023).
Credit: Birru Lucha, Augusto Agazzi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

In transport, HVO and HEFA are growing share, while advanced technologies are being developed to produce drop-in fuels

Global biofuels consumption (actual to 2022, projection to 2050), *Mboed*



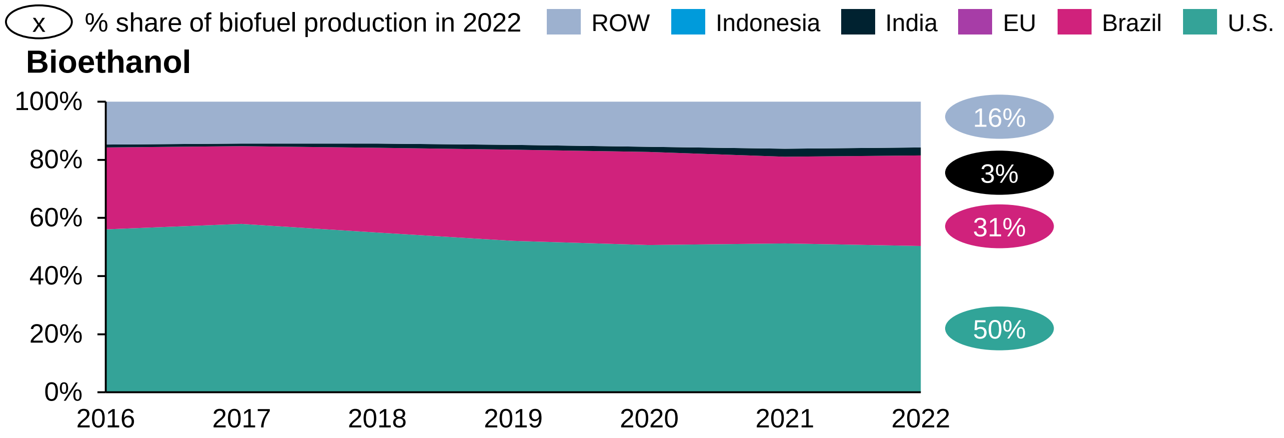
Observations

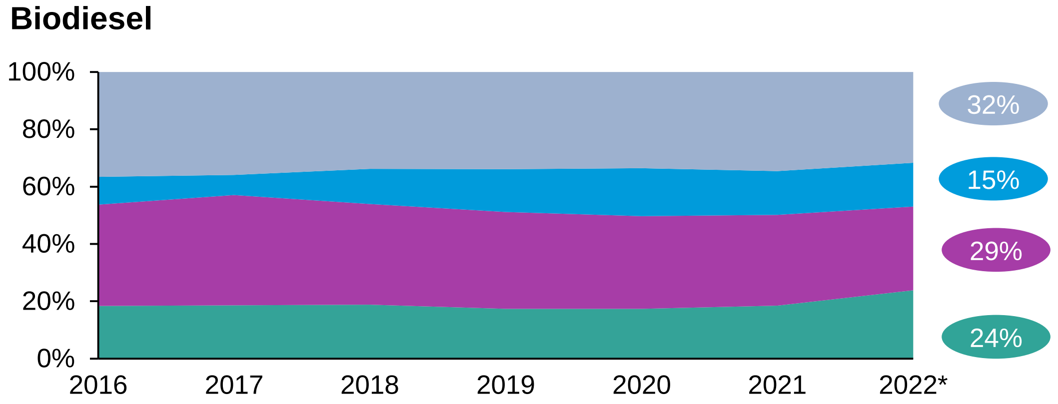
- **Biodiesel and bioethanol expect continuous growth at least until 2035**, predominantly supported by blending and production mandates.
- The recent growth in **HVO is primarily driven by technological advancements**, including the coprocessing capability with existing oil refining facilities. In addition, HVO can **replace traditional diesel without blending**, offering an attractive means to decarbonize the diesel market.
- **Biojet (HEFA) is gaining traction** following the increased blending target of sustainable aviation fuel (SAF) set by the EU, CORSIA,[1] and WEF CST.[2] **Diversification of feedstock and SAF technology (e.g., FT-SPK, pyrolysis, AtJ)** is critical to meet its demand toward net-zero emissions.

Note: Total may not sum exactly due to rounding.
1) Carbon Offsetting and Reduction Scheme for International Aviation. 2) World Economic Forum Clean Skies for Tomorrow.
Sources: IEA, Net Zero Roadmap (2023); IEA, Transport Biofuels (2023).
Credit: Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

U.S., Brazil, EU, and Indonesia lead global production of biodiesel and ethanol, supported by the blending and production mandates

Share of bioethanol/biodiesel production by country/region





* China produces ~3% of biodiesel (2022)

Biofuel production mandate by country/region[1]

U.S.
- Target volume of 22.33 billion RINs (1 ethanol equivalent gallon) of renewable fuel and total ~12 billion RINs of cellulosic, biomass-based and advanced biofuel

Brazil
- E27 as of 2023 and reviewing potential increase to E20
- B12 as of 2023, target to reach B15 by 2026

EU
- No specific blending mandate, target 14% renewable energy in transport by 2030
- Largest global biodiesel producer (~13M tons annually) but faces rising imports from China

India
- E10 as of 2022, target to reach E20 by 2025.
- Rapid ethanol production growth, targeting 6.35B liters in 2024, with grain-based ethanol doubling by 2025

Indonesia
- Introduced E5 in 2023
- B30 as of 2023 and target rising to B40 in 2025

China
- 2023: Biggest biodiesel exporter to EU ~2.01B liters (43%, benefiting from domestic tax rebates)
- 2024: EU imposed anti-dumping tariffs (from 12.8% to 36.4%), decreasing the volume by 51% (Δ~567K tons/~1.3B liters)

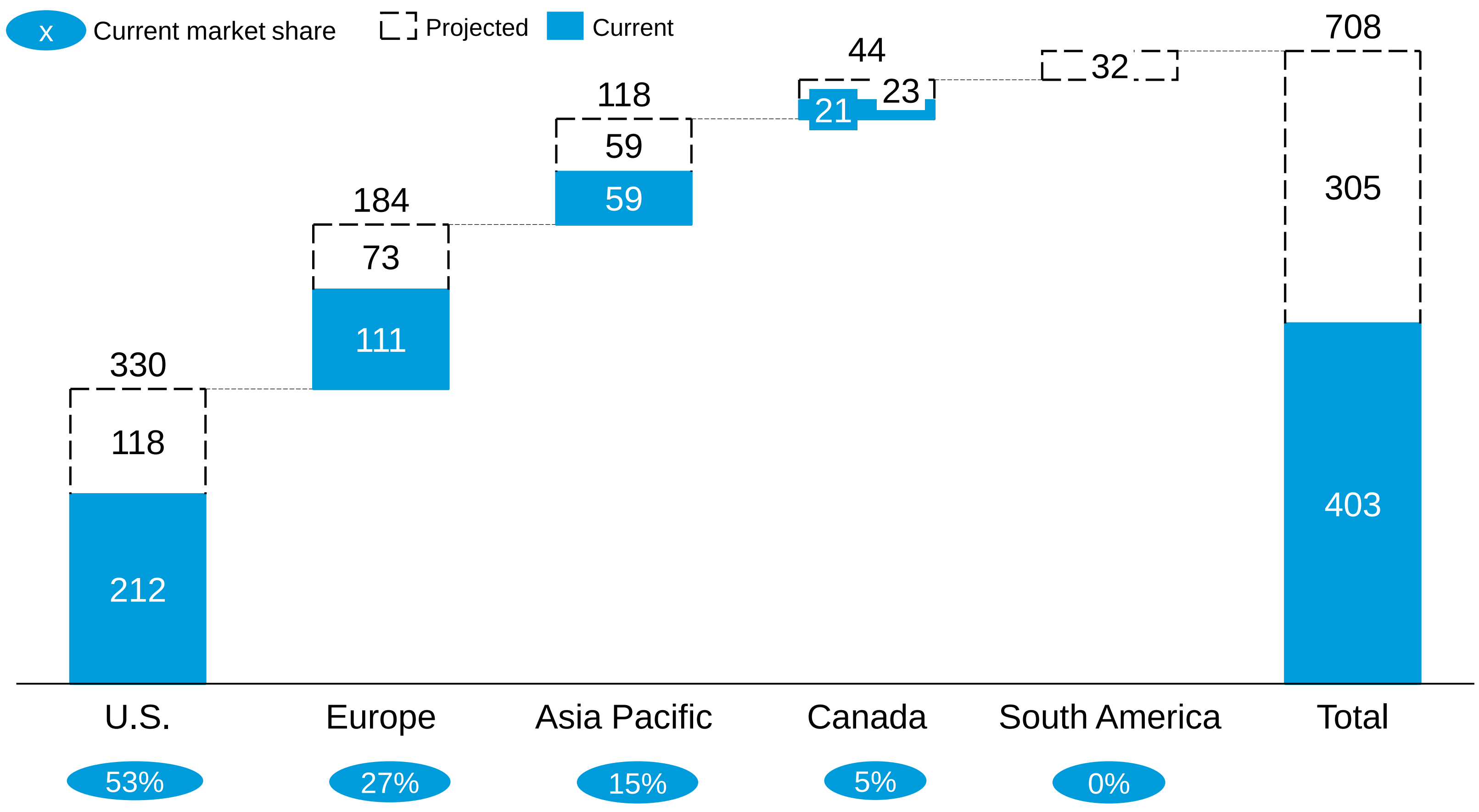
1) EX represents % volume in bioethanol blending in gasoline; BX represents % volume in biodiesel blending in diesel.

Sources: IEA, Biofuel Production by Country/Region and Fuel Type (2021); IEA, Biofuels (2023); USDA, Biofuels Annual (2025); EPA, Renewable Fuels Standards (2023); EBB, EU Biodiesel Industry May Not Survive 2024 If Left Unprotected from Chinese Unfair Imports (2024).

Credit: Birru Lucha, Augusto Agazzi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

The U.S. and Europe lead with 80% of the global market share; global capacity is expected to almost double by 2028

HVO production globally in 2023 and projected capacity by 2028, *Kboed*



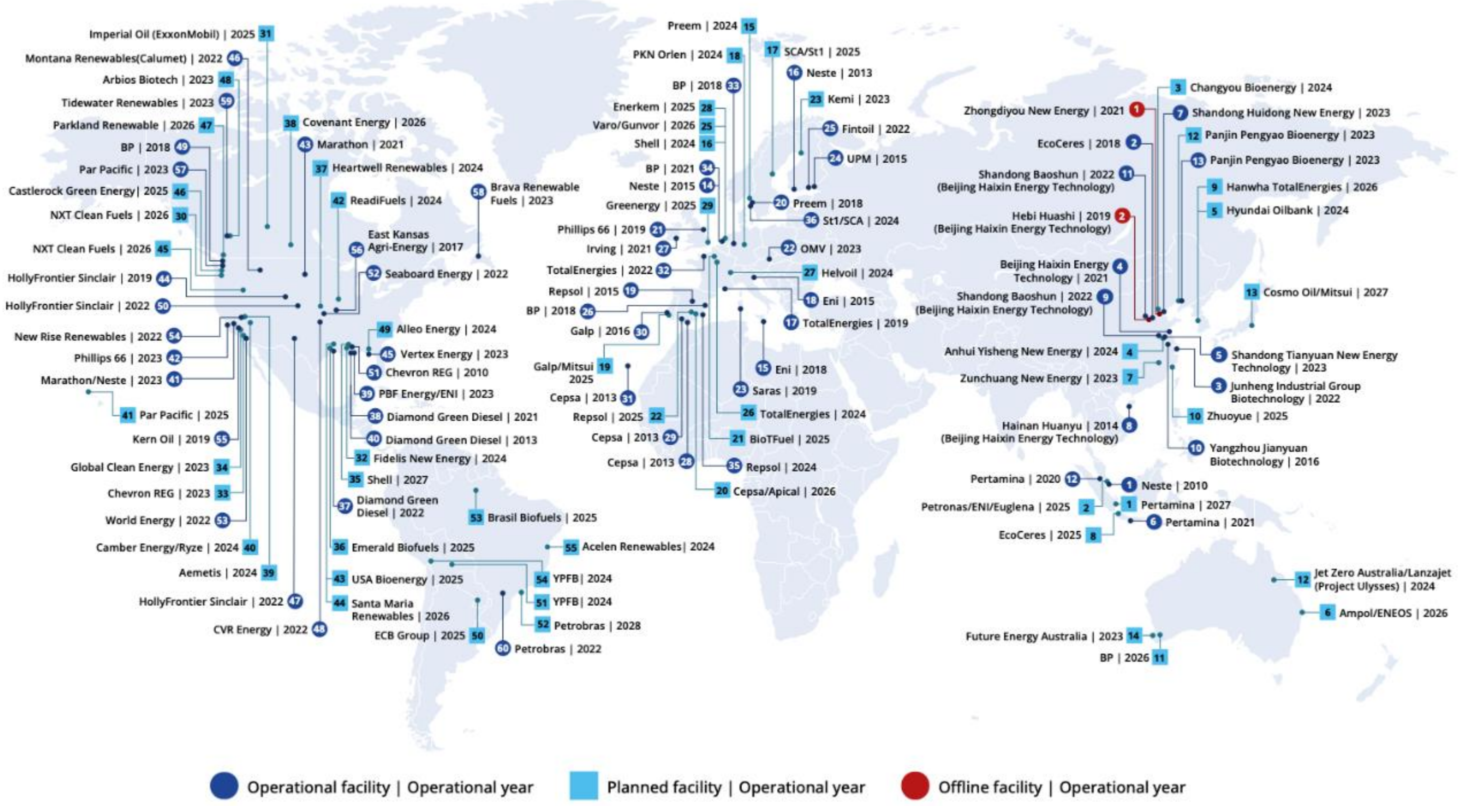
Observations

- Growth in HVO will **meet most new demand for sustainable fuels,** reaching **$40 billion to $50 billion** by the end of 2028, with **CAGR of 16%.**
- European companies like **Neste** (Finland), **Preem** (Sweden), and **ENI** (Italy) have pioneered HVO production and technological development.
- In the past few years, U.S. production has seen **500% growth** across American companies (Chevron, Phillips 66, Diamond Green Diesel, etc.) due to incentives in the **Inflation Reduction Act.**
- HVO growth has **replaced biodiesel investments**, as mineral oil groups are focusing on building new HVO facilities due to HVO's **"drop-in" properties** and **higher blending percentages.**
- Manufacturers are seeking **private and public partners** to expand production and use (e.g., **Shell** and **German National Railway** using HVO for non-electric trains and **Amazon Web Services** switching to HVO in Europe).

Sources: Argus Media, Global HVO/Renewable Diesel Capacity (2024); BCC Research, HVO Market (2024); McKinsey, Global Energy Perspective (2024); ETIP Bioenergy, HVO Factsheet (2020); Renewable Carbon, HVO Gains Importance in the U.S. (2024); Mining Stock Education.com, HVO Market Gains Momentum (2024); DCD, HVO Supply Chains (2023).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Existing and new players are focused on increased production

Global HVO Capacity Map (operational and planned facilities) *from Argus Media in 2024*



Global production (current and 2027 projected combined) is ~620,000 Mboed. **Diamond Green Diesel** has the largest operational capacity of ~69,000 Mboed; **Neste's** operational capacity is ~50,000 Mboed.

Observations

Major players (current and projected production combined):

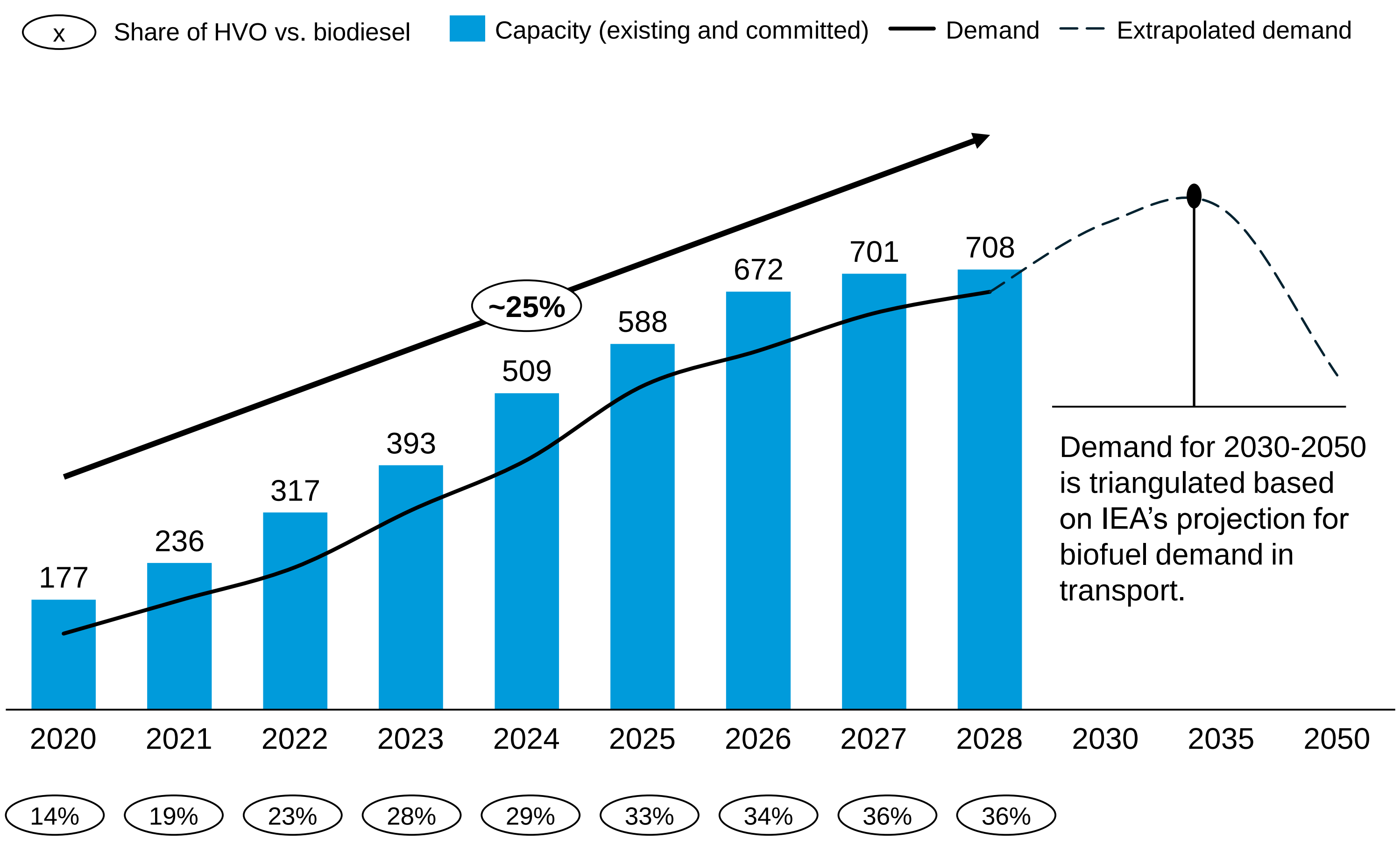
- **Diamond Green Diesel** (three plants in the U.S.): 11% of global production
- **Neste** (four plants across Singapore, U.S., Netherlands, and Finland): 8% of global production
- **NXT Clean Fuels** (two plants in the U.S.): 5.8% of global production
- **HollyFrontier Sinclair** (three plants in the U.S.): 3.5% of global production
- **Pertamina** (three plants in Indonesia): 3.5% of global production
- **Preem** (two plants in Sweden): 3.3% of global production

This list represents a mix of companies solely dedicated to renewable diesel production and traditional energy providers seeking to diversify away from fossil fuels.

Sources: Argus Media, Global HVO/Renewable Diesel Capacity (2024); Greenea, New players join the HVO game (2025).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Current planned capacity has exceeded the projected demand; growth opportunity beyond 2035 is uncertain

HVO global demand vs. capacity, actual to 2023 and projected up to 2050, *Kboed*



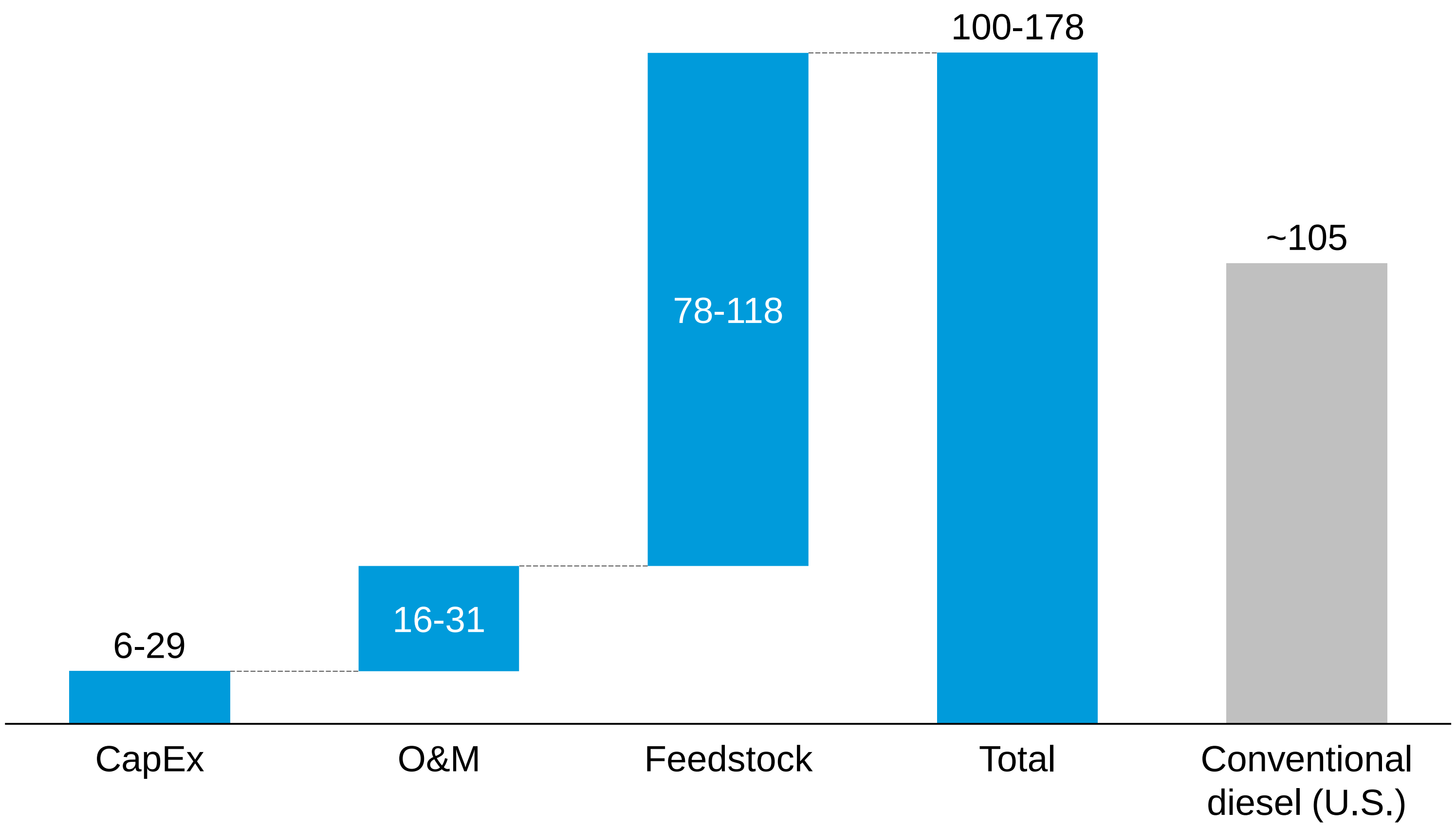
Observations

- **HVO demand is expected to reach ~700 Kboed in 2028** with growing share vs. biodiesel.
- Despite the strong growth since 2020, **demand for HVO in road transport could peak in 2035 as EV takes over the share**, making it crucial to capitalize on existing and developing biofuels projects.
- It is also important to understand that the 2035 threshold **does not necessarily apply to all countries equally** – some countries, especially in transitioning and developing economies, **will continue to rely on fossil fuel-based road transport** because they do not have the necessary infrastructure or capital to support widespread electrification of transport, **giving biofuels an important opportunity.**
- Therefore, **it is essential to thoroughly consider a long-term investment in HVO** by closely examining the **signposts in the road transport sector**, such as incentives in EV investments, carbon credits for biofuels, etc., across regions.

Sources: IEA, Net Zero Roadmap (2023); IEA, Transport Biofuels (2023); Argus Media, Global HVO/Renewable Diesel Capacity (2024); Energies Nouvelles, Biofuels Dashboard (2023); BCC Research, Hydrotreated Vegetable Oil (HVO): A Green Fuel Solution for a Sustainable Future (2024).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Production costs are mainly driven by feedstock, and only 3% cost reductions can be achieved with lower cost of capital

HVO cost structure in 2020, *$/boe* (1 EUR = $1.15 conversion rate)



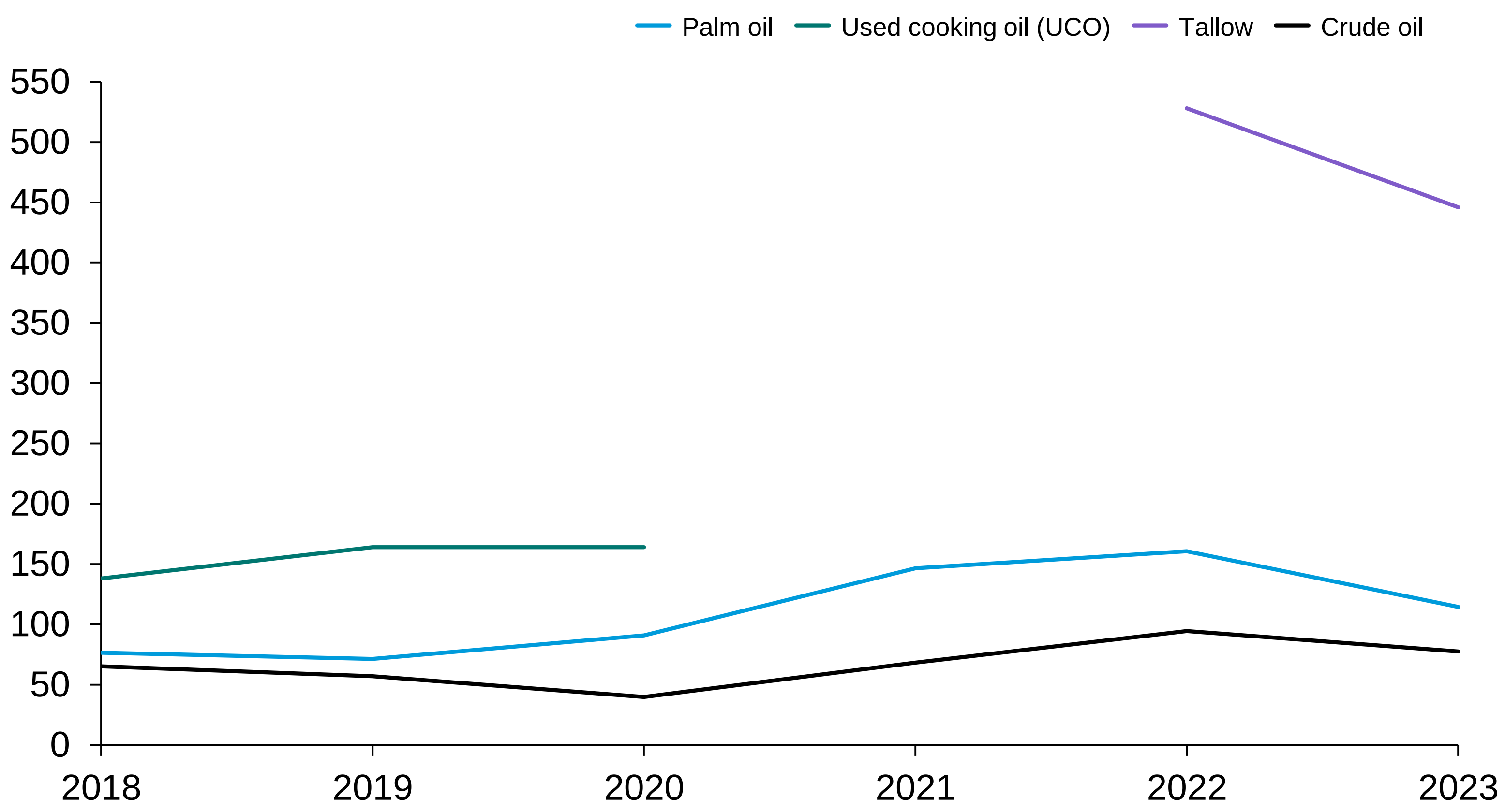
Observations

- HVO technology is **mature and developed on a commercial scale**, meaning most operational and capital expenditure-related **cost reductions have already been made.**
- Process improvements and a lower cost of capital will **only provide up to 3% cost reductions**; the ability to source sustainable and cost-effective feedstock will **determine the future direction of HVO prices.**
- Feedstock costs are **65-80% of overall production costs**, with **90% of current feedstock** comprised of palm oil.
- Producers are **moving away from vegetable oils** and **toward waste and residue oils or fats**, as palm oil requires significant land use change and **cannot be sourced sustainably on a wide scale.**
- Market leader Neste has cut its share of palm in its feedstock mixes **from 90% palm to 80% waste and residue materials** like used cooking oil (UCO) and tallow (animal fats).
- European UCO producers are **having trouble meeting demand,** and users will **rely on cheap imports** from countries like China, Indonesia, and Malaysia to keep up with new renewable standards.

Sources: IEA, Advanced Biofuels: Potential for Cost Reduction (2020); BCC Research, HVO Making it Big (2018); T&E, UCO: High Hopes on Limited and Suspicious Materials (2024).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Feedstock's price volatility is linked to changes in crude oil prices, with UCO and tallow oil being 3-10x more expensive than palm oil

HVO feedstock price vs. crude oil, *$/boe*



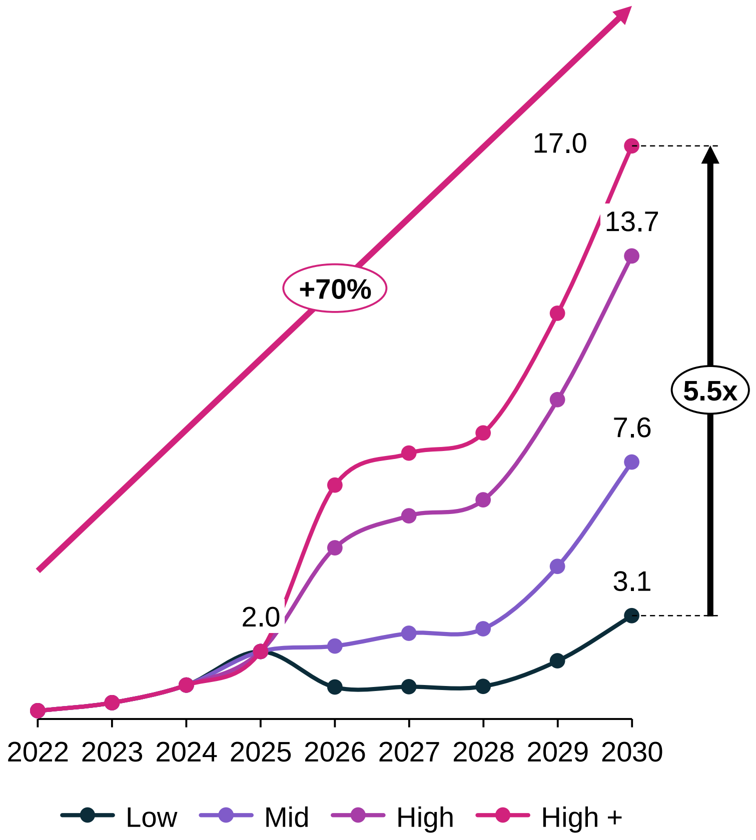
Observations

- All HVO feedstock — palm oil, UCO, and tallow — **follow similar price trends as crude oil**, with crude oil being the **least expensive option** for all end-market users.
- The price volatility of sustainable feedstocks is also driven by crude and palm oil prices.
- Palm oil is cheaper and more available for commercial biofuel production but is being **phased out of long-term use** due to policy updates, improved fuel standards, and sustainability concerns.
- Many HVO producers **will encounter difficulties in sourcing inexpensive and quality renewable fuels** without relying excessively on imports or harming domestic industry.
- China, the world's largest producer of UCO, will soon **run out of supply** due to high demand from the U.S. and Europe.
- Australia is **the world's largest exporter of tallow**, with industry growth driven by biofuel demand, but prices remain volatile.

Sources: Macrotrends, WTI Crude Oil Prices (2024); CME Group, Waste Oils Futures and Prices (2021); Tridge, Beef Tallow Prices (2024); FRED, Global Price of Palm Oil (2024); T&E, European and U.S. Used Cooking Oil Demand (2024); ABC News (Australia), Australian Tallow Exports (2024).

SAF production growth hinges on policy support, with potential to scale 5x by 2030

Global SAF production by policy support scenario (projected), *Mt*



Scenario	Implicit SAF policy landscape	SAF replacement ratio[1]
High+	SAF — emphasis in policies	**5.01**% (LTAG Scenario IS3)
High	Level-playing field between SAF and road transportation biofuels	**3.98**% (LTAG Scenario IS2)
Moderate	Some level of policy support for SAF, but it's lower than for road transportation biofuels	**2.54**% (LTAG Scenario IS1)
Low	No policy support	N.A. (not associated with an LTAG scenario)

Observations

- **SAF production could grow at a ~70% CAGR**, multiplying by a factor of ~57x compared to 2022 under a High scenario.
- 2025 updated expectations see production of 2 Mt in 2025.
- **Reality is aligning with the more moderate scenario of ~8 Mt per year by 2030.** This is short of what's needed yet an impressive 52% CAGR and 25x growth compared to 2022.
- **Stronger policy support** could push **SAF replacement ratios** from **2.54% (Moderate)** to **5.01% (High+)**, highlighting its dependence on regulation.
- **A level-playing policy framework (High scenario) enables SAF production to surpass 13,000 kt per year**, closing the gap toward long-term sustainability goals.

1) LTAG refers to Long Term global Aspirational Goals.
Source: ICAO, SAF projections (2022).
Credit: Nicolas Herrera Isaza, Augusto Agazzi, Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Columbia Business School
Climate Knowledge Initiative

SAF is an important alternative for net-zero aviation, with the majority coming from biofuel

○ R&D/pilot scale ◐ Ready for commercialization ● Mature and commercialized

Types of sustainable aviation fuel (drop-in fuels)

	Focus of this deck			Covered in Decarbonizing Aviation	
Fuel products	**HEFA**	**Fischer-Tropsch (FT-SPK)**	**Pyrolysis-derived SAF**	**Alcohol-to-jet (AtJ)**	**Power-to-liquid (PtL)**
Technology	Hydrotreating	Gasification & Fischer-Tropsch	Pyrolysis	Alcohol-to-jet	Power-to-liquid
Technology maturity	●	◐	○	◐	◐
Max blend % (ASTM)	Up to 50%	Up to 50%	10-50% (depends on feedstock, early study)	50-100% (varies by pathway)	50% (under ASTM D7566 Annex A7)
ASTM Approval Status	✓	✓	✗	✓	✓
Est. cost ($/bbl)	170-210	210-300	170-250	250-340	270-380
CO_2 reduction	~60-80%	~60-80%	~40–70% (depends on feedstock)	~50-85% (depends on feedstock and tech)	>90% (if powered with 100% renewable)
Challenges	Feedstock availability	Depends on renewable feedstock	Tech complexity	Tech complexity, feedstock scale	Cost, electricity need, carbon source purity

Observations

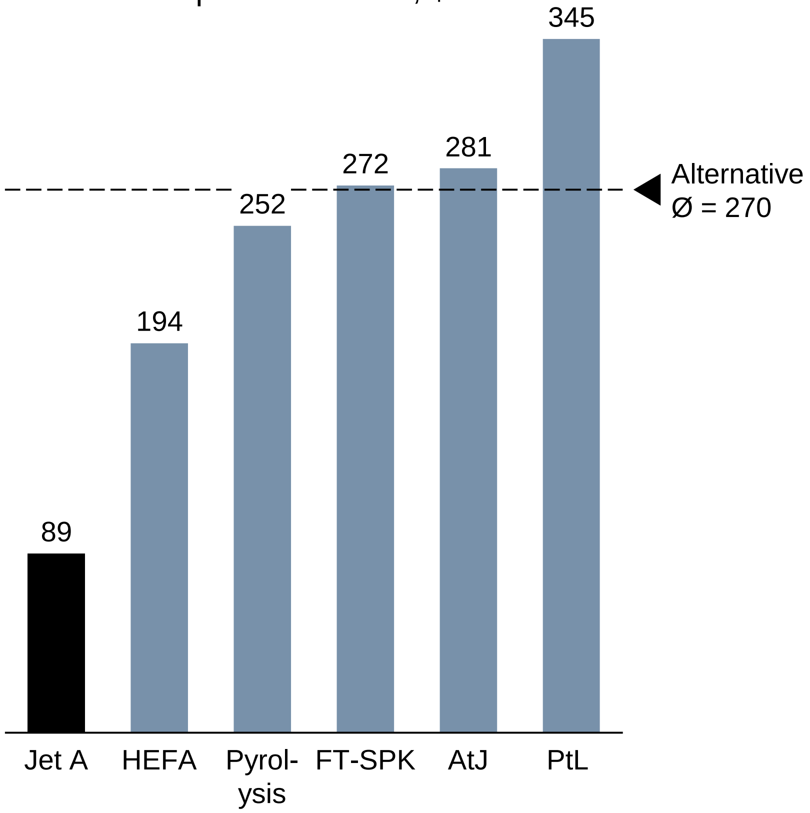
- **HEFA is leading** SAF deployment due to technical maturity, a wide feedstock base (e.g., UCO, animal fats), and ASTM certification (Annex A2). However, **feedstock scarcity may limit scale.**
- **FT-SPK, AtJ, and pyrolysis-derived SAF** offer **diverse feedstocks**, but technologies face **complex scale-up and cost challenges.**
- **PtL** has the **highest climate benefit but** is currently **cost-prohibitive** and highly energy-intensive and depends on **availability of green electricity and pure CO_2 streams.**
- **Policy frameworks like CORSIA,[1] ReFuelEU, and the U.S. SAF Grand Challenge** are accelerating commercialization, but **infrastructure, incentives, and mandates** are still needed to bridge the cost gap.

Note: Sustainable aviation fuel (SAF) refers to non-fossil-derived aviation fuels that meet strict technical and sustainability criteria.
1) Carbon Offsetting and Reduction Scheme for International Aviation, World Economic Forum Clean Skies for Tomorrow.
Sources: IEA, Net Zero Roadmap (2023); IEA, Transport Biofuel (2023); ICCT, SAF Policies Fact Sheet (2024); IATA, SAF Handbook (2024).
Credit: Augusto Agazzi, Andrea Castro, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Although HEFA is the most cost-effective SAF pathway, it is ~2x the price of Jet A and has higher feedstock costs than alternatives

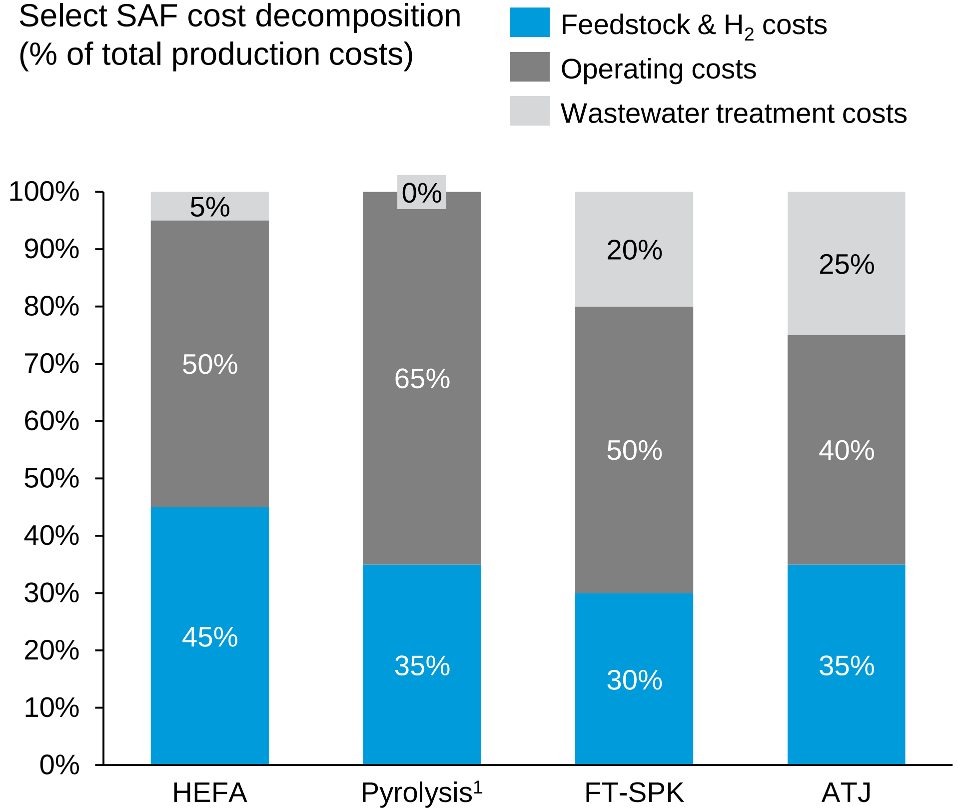
HEFA is cheaper than SAF alternatives

Median SAF production cost, $/bbl



Feedstock and H_2 costs are relatively high for HEFA

Select SAF cost decomposition
(% of total production costs)



Observations

- **HEFA is currently the most cost-effective SAF option (~2-3x Jet A)**, offering a solid balance of climate benefit and commercial readiness.
- Given most HEFA production facilities are still **subscale** (<200M gallons p.a.), economies of scale are not yet being realized, both within plants and across the global value chain.
- **Feedstock and H_2 costs** for HEFA-based SAF are relatively high, given required **pre-processing** (e.g., waste oil aggregation) and **transportation.**

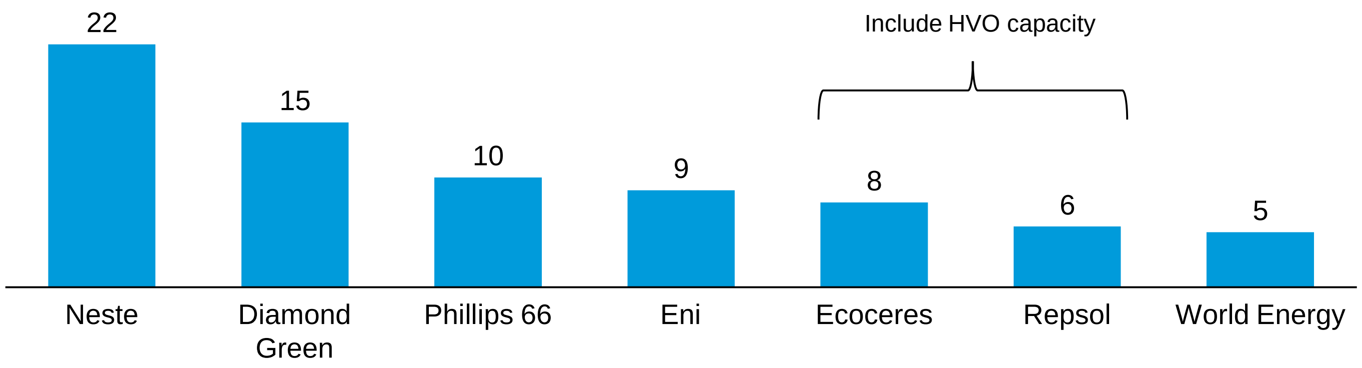
1) Wastewater treatment is part of the operating cost, assuming stand-alone facility (no coprocessing with oil refinery).

Sources: ICCT, SAF Policies Fact Sheet (2024); Federal Reserve Bank Saint Louis, Jet Fuel Prices (2025); Current Opinion on Green and Sustainable Chemistry, Current Outlook on SAF Feedstocks (2024); Green Air News, SAF Complications (2022); Carbon Capture Science & Technology, SAF Key Opportunities and Challenges (2024); BMC, Techno-Economic Assessment of Bio-Jet Fuels (2016);

Credit: Augusto Agazzi, Andrea Castro, Birru Refuel EU Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

HEFA production is still concentrated mainly in the EU and U.S. with Neste as the global leader

HEFA global top producers as of 2024 (non-exhaustive), *Kboed*



	Neste	Diamond Green	Phillips 66	Eni	Ecoceres	Repsol	World Energy
Facilities location	Rotterdam, Singapore, Finland	U.S.	U.S.	Italy	China	Spain	U.S.
Feedstocks:							
Vegetable oil	☑	☑	☑	☑			
UCO	☑	☑	☑	☑		☑	
Tallow oil/animal fats	☑	☑	☑	☑	☑		
Others (non-edible oils, waste, free fatty acid)					☑	☑	☑

Note: A live installation map of online, offline, and planned HEFA production facilities can be viewed at this link.

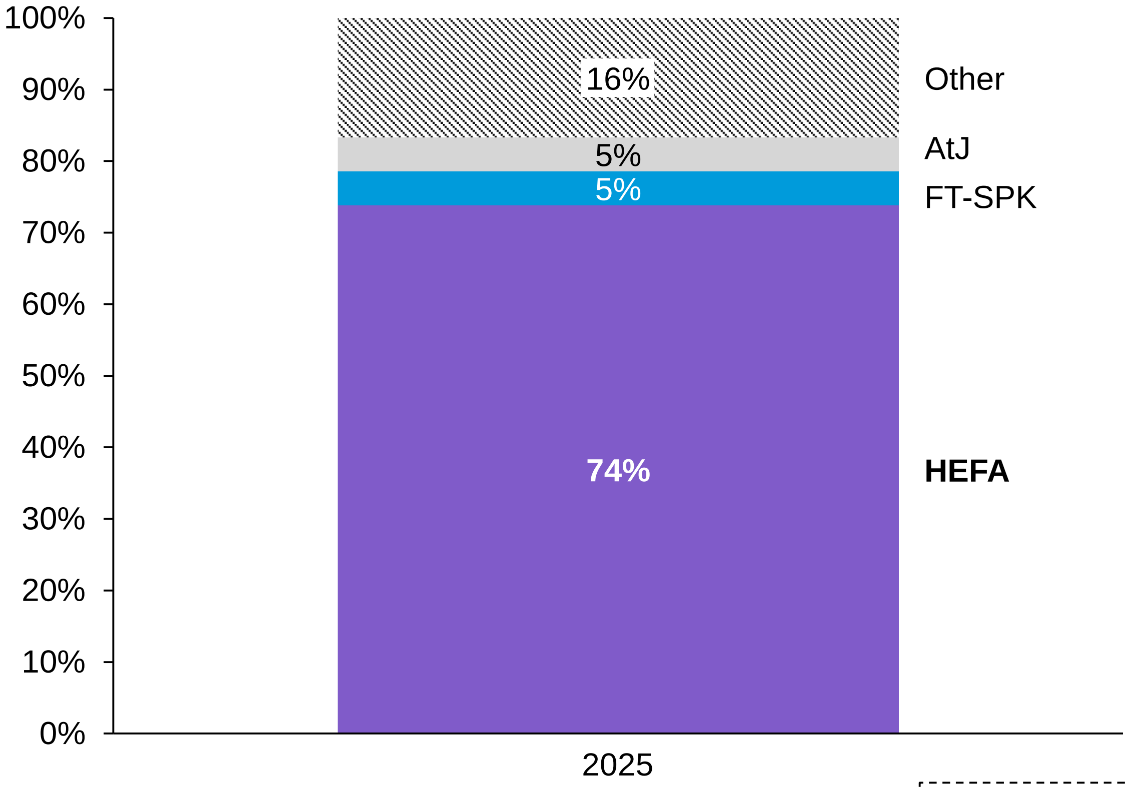
Observations

- **Oil and gas players are gradually converting their refineries into biorefineries** to produce renewable diesel (HVO) and SAF (HEFA) as coprocessing.
- **Global HEFA market size is estimated at ~$13B as of 2023** and expected to grow at 16% CAGR.
- **Over 100 new production facilities have been planned globally**, dedicated to producing HEFA.
- **Development has been bolstered by policy initiatives, partnerships, and supply agreements** between airlines, governments, and suppliers to incorporate SAF into aircraft refueling.
- **Feedstock:**
  - **Current feedstock** includes soybean oil, beef tallow, and UCO, allowing for up to 50% of blending with petroleum-based jet fuel.
  - **Waste feedstocks** such as municipal solid waste, sewage sludge, food processing waste, waste gases, and forest or other agricultural residues **are being explored,** but availability is still uncertain.

Given relative maturity, HEFA accounts for the majority of global SAF production capacity today, with usage driven by the EU/UK

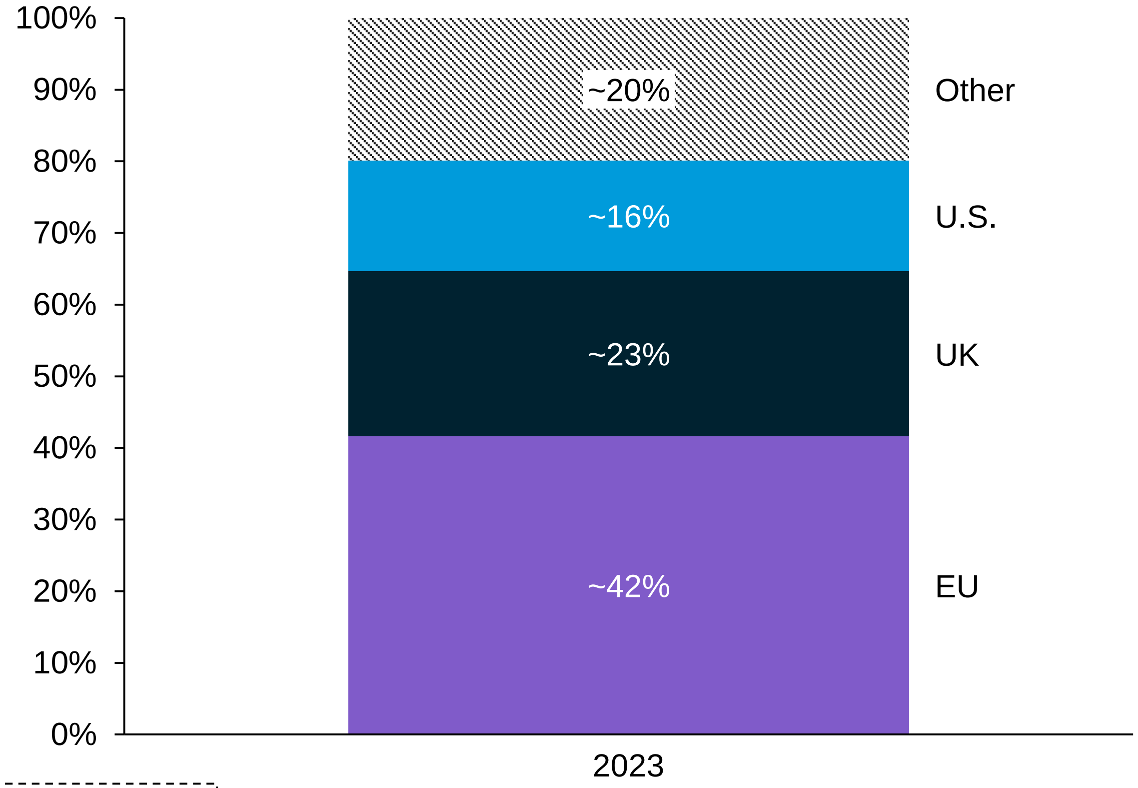
HEFA represents >70% of estimated global SAF capacity today

SAF production capacity share by types



Europe has a robust HEFA infrastructure, driving regional usage

HEFA consumption, by region (% of total)



***Estimate** (Triangulated from various sources)*

Sources: IATA, Net Zero Roadmaps (2024); Statista, Global SAF production capacity 2020-2030 (2022); IATA, Net Zero 2050: SAF (2025); RMI, Unraveling willingness to Pay for SAF (2024); Rhodium Group, Sustainable Aviation Fuels: The Key to Decarbonizing Aviation (2022); ICAO, Environmental Report (2022); ICCT, Unlocking the role of SAF (2024).
Credit: Andrea Castro, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Technological development remains at a pilot scale, led by the EU and U.S., with plans for commercialization by 2030

Current market status

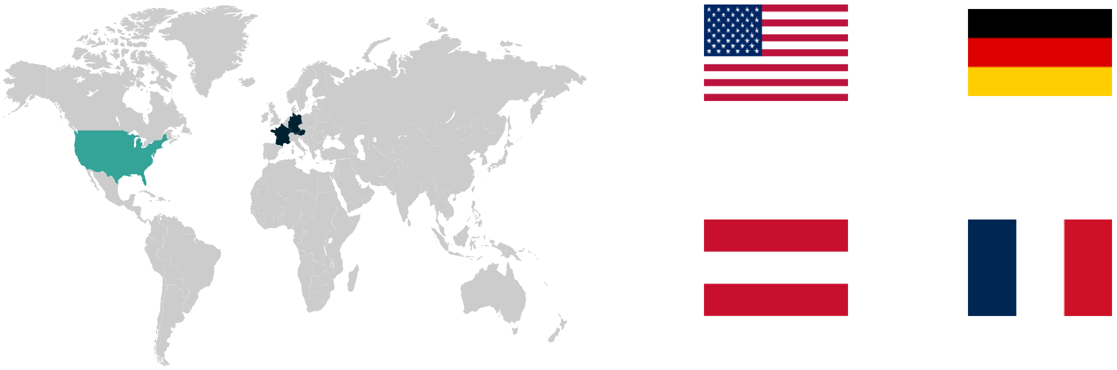
Market landscape:

- **Europe leads FT-SPK adoption** due to strict energy regulations, while **North America** and **Asia Pacific** are **scaling up production.**
- **Governments** and **airlines** are **collaborating** to accelerate SAF adoption through incentives and mandates.
- Companies are **investing** in **R&D** to improve FT-SPK commercial viability.

Technology and production:

- FT technologies fall under **biomass-to-liquids** (BtL) or **gas-to-liquids** (GtL) depending on feedstocks.
- The transition from lab-scale to commercial operations is **underway**, with multiple projects launching in the U.S. and Europe.

Fischer-Tropsch plants at commercial size (2022)



Plants focused on sustainable feedstocks like municipal solid waste (MSW) and forest residues are supporting the transition to low-carbon aviation fuels.

Top projects

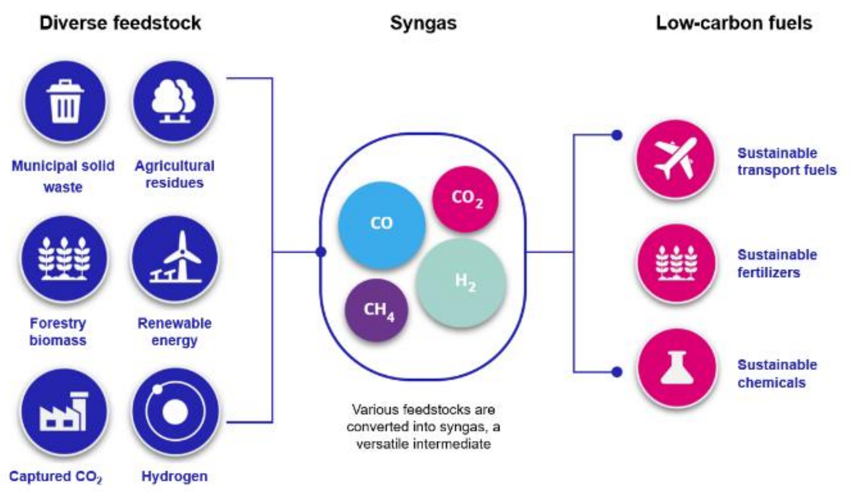
Company	Country/Start operation	Production/Feedstock
Nordic Blue Crude	Norway, 2022	8,000 ton/year FTP, DAC Co2
Altalto team/Velocys	UK, 2020	1,034 bpd FT liquids, MSW
Red Rock Biofuels	U.S., 2021	1,100 bpd FT liquids, forest/sawmill residue
Fulcrum Bioenergy	U.S., 2021	657 bpd FT liquids, MSW

Sources: Research Nester, FT-SPK market analysis (2023); JM Johnson Matthey, FT CANS technology (2025); IEA Bioenergy, Facilities (2025); ETIP Bioenergy, BTL Review (2021); ETIP Bioenergy, FT Synthesis (2021).

Credit: Sean Lee, Augusto Agazzi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Case study: DG Fuels has made a $4B investment to produce 600,000 Mt/year SAF via CANS technology in Louisiana, U.S.

FT technology (Johnson Matthey-BP CANS)



Overview

Technology

- DG Fuels has chosen **Fischer-Tropsch (FT) CANS technology**, developed by Johnson Matthey and BP, to drive the **first production plant dedicated to SAF globally.**
- CANS technology provides **a unique reactor design** that improves scalability. It also **drastically reduces capital expenditures** compared to competitors while **mitigating the operational expenditures** of plant management.

Plant operations

- The plant, located in St. James Parish, Louisiana, will produce **600,000 Mt of SAF per year once completed in 2028,** fueling over **30,000 transcontinental flights annually** (more than 3% of annual traffic from London to New York) with a 50% blend rate with fossil kerosene.
- DG Fuels has dedicated **$4 billion** to the project and has formed **direct partnerships with major airlines** including Air France-KLM, Delta Air Lines, and Airbus.

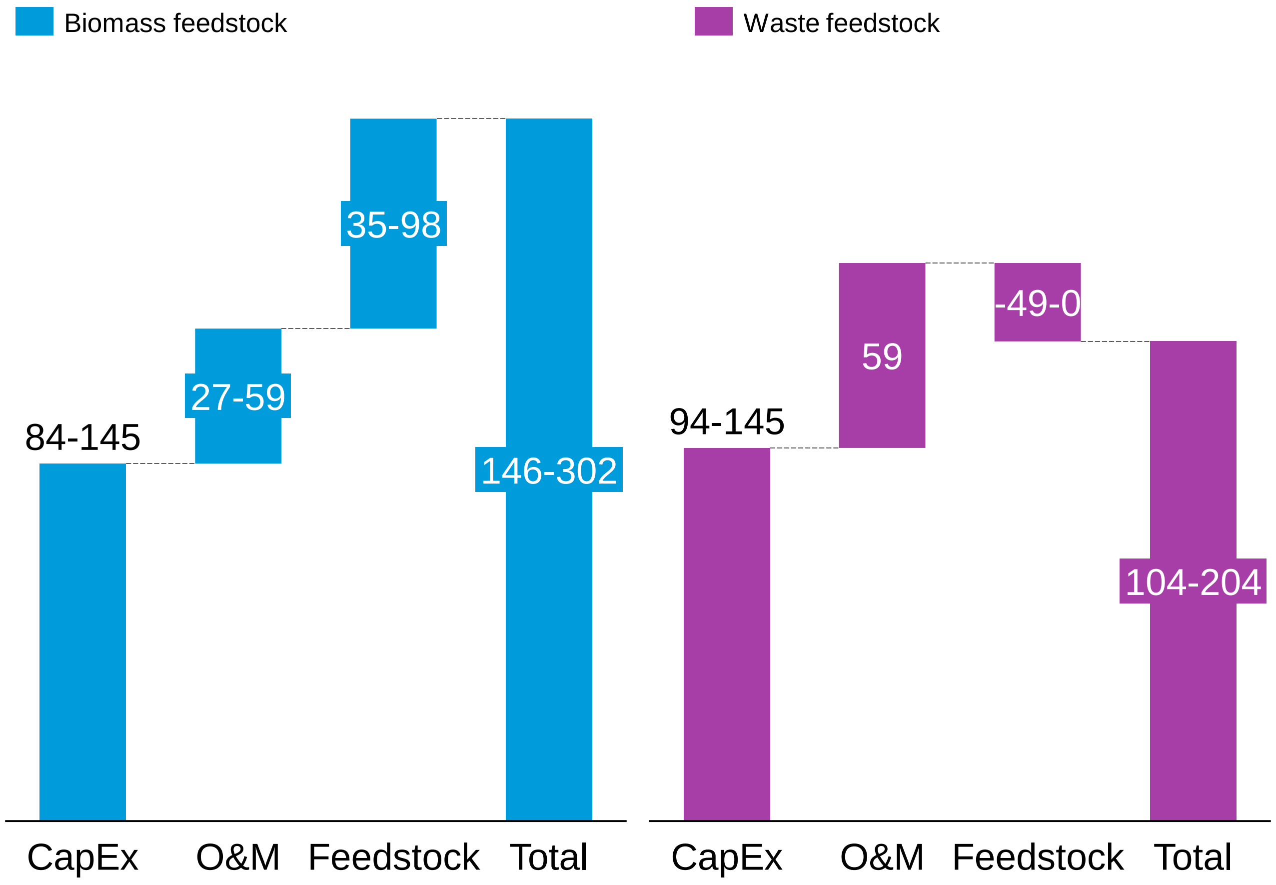
Future

- The plant will use **waste biomass** to develop synthetic kerosene through the FT process, representing **the largest use of FT technology to date.**
- DG Fuels is planning to establish **10 additional SAF production plants across the U.S. in coming years.**

Sources: PR Newswire, Johnson Matthey and BP SAF Plant (2024); Johnson Matthey, Matthey FT Technology (2025).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Depending on feedstock, major cost reductions can be achieved in FT production processes, but more research is necessary

FT cost structure in 2020, *$/boe* (1 EUR = $1.15 conversion rate)



Observations

- The **FT process produces a range of products** in various quantities depending on how upgrades and process design are implemented. It can be optimized to meet specific market demands to generate **diesel, gasoline, or synthetic paraffinic kerosene (SPK) and bio-kerosene for SAF.**
- The **overall conversion efficiency** from biomass feedstock to FT products ranges from **40-55%** depending on feedstock, gasification and FT technology, and the range of products produced.
- **CapEx and O&M:**
  - **CapEx accounts for 40-60% and O&M 20-30% of total cost.** Similar ranges apply for both biomass and waste feedstocks.
  - **Drivers of high costs** are complex processing units and energy-intensive thermal processing.
  - Economies of scale and efficiency improvements could result in a **10-20% cost reduction.**
- **Feedstocks:**
  - **Biomass feedstock** is more expensive, reaching up to 35% of total cost.
  - **Waste-based feedstocks** could significantly reduce costs.

Source: IEA, Advanced Biofuels (2020).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Current technology focuses on biomass feedstock, process improvements, and environmental concerns

Feedstock

- Biomass feedstocks are favored for their **"drop-in" capabilities,** meaning they can be used without post-treatment, and for their role in **reducing waste and sequestering carbon.**
- Plastic-based feedstocks, while explored, pose greater environmental and regulatory concerns.

Process

- Technological advances focus on **improving efficiency and output quality** through better catalysts and sophisticated reactor designs.
- New **continuous feed systems** are enhancing scalability and reducing costs, though commercialization of pyrolysis products like bio-oils still faces challenges.

Environment

- Production remains **energy-intensive**, often requiring external heat sources, and can emit **harmful byproducts** depending on the feedstock used.
- **Plastic pyrolysis:** Environmental risks and regulatory scrutiny have raised questions about its sustainability and classification.

Conversion pathways currently under evaluation by ASTM

Conversion process under evaluation	***Developers***
Integrated hydropyrolysis and hydroconversion (IH2)	Shell
Pyrolysis of non-recyclable plastics (ReOIL)	OMV
Co-processing of pyrolysis oil from used tires (TPO)	Philips 66
Biomass pyrolysis	Alder
Biomass/Waste pyrolysis	Green Lizard

Pyrolysis-derived SAF is currently not an ASTM-approved drop-in fuel; early-stage R&D and pilot scale production underway for ASTM approval

Observations

Innovation focus:

- Continuous feed systems and improved efficiency.
- Pilot-scale biomass-to-gas advances (e.g., Alder Renewables).

Development leaders:

- **Europe** leads in **pyrolysis research**, especially for biomass-based products like bio-oil and synthetic gas.
- **Alder Renewables** is advancing **biomass-to-gas tech** and already has major purchase agreements (**1.5 billion gallons** of **SAF** for the next 20 years).

Feedstock evolution:

- Favorable drop-in biomass inputs (vs. plastic).
- Reduction in waste and carbon footprint.

Challenges:

- High energy use and harmful byproducts.
- Regulatory scrutiny of plastic pyrolysis.

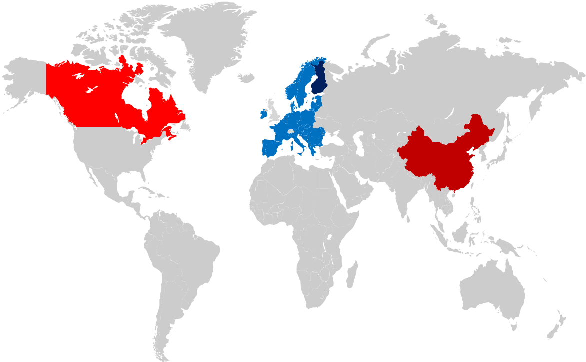
Sources: ICAO, SAF Conversion processes (2025); MDPI, Review of the Current State of Pyrolysis (2024); IDTechEx, Future of Pyrolysis Market in Light of a Changing Regulatory Landscape (2024); MDPI, Effects of Bio-Oils on Fuel Atomization (2021); IEA, SAF report (2024); Metso, Challenges and opportunities in bio-oil plants (2012); Progress in Energy and Combustion Science, Multi-scale issues of biomass pyrolysis (2018).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

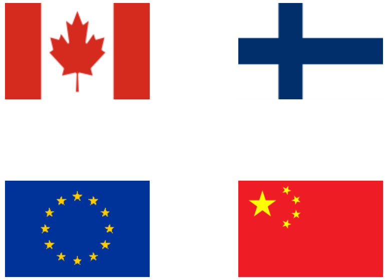
Market is still nascent but quickly growing; EU is leading in technological development and waste feedstock supply

Current market status

- **Market size**
  - The pyrolysis oil market is valued at ~**$300 million (as of 2020)** and is expected to grow at a **CAGR of 4%** through 2031.
  - From 2021 to 2024, global input capacity of plants (amount of raw materials that can be processed by facilities) has risen by 60%.
- **Market breakdowns**
  - Pyrolysis is currently the **dominant form of chemical recycling in Europe**, but the market is nascent due to regulatory, financial, and feedstock challenges.
  - Asia Pacific is projected to be the fastest growing market; the rubber market is the fastest growing, while the plastic segment has the highest share of revenue.
- **Feedstock trend**
  - The biggest obstacle to further expansion of the market is a shortage of feedstock (plastic waste), due to inefficient and expensive sorting processes, lack of standardization, and ambiguous legislation.
  - **Biomass feedstock** from agricultural and forest residue **has been the subject of increased research and focus given its environmentally friendly properties.**
- **A rise in fossil fuel prices**, in addition to infrastructure expansion, will continue to **drive growth of the pyrolysis market.**

Current pyrolysis plants at the commercial stage in 2022





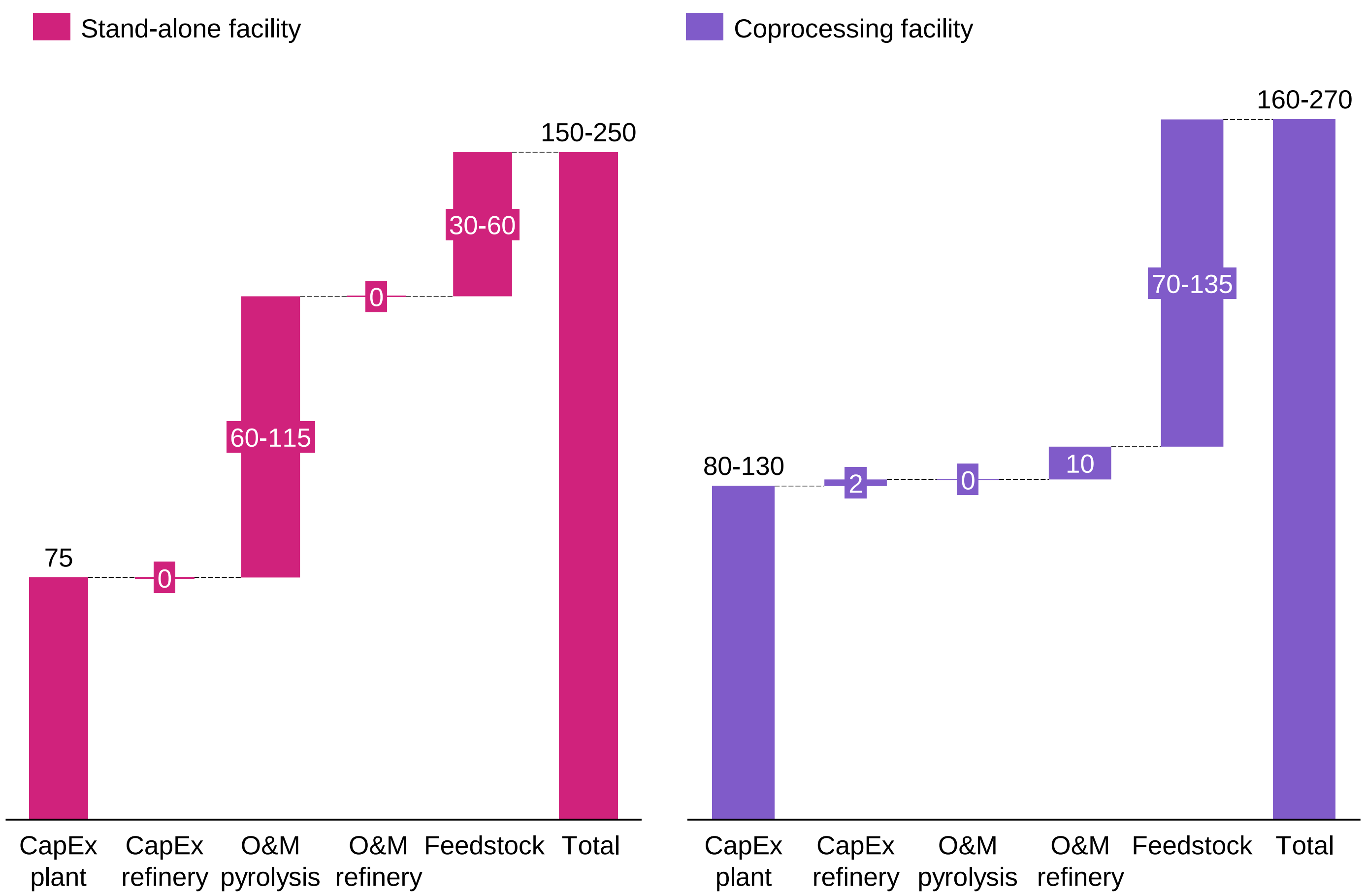
Top producers

Country	No. plants	Pyrolysis oil production (ton/yr)	Feedstock
Canada	3	~61,000	Forest residue
Finland	2	~25,000	Forest residue
Sweden	1	~24,000	Organic residues, waste streams
Netherlands	2	~48,000	Forest residue
China	1	12 MW electricity	Agricultural residues

Sources: Transparency Market Research, Pyrolysis Oil Market (2021); Allied Market Research, Pyrolysis Oil Market (2021); ICIS, Pyrolysis Oil Demand (2025); IDTechEx, Future of Market and Regulatory Landscape (2024); MDPI, Review of the Current State of Pyrolysis (2024); IEA Bioenergy, Facilities (2025).
Credit: Sean Lee, Augusto Agazzi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Technology still in pilot stage, leading to high costs; coprocessing with existing refineries is being tested but remains low yield

Pyrolysis oil cost structure in 2020, *$/boe* (1 EUR = $1.15 conversion rate)



Observations

- **Upgrading pyrolysis oil into SAF is currently processed through two main routes:**
  - Hydrogenation carried out as an **integrated part of the pyrolysis plant facility (stand-alone).**
  - **Coprocessing** with fossil fuel in fossil fuel refinery.
- **Costs vary based on production status between coprocessing or stand-alone plants;** coprocessing has been explored only on a lab scale, and recent focus has been on improving intermediary products such as bio-oil rather than on a final product of pyrolysis oil.
- **Conversion efficiency is 68% for stand-alone plants and 29% in coprocessing plants, resulting in higher feedstock cost for coprocessing facilities.**
- **Cost reductions will occur mainly on the feedstock level**, while process improvements and lower cost of capital can provide marginal reductions.
- **Economies of scale** could further reduce the capital cost, subject to technology advancement.
- Stand-alone facilities **have much higher conversion efficiency than coprocessing.** As such, to balance costs and production, a larger data set must be considered.

Source: IEA, Advanced Biofuels (2020).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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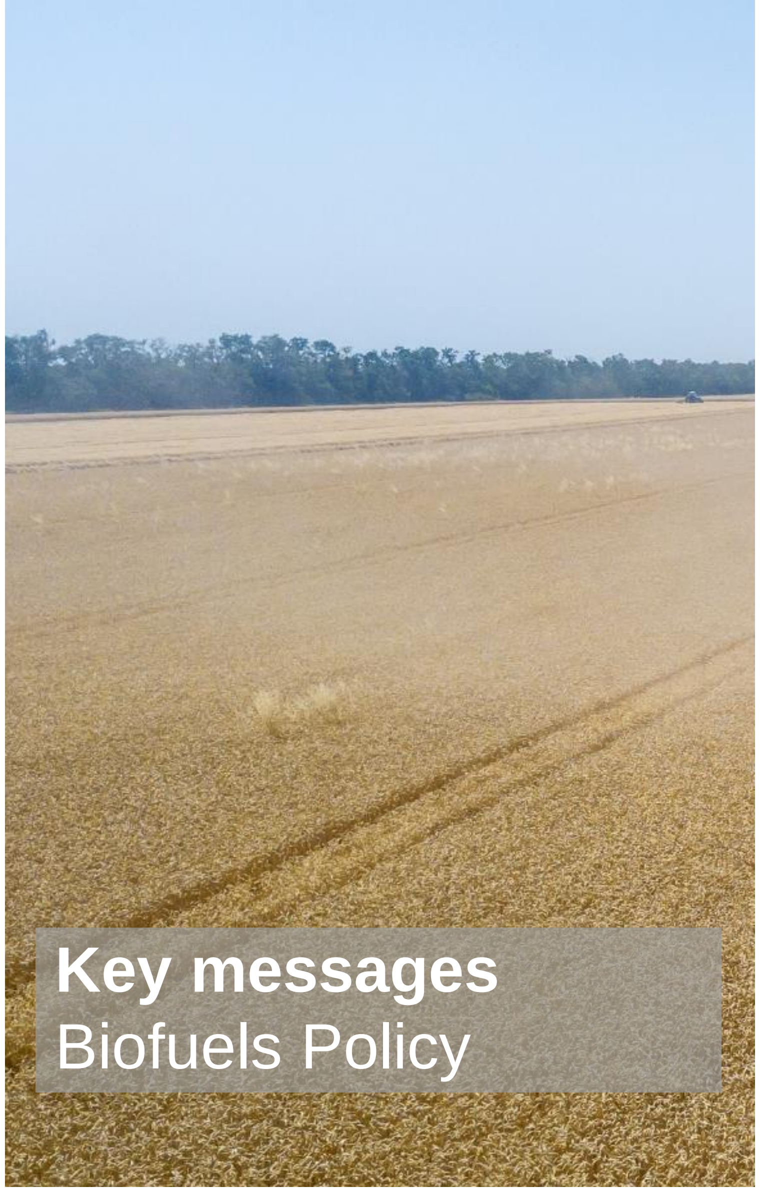
Biofuels Policy



Biofuel policies are rapidly evolving worldwide, with various countries implementing diverse approaches such as market-based incentives, compliance-driven mandates, and direct policy.

In the U.S., **Renewable Fuel Standard (RFS)** mandates renewable fuel volumes yearly target with a range of **financial incentives** to promote waste- and residue-based biofuel and SAF.

- **Recent OBBBA reinforces conventional biofuels but dampens momentum for advanced biofuel and SAF**, reflecting the exclusion of ILUC from carbon-intensity metrics and reduction of SAF incentive caps.
- **California's performance-based Low-Carbon Fuel Standard (LCFS)** drives lower GHG emissions in transportation through a market-based credit system.

In the EU, the **Fit for 55 package provides a set of measures to reduce GHG by 55% by 2030** compared with 1990 levels.

- The **Renewable Energy Directive (RED) sets specific targets for biofuels,** complemented by ReFuelEU Aviation and FuelEU Maritime, which establish specific goals for the aviation and maritime sectors.

In Brazil, a **"fuel matrix"** combines targets, mandates, efficiency scores, and decarbonization credits for biofuels.

- **RenovaBio** brings together producers, consumers, and investors to create a market for **decarbonization credit (CBio).** Fuel distributors can purchase CBio to comply with reduction targets, and investors can trade CBio.

In China, Indonesia, and other Asian countries, **biofuel is being adopted as a key pillar of their renewable energy ambitions.** However, efforts are mostly government-led with a varying degree of commitments.

Biofuel policy should align with a country's renewable energy strategy. **Biofuels can serve either as a transition fuel in road transport as electrification scales** (e.g., Norway) or **as a primary fuel across transport modes**, alongside other renewables.

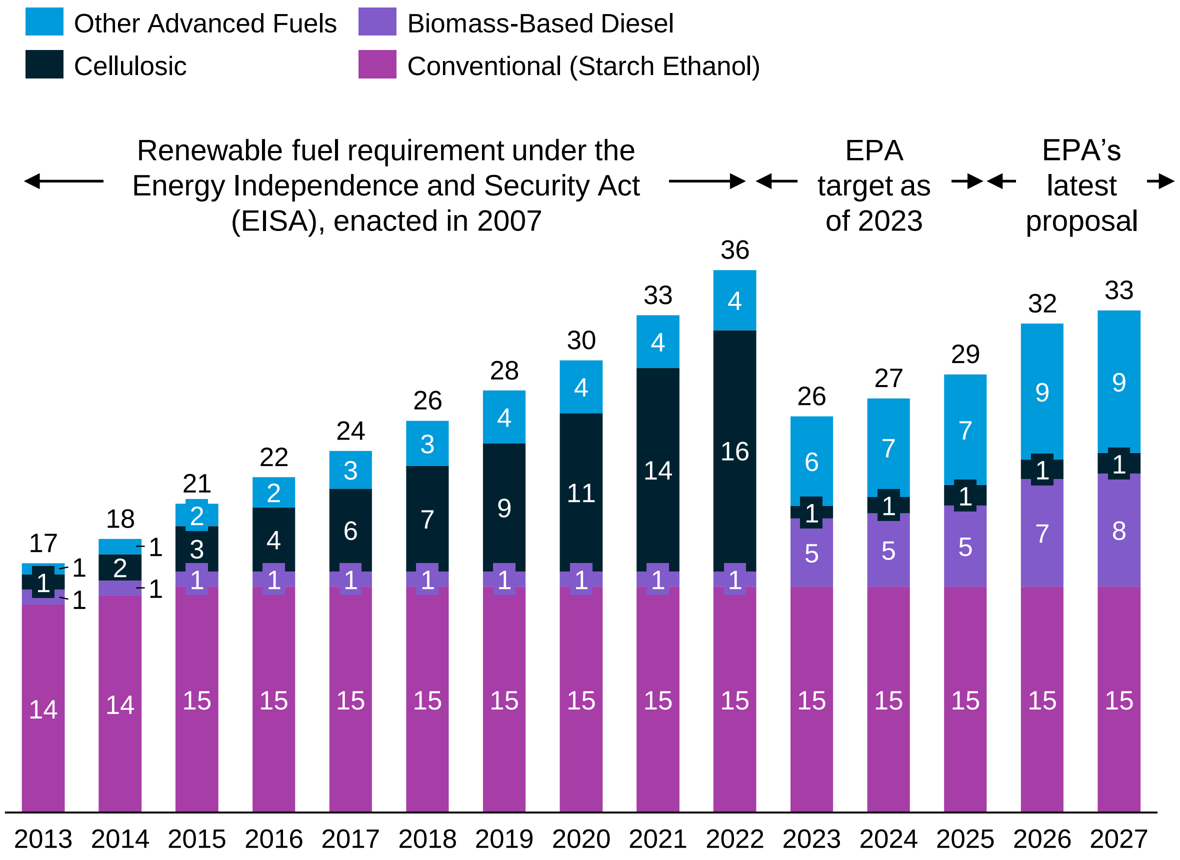
Biofuel policies are evolving quickly with different schemes observed across the globe

	U.S.	EU	Brazil	China	Indonesia
Policy framework	• Market-based, with government support*	• Regulatory, with market mechanism	• Regulatory, with market mechanism	• Government-led, with market development	• Government-led, with market development
Objective	• Reduce reliance on fossil fuels; reduce GHG emission; energy security; stimulate growth of renewable energy				
Key legislation	• Renewable Fuel Standard (RFS)	• Renewable Energy Directive (RED), ReFuel Aviation, FuelEu Maritime, FQD	• RenovaBio, ROTA 2030, Proconve, Brazil National Energy Plan	• Renewable Energy Law, 14th Five-Year Plan for a Modern Energy System	• Ministerial Decree – Energy and Mineral Resources No 12. 2015
Financial incentives	• Broad incentives in place (e.g., blenders tax credit, biomass crop assistance program)	• No uniform incentives across EU; member states have flexibility to introduce national incentives	• Decarbonization credits provided based on efficiency scores for producers, traded on stock exchange market	• Lack of incentives for biodiesel producer and user • Ethanol subsidies for Gen 2	• Offers limited financial incentives (e.g., grants, tax credit for producers)
Mandates	• Lower GHG emission across four biofuel categories: conventional biofuel, advanced biofuel, cellulosic, biomass • Annual production target for renewable biofuels	• Road: 16% GHG reduction by 2030 • Maritime: 6% GHG intensity reduction by 2030, 75% by 2050 • Aviation: 5% SAF by 2030, 63% SAF by 2050	• National target: 11% reduction until 2033 • Aviation: 10% reduction per year by 2037 • Fuels: 27% ethanol mandate and 12% biodiesel mandate	• E10 mandate by 2020 but suspended for nationwide implementation due to corn supply concerns • B5 mandate implemented in select provinces	• Gradually increased biodiesel blending from 15% in 2015 to 35% in 2023 • Further hike to 40% expected by 2025
Feedstock preference	• Gen 1 (corn)	• Gen 1 (rapeseed oil) but shifting to Gen 2	• Gen 1 (soybean oil)	• Gen 1 (corn)	• Gen1 (palm oil)
Future directions	• Expansion of advanced biofuels, cellulosic ethanol	• Focus on sustainability, advanced biofuels	• Expansion of SAF and cellulosic ethanol, diversification of feedstock	• Innovation in feedstocks (cellulosic) • Growing focus on electrification (vs. biofuel)	• Increased production capacity • Diversification of feedstocks

Sources: U.S. EPA, Overview of the Renewable Fuel Standard Program (2025); CATF, U.S. Renewable Fuel Standard (2023); European Court of Auditors, The EU's Support for Sustainable Biofuels in Transport (2023); TransportPolicy.net, EU: Fuels: Biofuel Policy (2024); IEA Bioenergy, Biofuels Production and Development in China (2023); Climate Action Tracker, Indonesia (2025); USDA, China: Biofuels Annual (2023); IEA, RenovaBio (2023); IEA, Biofuel Policy in Brazil, India and the United States (2023).
Credit: Yosafat Partogi, Birru Lucha, Sean Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Regulation through the Renewable Fuel Standard is still the biggest driver of demand for biofuel in the U.S.

RFS volume requirement by year, *billion RINs*



RFS Overview

Overview

- Oil refiners and gasoline/diesel importers are required to blend biofuels into their supply or purchase RINs (tradeable credits for each gallon produced) to meet the **Renewable Volume Obligation (RVO) based on sales.**

Mandates

- The U.S. EPA sets **specific volume requirements** for renewable fuels to be blended into gasoline/diesel, which are adjusted annually.
- Categories are based on reduction of lifecycle GHG emission (vs. conventional fuel):
  - Conventional biofuels (corn ethanol – Gen 1): 20% reduction
  - Advanced biofuels (Gen 2): 50% reduction
    - → Cellulosic biofuels (non-food biomass – Gen 2): 60% reduction
    - → Biomass-based diesel (Gen 1 and 2): 50% reduction
- The **EPA cellulosic target from 2023 was significantly adjusted** due to technical challenges.
- Despite ongoing debate over the **negative environmental impacts of corn ethanol**, particularly from land-use change, RFS targets continue to include ethanol (conventional fuel) as the majority share of the volume target.

Challenges

- **Lack of emission-reduction incentives:** RFS mandates only minimum GHG reductions (20%, 50%, 60%) without incentivizing further reductions.
  - Unlike California's LCFS, which is performance-based, the RFS does not reward lower carbon intensity beyond the thresholds mentioned above.

Note: Total may not sum exactly due to rounding.
Sources: U.S. EPA, Overview of the Renewable Fuel Standard Program (2025); U.S. GPO, Standards for 2023-2025 (2023); CATF, U.S. Renewable Fuel Standard (2023); CME Group, Biofuel Feedstocks in the United States (2023); AFPM, How RFS Biofuel Mandates Drive Imports (2019); WRI, EPA's New RFS (2023); EPA, Proposed RFS for 2026-27 (2025).
Credit: Yosafat Partogi, Birru Lucha, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

U.S. pushes biofuel adoption agenda through tax credits and subsidies

Detailed assessment of post-OBBBA impact

Feedstock Producers | Biofuels Production | Connection/ Infrastructure

Ethanol | Biodiesel | Advanced/RD

Advanced biofuel feedstock incentives
- 50% cost reimbursement for establishing a feedstock crop

Advanced biofuel production grants and loan guarantees
- Maximum loan guarantee of $250 million
- Maximum grant funding of 50% project costs

Integrated biorefineries grant
- Scale-Up/Scale-Up+ Program: DOE funding to reduce carbon emissions in first-gen corn ethanol facilities and scale up integrated biorefineries

Advanced biofuel production payments (Sec. 9005)
- Payment to support expanded production of advanced biofuels

Clean fuel production credit (45Z)
- Tax credits for the production and sale of low-emission transportation fuels that meet carbon reduction criteria, including sustainable aviation fuel (SAF)

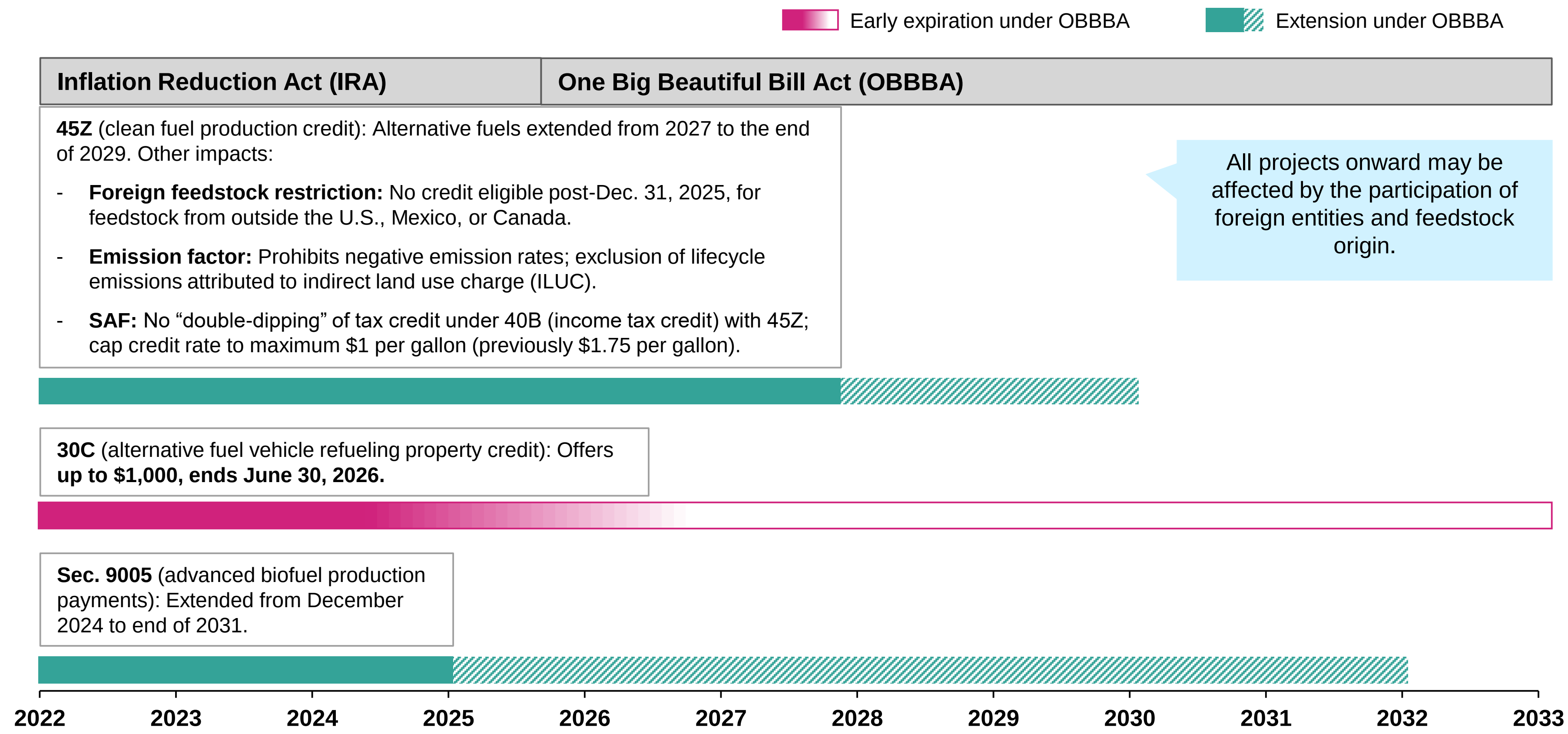
Biodiesel and ethanol infrastructure grants
- 50% of total project costs or $3 million (whichever is less)

Alternative fuel infrastructure tax credit (30C)
- 6% of depreciable cost up to 100K per item
- 30% of cost with wage and apprenticeship requirements

Source: DOE, Federal Laws and Incentives (2025).
Credit: Yosafat Partogi, Birru Lucha, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

OBBBA extends IRA support for conventional biofuels and undercuts advanced/SAF momentum

Federal incentives on clean fuels



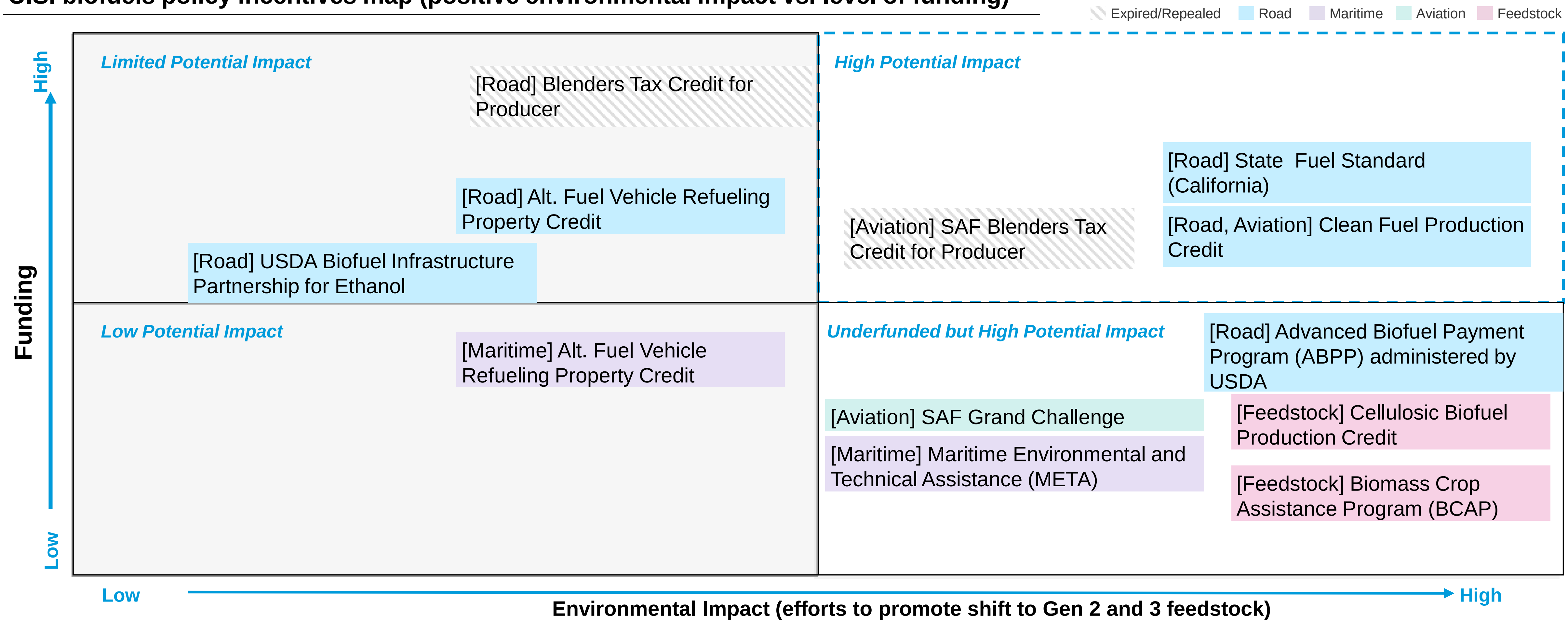
Observations

- Linked with the Renewable Fuel Standard target, **OBBBA shifts the marginal credit value toward conventional biofuels, due to:**
  - Exclusion of ILUC from the carbon emission intensity (CI) calculation, which benefits the crop-based biofuels
  - Lower incentive for SAF
- **OBBBA promotes lower abatement efficiency per dollar of incentive** by favoring higher volume, mid-CI fuels over lower volume, very low CI options, absent tighter CI standards or complementary measures.

Sources: Arnold & Porter, From IRA to OBBBA (2025); RSM, Modified clean fuel tax credit (2025); DoerenMayhew, OBBBA viewpoints (2025); CATF, 45Z clean fuel tax credit (2025).
Credit: Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

U.S. incentives for Gen 2-3 feedstock vary in funding and impact; opportunities to bolster underfunded initiatives with high potential

U.S. biofuels policy incentives map (positive environmental impact vs. level of funding)



Sources: U.S. EPA, Overview of the Renewable Fuel Standard Program (2025); U.S. GPO, Standards for 2023-2025 (2023); U.S. DOE, Biodiesel Laws and Incentives in Federal (2025); U.S. DOT (Transport), META overview (2025).

Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

EU promotes biofuel adoption through a compliance approach; opportunity to drive growth through more financial incentives

EU has a robust framework and compliance approach for biofuel…

Objective

- **European Green Deal (EGD):** Overarching vision of EU's climate neutral ambition by 2050
- **Fit for 55:** Package of proposals adopted by the EU Commission (July 2021) to achieve EGD ambitions; aims to reduce net GHG emissions by at least 55% by 2030 (vs. 1990 levels)

Key items: Fit for 55 package

- **Renewable Energy Directive (RED) III** *(provisionally adopted):* Set 14% renewable energy in transport by 2030

RED Biofuel Policy	
Mandates	Flexibility to implement specific blending mandates within the overall RED framework
Types	RED promotes the use of advanced biofuels and pushes from Gen 1 to Gen 2 feedstocks (e.g., waste, residues)
Certification	Certification system to ensure that biofuels comply with sustainability criteria and can be traded in EU
Feedstock	Specifies which feedstock can be used for biofuel production (to prevent competition with food production)

- **FuelEU Maritime:** Achieve 6% GHG intensity reduction by 2030; 75% by 2050 in maritime
- **Fuel Quality Directive (FQD) amendment:** Sets 6% reduction in GHG intensity of fuels by 2030 (vs. 2010)

… but member states perceive challenges

1 Financial incentives

- Member states vary in incentives to promote biofuel adoption; EU regulations limit government support to avoid distorting competition.

2 Cost competitiveness

- Biofuels are inherently more expensive than fossil fuels, making them less attractive without subsidies.

3 Electrification

- A heavy bet on electric cars, combined with the planned end of new ICE cars by 2035, may suggest that biofuels have no large-scale future in road transport.

4 Compliance

- Biofuel standards vary between countries and transportation subsector, which can make navigating through the ever-evolving regulations complex, hindering biofuel adoption rates.

Sources: European Court of Auditors, The EU's Support for Sustainable Biofuels in Transport (2023); TransportPolicy.net, EU: Fuels: Biofuel Policy (2025); Now.Gmbh.De, Renewable Energy Directive III (2024); KPMG, The European Green Deal & Fit for 55 (2023); EcoLogic, Analysis of the Implementation of EU Provisions for the Clean Energy Transition in Selected Member States (2024); Open Democracy, UK airlines' new 'sustainable' fuels may be causing deforestation in Asia (2023); European Energy Agency, EVs (2024); NorthStandard, IMO Removes Regulatory Barriers for Biofuel Blends (2022); Wallenius Wilhelmsen, Carbon Intensity Indicator (2023).

Credit: Yosafat Partogi, Birru Lucha, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

EU uses a 'stick' approach to push SAF adoption, while the U.S. uses a 'carrot' approach with tax credits and grants

	EU drives SAF adoption through compliance measures	U.S. pushes SAF adoption through a series of incentives
Objective	• **ReFuelEU Aviation:** Legal initiative for aviation as part of the EU's ambition to reduce GHG emissions by 55% (vs. 1990 levels) by increasing uptake of sustainable aviation fuels (SAF) in the EU.	• **Wide range of market-based incentives:** U.S. Sustainable Skies Act (2021), SAF Grand Challenge, etc.
Key items	• **Aviation fuel suppliers are bound by law to include a certain percentage of SAF** in fuel provided to aircraft operators at EU airports: – 2% by 2025, reaching 70% by 2050; from 2030, minimum synthetic fuels will be required, starting at 1.2% and increasing to 35% by 2050 • **Implementation:** Expected to come into force in 2025; airlines can purchase more SAF than required and sell excess credits • **Monitoring:** Member states responsible for implementing regulation and determining non-compliance penalties	• **Clean fuel production credit:** Provides up to $1 per gallon of SAF production credit when wage apprenticeship requirements are met • Grant of $1 billion over five years to **expand the number of SAF facilities** in the U.S. • **Fueling Aviation's Sustainable Transition (FAST) grants** amounting to $300 million in awards for SAF tech • **SAF Grand Challenge:** U.S. to increase SAF to at least 3 billion gallons per year by 2030
Challenge	• Limited SAF production scale; **>2x more costly than traditional jet fuel**; more government subsidies required • **Feedstock availability** and balancing biofuel needs while avoiding displacement of food crops • **Aligning member states' SAF incentives** with global standard and policies	

Sources: IATA, CORSIA Fact Sheet (2024); European Commission, ReFuelEU Aviation (2025); The Green Mobility Magazine, Green Mobility (2025); ICAO, About ICAO (2025); US DOT (Transport), Biden Harris Administration Announces Nearly $300 Million in Awards for Sustainable Aviation Fuel (2024).

Credit: Yosafat Partogi, Birru Lucha, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Brazil uses a ‘fuel matrix,’ combining targets and mandates, efficiency scores, and decarbonization credits to expand biofuels

Long-term strategy for biofuels adoption

Objective

- **Brazil National Energy Plan:** Sets direction for future energy supply and demand across the country
- **RenovaBio:** National biofuels policy with three axes that bring together producers, consumers, and investors to create a decarbonization credit market and provide financial benefits

RenovaBio and fuel matrix policy integration

RenovaBio axes and policy integration:	
National targets	Establishes 11% emissions reduction target until 2033, defined by the National Council for Energy Policy
Certification	Efficiency scores given to producers based on lifecycle analysis from well to tank
Decarboni-zation credits	CBio credits traded on the Brazilian stock exchange based on reduction of emissions
Fuel of the future	Integration of RenovaBio, Rota 2030 program, air pollution control program, and vehicle labeling program

- Fuel distributors can purchase CBio to comply with reduction targets or **face penalties and sanctions**; investors can trade CBio
- CBio provides **additional income for producers and importers** in addition to sales of biofuels, extra income amounting to R$0.15 per liter produced for producers; **expected market financial volume of $700 million**

Benefits of a long-term integrated strategy

1 Policy synergies

- RenovaBio plus ROTA 2030 allows for specific goal-setting within the automotive industry; the Proconve program harmonizes the Rota 2030 schedule with air pollution control mechanisms; national SAF and green diesel programs encourage production of biofuels within the energy matrix system.

2 Investment signals

- Clear mandates and policy certainty for ethanol and biodiesel, as well as for blending rates, provide clear signals to investors who are interested in the clean energy economy.

3 Financial incentives

- Provides tax incentives for flex-fuel and ethanol vehicles; the Brazil National Bank for Social and Economic Development provides lines of credit for sugar, ethanol, logistics, transport, and feedstock investment, as well as a climate fund focused on reducing carbon intensity.

4 Innovation and cooperation

- Continual proposal of new measures is aimed at increasing adoption of low-carbon fuels, including participation in global bioenergy partnerships to facilitate industry growth.

Sources: IEA, RenovaBio (2023); IEA, Global Biofuel Alliance (2023).
Credit: Sean Lee, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Indonesia commits to biodiesel while China shifts focus elsewhere

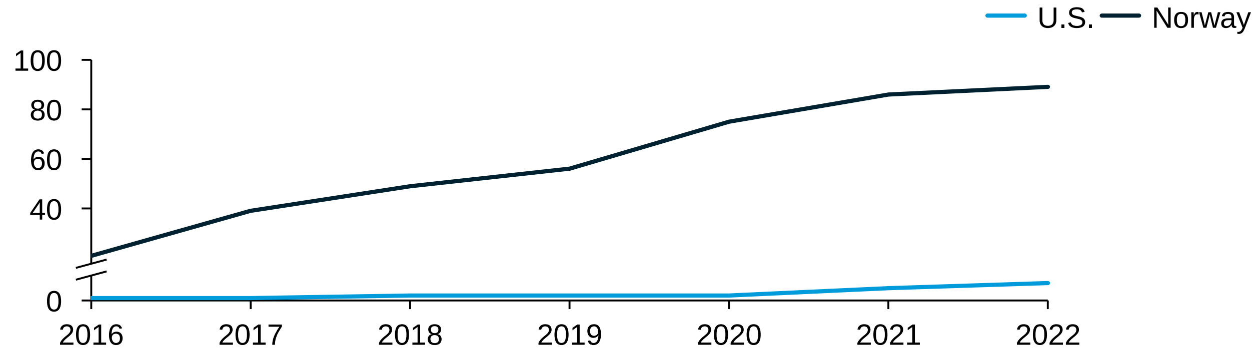
	China: Biofuel ambition dimmed by EV push	Indonesia: Strong push for biodiesel production
Legislative policy	• **Renewable Energy Law:** Provides overarching framework for renewable energy development including biofuels, supplemented by the **14th Five-Year Plan** (2021-25).	• **Ministerial Decree No.12, 2015:** Issued by the Ministry of Energy and Mineral Resources, mandates use of biofuels in the country.
Key items	• **Mandatory blending:** Aim is to satisfy E10 blend mandate by 2020; the enforcement target was **scaled back nationally** due to feedstock supply concerns. – The country relies on **corn crops as primary feedstock** for bioethanol. – **Some financial incentives** are in place, including subsidies for ethanol producers and a tax exemption on fuel ethanol. • China piloted a **B5 biodiesel mandate,** but implementation has been limited to select provinces with limited adoption.	• **Mandatory blending:** Current blend is B30 (30% biodiesel, 70% petroleum) for the transportation/industrial sector, with a gradual increase in target ratio. – The country relies **on palm oil** as the primary feedstock for biodiesel. – Biodiesel **mandates have not fully displaced conventional diesel,** partly due to consumer concerns about its impact on vehicles. – **Biodiesel subsidy:** The government collects export levies on Crude Palm Oil (CPO) to subsidize biodiesel producers, to cover the price differential between biodiesel and petroleum diesel.
Trends	• Exploration of **advanced biofuels** (i.e., cellulosic ethanol), to reduce reliance on food crops. • Focus on the **commercial application of SAF,** with the goal of reaching more than 50K ton of consumption by 2025. • **Policy shift** in recent years, with more emphasis on **electrification** vs. biofuels.	• Policy and implementation heavily skewed toward biodiesel, struggling to meet the E5 blending mandate. • Focus on bolstering biofuel sector by enhancing **biodiesel adoption incentives**, **revitalizing its dormant bioethanol program**, and **diversifying feedstock sources.**

Sources: IATA, CORSIA Fact Sheet (2024); The Green Mobility Magazine, Green mobility (2025); ICAO, About ICAO (2025); U.S. DOT (Transport), Biden Harris Administration Announces Nearly $300 Million in Awards for Sustainable Aviation Fuel and Technologies as part of Investing in America Agenda (2024).

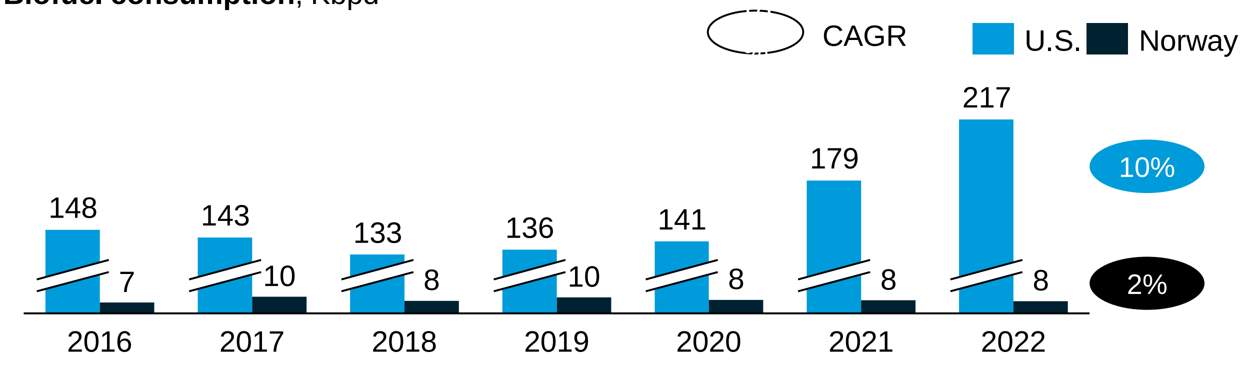
Biofuel adoption differs by country; in Norway, rapid EV penetration has suppressed biofuel growth

Rapid EV uptake has coincided with slower biofuel growth in Norway relative to the U.S. …

Share of EV sales (vs. internal combustion engine), %



Biofuel consumption, Kbpd



… fueled by the country's aggressive EV subsidies

Mandate	• **Biofuel mandate:** 24.5% of the volume of fuels supplied to be biofuel; a minimum of 9% must be advanced biofuels (in liquid form) • Mandated share of biofuel by transport mode: Road at 19%, aviation at 0.5%, and shipping at 6% • **Current biofuel growth is driven more by aviation and shipping**, also in line with the EU's ReFuelEU Aviation and FuelEu Maritime.
Incentive	• **Green tax incentives:** EVs are exempt from purchase, import, and road taxes, while fossil fuel cars face a hefty 25% tax. – EV is more price competitive to customers than ICE. – One-quarter of cars on Norwegian roads are electric, contributing to an 8.3% decrease in surface transportation emissions from 2014 to 2023.
Infra-structure	• **Network of public charging stations:** One fast-charging station every 50 km (31 miles) on major highways, totaling 15,000 public charging points nationwide
Challenges	• **Large budget allocations for EV subsidies** • **Lower public transport rates**, making it difficult for those without cars, as pricing becomes uncompetitive compared with EV ownership

Note: Electric car includes fully battery-electric and plug-in hybrids; non-electric car includes petrol, diesel, and non-plug-in hybrid.

Sources: Forbes, How Norway Increased EVs to 82% Of New Car Sales (2024); Vox, Why Norway — the poster child for electric cars — is having second thoughts (2023); McKinsey, What Norway's Experience Reveals About the EV Charging Market (2023); OurWorldInData, Number of new cars sold, by type (2025); Robbie Andrew, CICERO, Norway EV Sales and Related Data (2025); GlobalEconomy, USA: Biofuels production (2025); IEA, State Budget – Biofuel blending requirement (2024).

Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

California's Low-Carbon Fuel Standard (LCFS) lowers GHG emissions in transportation through a market-based credit system

California's LCFS carbon intensity-based trading system

Objective

- **LCFS: Designed to reduce GHG emissions from transportation using a market-based mechanism that caps the carbon intensity (CI) of fuels.**
  - CI is a measure of lifecycle GHG emissions associated with the production, distribution, and consumption of transportation fuels.
  - The California Air Resources Board (CARB) set CI targets to gradually decline 80% from a 2010 baseline by 2030 and remain constant.

Mandate

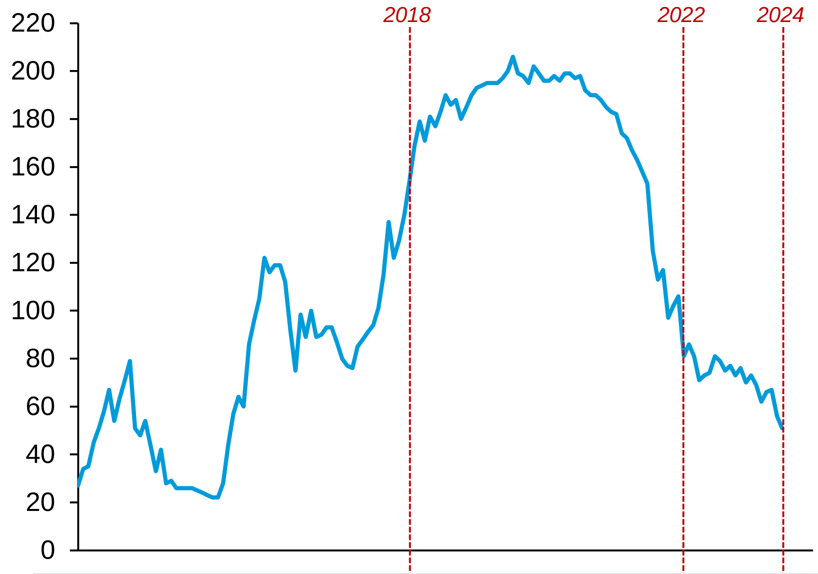
- **Type of fuels covered:** All fossil fuel (gasoline, diesel), CNG, LNG, biofuels, electricity, and hydrogen
- **Regulated parties:** Fuel producers/importers, plant owners, electric distribution utilities (EDUs), EV service providers (EVSPs), and fleet operators for private access charging
- **Credit and deficit system:** Fuels with higher CI than the benchmark (gasoline/diesel) generate deficits while those with lower CI generate credits.
  - If a regulated party has a deficit at the end of reporting year, they must **purchase credit from parties that generated a surplus.**

Pricing

- **1 LCFS credit = 1 Mt CO_2 of avoided GHG emissions**
- **Pricing drivers:** Difference in CI between the baseline and alternative fuel, volume of baseline fuel displaced, energy density, and volume and energy efficiency ratio of the alternative fuel
- **CARB put a $200 cap on credit prices per Mt** in 2016 dollars, adjusted for inflation annually.

LCFS credit price drops

Monthly average LCFS credit price
in $ between 2013-2024

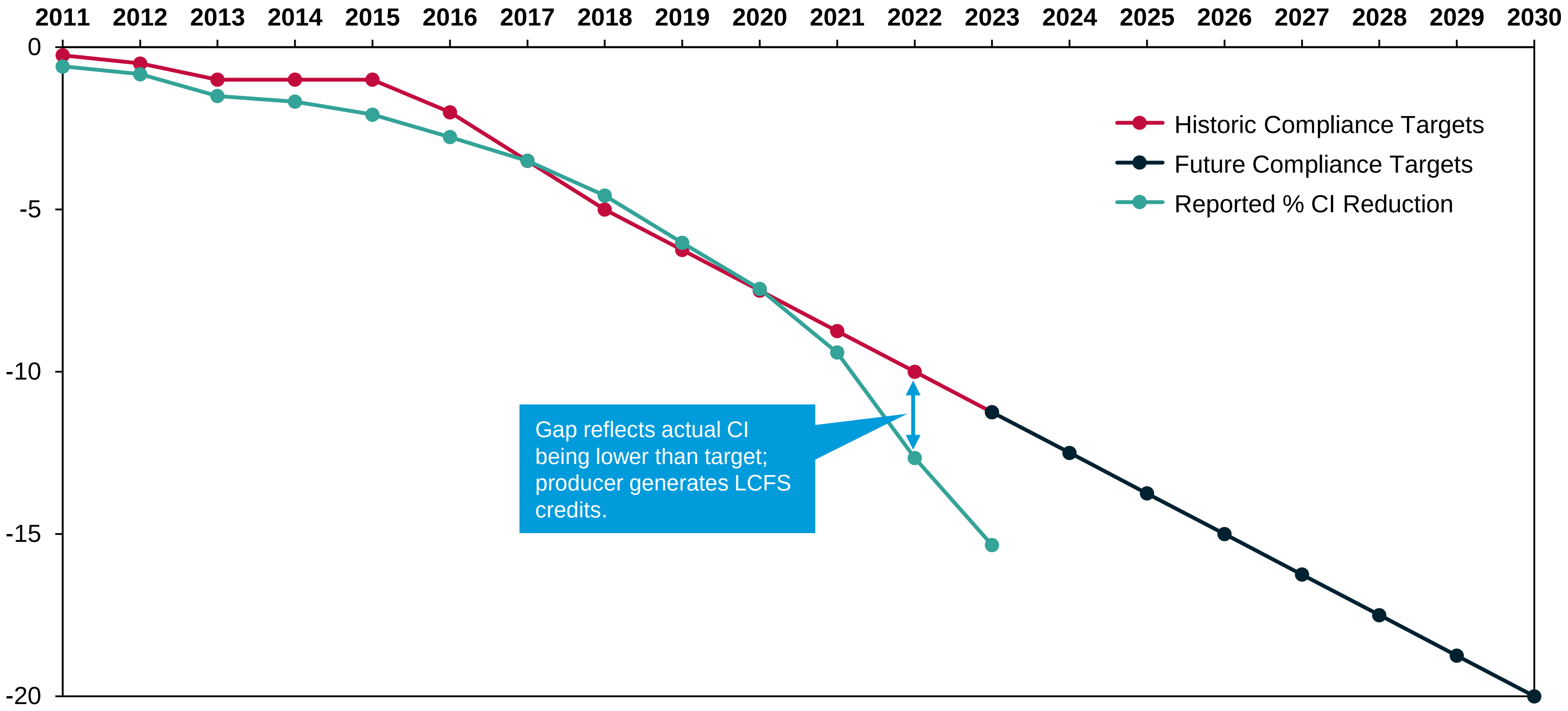


- **The steep decrease in the LCFS credit price** was driven by a surplus of credits in the market, caused by an increase in the use of renewable fuels, EVs, and other low-carbon fuels.

California's LCFS performance is on track to meet the 2030 carbon intensity (CI) reduction target; LCFS can also support EV adoption

CA's transportation fuel market appears on target to fulfill the 2030 CI reduction target

Performance of California LCFS carbon intensity
in relative % CI reduction from 2010 level



LCFS to support EV adoption

Scenario 1: EV fueling stations

- **Cost of electricity: $0.20-$0.30/kWh**
- **EV fueling at public charging stations:**
  - Charges higher for additional infrastructure, low utilization from limited EVs on the road
- **Incentives for EV fueling stations, as LCFS credit can cover 50-80% of electricity cost**
  - **Assumption:** With a max LCFS credit price of $200/Mt, a fully charging 65 kWh Chevy Bolt battery could earn $10.25 in LCFS credit, or $0.16/kWh (using an LCFS CARB calculator).

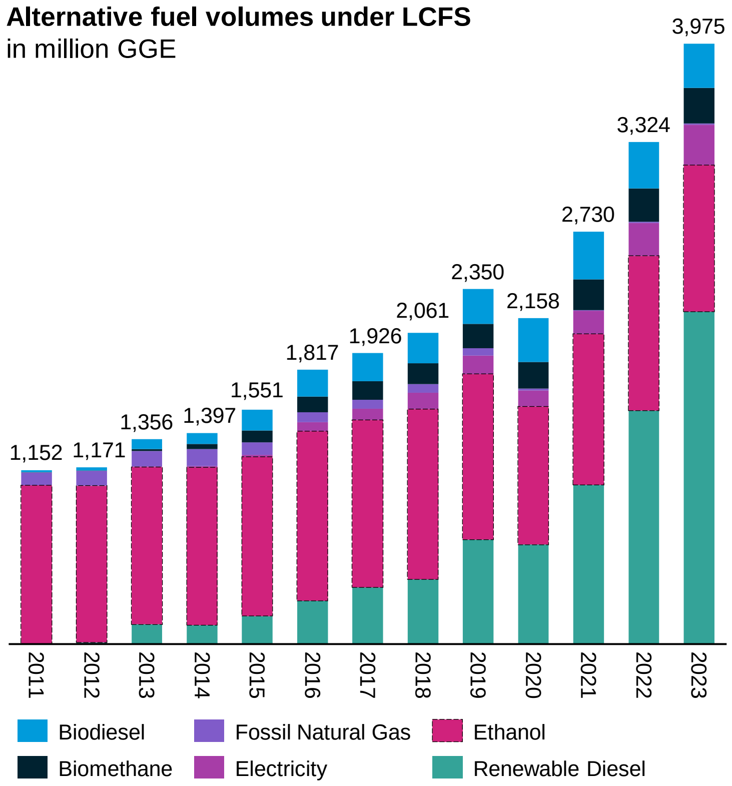
Scenario 2: EV fleet operators own fueling stations

- **EV fleet operators can own or partner with EV service providers to share LCFS credit revenue**, which could lower total cost of ownership by lowering fuel cost.

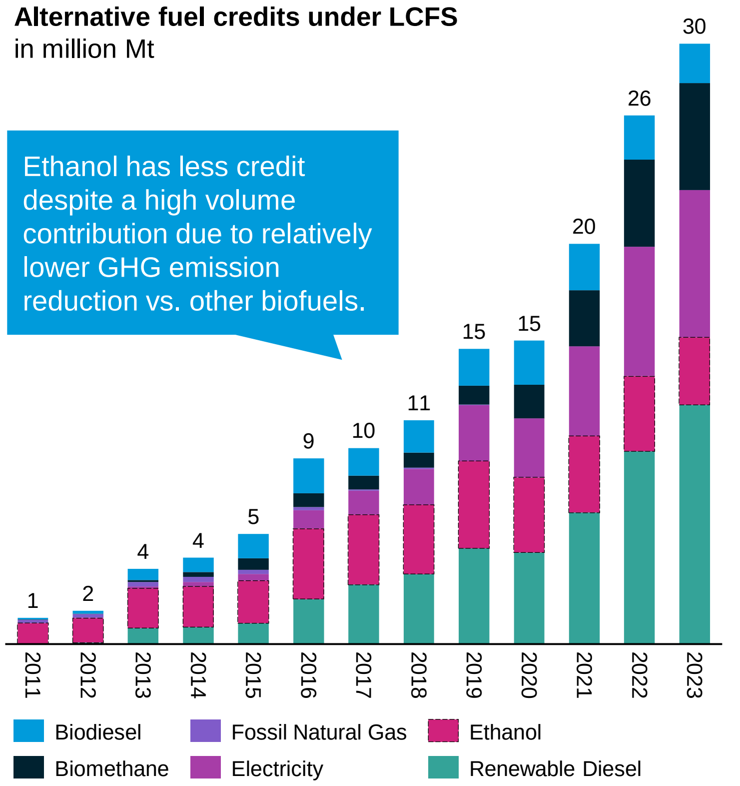
Source: California Air Resources Board, LCFS Data Dashboard (2025).
Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Ethanol contributes large volume for LCFS but earns less credit than renewable diesel & electricity; producers have positive margin

Ethanol and renewable diesel: LCFS volume driver



Ethanol is not the largest credit generator for LCFS



E85 has positive margin but lacks demand vs. traditional fuel

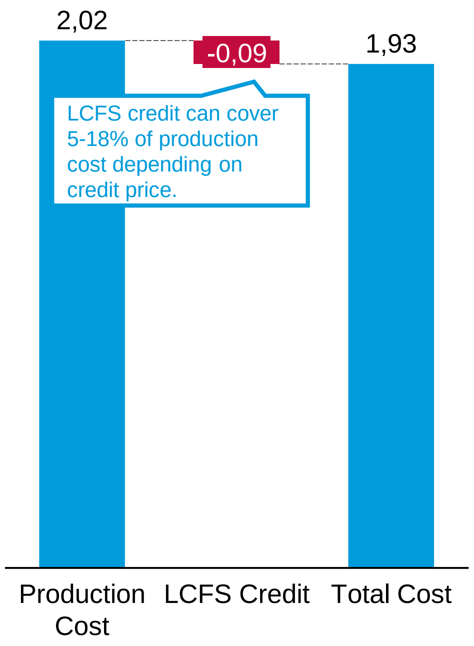
- **Average fuel retail price of biofuel in the U.S. (2020):**
  - E85: $2.04 per gallon (vs. $2.65 for gasoline)
- **Estimated cost of producing biofuel in the U.S. (2020):**
  - E85: $1.99 per gallon (vs. $1.90 for gasoline)
- **While E85 can be cheaper by 30 to 70 cents per gallon than gasoline, energy density is lower and requires more gallons per mile.**
  - E85 users tend to have 20-30% less mileage than with traditional gasoline.
  - In terms of gallon of gasoline equivalent (GGE), the price of E85 must always be ~30% lower than gasoline to be commercially competitive.
- **A limited number of cars in the market are compatible with E85 (only flex-fuel cars).**

Sources: California Air Resources Board, LCFS Data Dashboard (2025); U.S. EPA, Science Inventory (2025).
Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Today, LCFS credit can reduce the production cost of renewable diesel by approximately 3x more than it does for E85

E85 producers can offset 5% of their production costs …

Breakdown of E85 cost
in $ per gallon, 2020

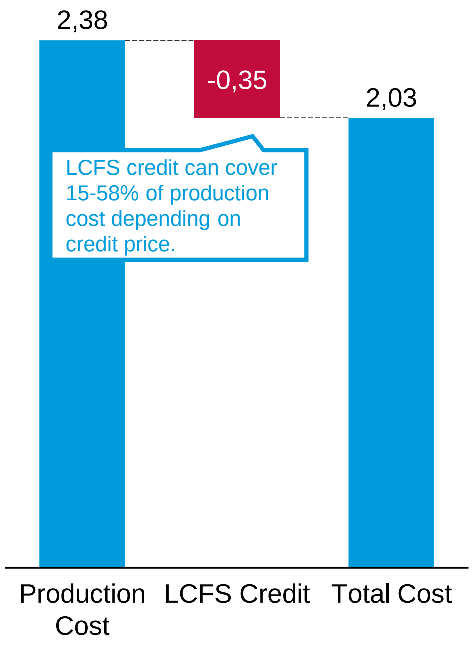


- **E85 cost of production:** Driven by feedstock price; relatively low CapEx, as it is considered a mature tech
- **Estimated price per barrel (2020):** Between $85 and $200/boe, or around $2.02 per gallon
- **E85 has a gCO2/MJ of 64.7** (well-to-wheel estimate).
- **Incorporating carbon intensity of renewable diesel into California's LCFS credit calculator:**
  - A credit of $0.09 per gallon is produced at the current credit price of $50 per unit.
  - However, at the peak credit price of $200, the credit from renewable diesel could rise to $0.36 per gallon.

LCFS credit can cover between 5% and 18% of production costs subject to the volatility of the LCFS credit price.

… while renewable diesel can offset 15% to 58%

Breakdown of renewable diesel cost
in $ per gallon, 2020



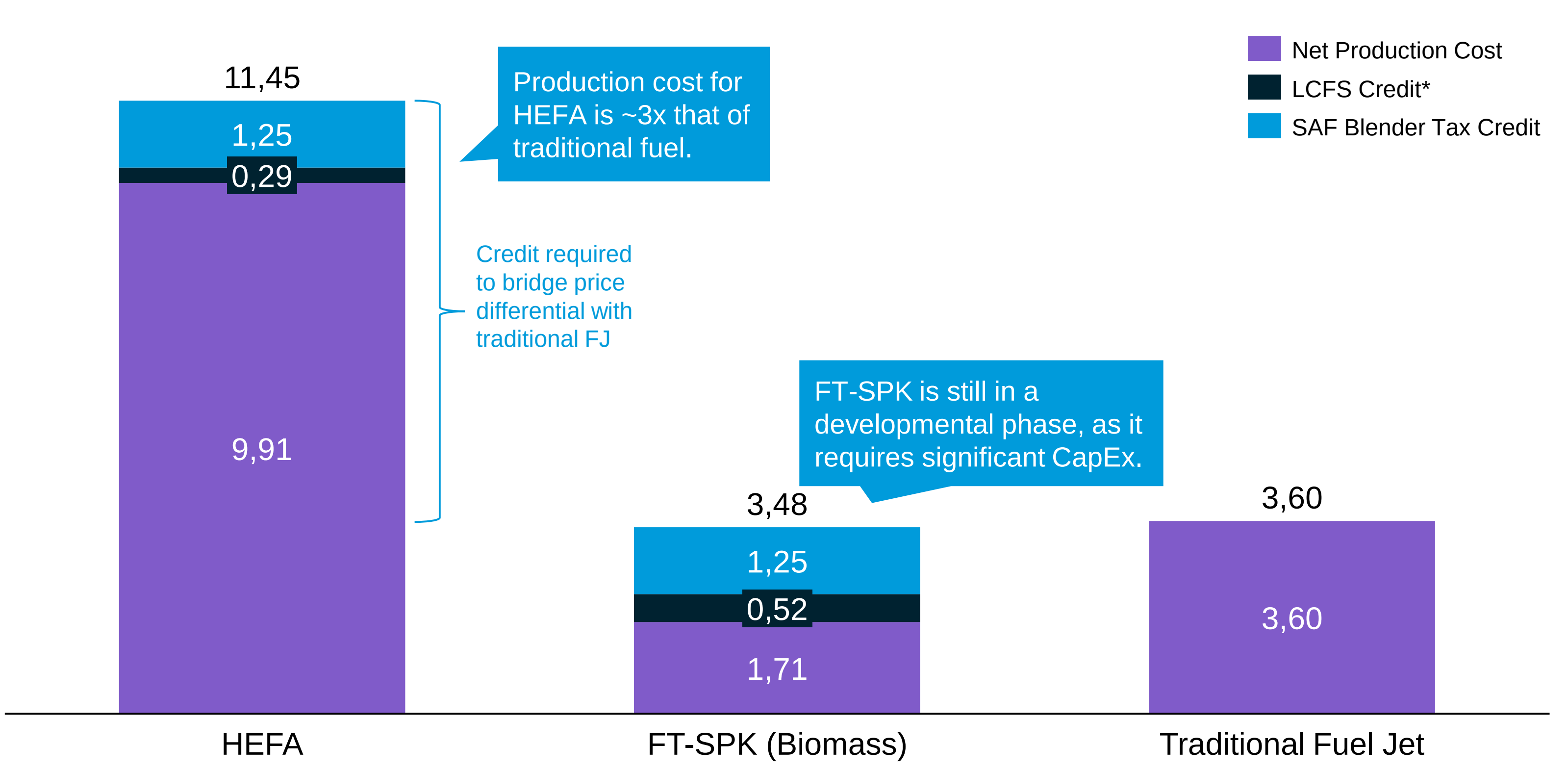
- **Renewable diesel cost of production:** Driven by feedstock price
- **Estimated price per barrel cost (2020):** Between $100 and $178/boe, or approximately $2.38 per gallon
- **Renewable diesel has a gCO2/MJ of 33.6** (well-to-wheel estimate).
- **Incorporating carbon intensity of renewable diesel into California's LCFS credit calculator:**
  - A credit of $0.35 per gallon is produced at the current credit price of $50 per unit.
  - However, at the peak credit price of $200, the credit from renewable diesel could rise to $1.38 per gallon.

LCFS credit can cover between 15% and 58% of production cost subject to the volatility of the LCFS credit price.

Sources: IEA, Advanced Biofuels (2020); California Air Resources Board, LCFS Data Dashboard (2025).
Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Even with subsidies and California's LCFS credit, SAF pricing is still uncompetitive; scaling up is crucial to lower production costs

SAF production cost in $ per gallon, 2020 (FT-SPK) and 2022 (HEFA)



GHG emission**, gCO2/MJ:	HEFA	FT-SPK (Biomass)	Traditional Fuel Jet
	42.3	5.3	84.7

(*) LCFS credit is simulated at the price of $50 per MTCO2e using California's LCFS. (**) Cradle-to-grave emission.
Sources: IEA, Advanced Biofuels (2020); California Air Resources Board, LCFS Data Dashboard (2025).
Credit: Yosafat Partogi, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Observations

SAF pricing remains uncompetitive even with subsidies.

- Today, **SAF HEFA is the most commonly available** SAF in the market.
- The production cost of sustainable aviation fuel remains higher than traditional jet fuel.
  - The price differential can be up to **$8 per gallon** depending on feedstock and production techniques.
- Even with incentives like the SAF blenders tax rate, offering producers $1.25 per gallon and an additional $0.01 per gallon for every 1% reduction in GHG emissions beyond 50%, HEFA and FT-SPK (biomass) fuels remain uncompetitive with traditional jet fuel.
- For HEFA, credit must be at least 2-3x of the traditional jet fuel price (per 2022 price).

Biofuels are crucial in decarbonizing transportation in developing countries as EVs become accessible and infrastructure develops

Most new biofuel demand comes from developing economies

	Biofuels	Electric vehicles
Tailwinds	• **Ample resources**, land availability, and favorable conditions to grow feedstock crops or leverage waste byproducts from other popularly grown crops • **Motivated by energy security**, improved energy access, and reduced reliance on imported energy sources • **Favorable conditions for economic development:** – **Foreign investments** in the sector/country and job creation in the sector	• **Potential for smaller vehicles** and growing market demand for E2Ws (two-wheel vehicles) – Developing economies represent **90% of current market demand** for 2W and 3W vehicles • **International efforts to support governments** in EMDEs to advance deployment of EVs, such as through the Global Electric Mobility Programme and financing from multilateral development banks
Headwinds	• Concern for **competing priorities**, especially between G1 biofuel feedstock and food crops • **Need for improved infrastructure**, particularly connecting fields, refineries, and generators or ports in a cost-effective way • Further need for **supportive policy**	• Traditional EVs (E4Ws – four-wheel vehicles) adoption will be hindered by **price hurdles** for most developing populations • **Lack of access to conventional energy** and **limited grid reliability** for current daily activities • **Need** for **more accessible driving** and **charging infrastructure**
Policies and commitments	• The IEA established the **Bioenergy Technology Cooperation Programme** and the UN **Industrial Development Organization.** • **Argentina**, **Brazil**, **Colombia**, **Guatemala, Ethiopia**, **Kenya**, and **Madagascar** have **implemented** or **expressed intent** to implement **policies supporting biofuel production**, **blending**, and **trade.**	• **Dominican Republic (5%), Pakistan (50%), and Rwanda (30%)** have set **targets** to **electrify** a percentage of their 2Ws and 3Ws by **2030** • **Chile, Colombia, Ecuador, Philippines, Solomon Islands, Dominican Republic, Nepal, Pakistan, Panama, Indonesia, Uzbekistan, and Argentina** have **commitments** to **electrify** their **public bus fleets.**

Sources: IEA, Bioenergy and Biofuels in Developing Economies (2023); SCOPE, Biofuels in Developing Countries (2009); IEA, Modern Bioenergy (2023); IEA, Outlook for Electric Mobility (2024).

Biofuel policy to align with country's renewable energy vision; policy to adapt to growing electrification and SAF demand

	1 Biofuel as a transitional bridge	2 Biofuel as the primary driver
Strategy	• **Short- to mid-term solution** during the transition from fossil fuels to electrification	• **Main pillar along with other renewable sources** of the country's climate strategy and energy policy
Mandates	• **Biofuel blending mandates (e.g., E10)** while phasing in electrification • **Implement GHG emission reduction goals** • **Mandates on aviation and maritime that are hard to electrify** (e.g., minimum SAF volume increasing each year)	• **Aggressive targets for biofuel use across all sectors** (road, maritime, aviation) • **Implement carbon intensity and GHG emission reduction goals** • **Enforce sustainable feedstock production** with ambition to shift toward Gen 2 and Gen 3 • **Develop specific policies** for different transportation sectors
Incentives	• **Tax credits, subsidies, grants to producers** • **Designed to scale down production as electrification matures**	• **Tax credits, subsidies, grants, R&D funding to key players** • **Establish a carbon credit market** for all transport sectors
Timeline	• **Establish timelines with clear milestones** (e.g., 50% of new vehicles EVs while biofuels fill the gap for older vehicles)	• **Establish timelines with clear milestones across three phases**: 1) Laying the Foundation, 2) Scaling and Expansion, 3) Maturity and Leadership
Regulatory framework	• **Compliance driven with market mechanism** • **Incorporate flexibility into policy to adapt tech advancements** (adjusting incentives and mandates)	• **Market-driven with some degree of government intervention** • **Establish a national governing body for monitoring, implementation, and coordination** • **Cross-sector coordination** (policy alignment across energy, feedstock origination, transport)
Infrastruc-ture	• **Refinery conversion:** Modify existing refineries to process biofuels • **Charging stations:** Invest in the deployment of EV stations	• **Develop national/regional supply chains** to support large-scale biofuel production and distribution, including refinery conversion • **Build financing schemes for various investments**

Source: CKI analysis.

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Financial and Investment Landscape

Key messages
Financial and Investment Landscape

Three main factors drive investments in biofuels: **energy security, agricultural surpluses, and environmental concerns.**

Industry Landscape Analysis:

- **Gulf Coast states and California are the largest producers of renewable biofuels**, whereas the Midwestern states lead in both ethanol and biodiesel production.
- The ethanol/biodiesel market has stayed relatively fragmented, and **renewable biofuels are quickly becoming competitive** as new players actively enter the market.
- **M&A has been largely driven by small-scale ethanol plant acquisitions** with a few large-scale renewable biofuel transactions with higher acquisition multiples ($/gallon).

Operating Margins and Efficiency Analysis:

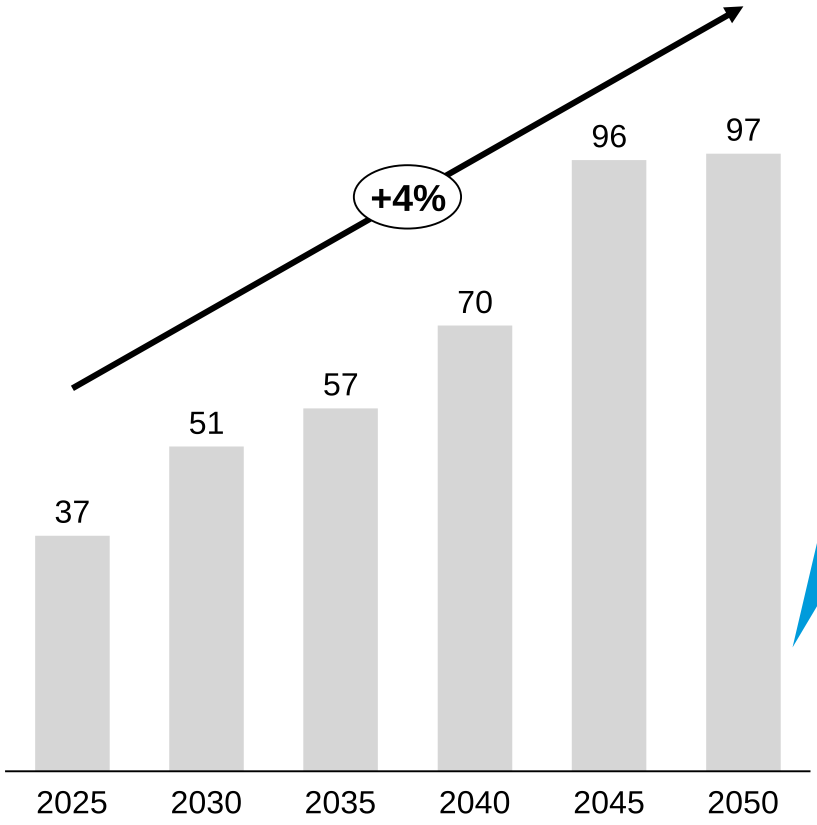
- **Biofuel prices** have increased steadily over time and are **closely reflecting traditional fuel prices.**
- Ethanol production has been consistently profitable (operating profit margins of 10% to ~21% during 2020-24), while **renewable biofuel production margins eroded significantly**, from 50% to 6% (2020-24), due to oversupply and increased competition.
- Biofuels' **cost of energy per GGE ($3.80 to ~$5.40) still exceeds that of conventional fuels ($3.20 to ~$3.80);** electricity has the highest cost of energy per GGE ($8.50 to ~$14.90).

Investment challenges:

- Biofuel adoption and technology development require **a mix of funding sources to drive market innovation and adoption.**
  - **Various de-risking options for both investors and producers**, such as **public-private partnerships and cross-corporation partnerships**, are important to fully increase advanced biofuels production to commercial scale.
- Developing economies will constitute the newest biofuel demand, while **increasing EV adoption in developed economies will pose a challenge** to the industry.

Global: Investment in biofuels is growing, driven by the need for energy security, decarbonization efforts, and agriculture surpluses

Biofuel yearly investment projection globally, *$B*



Projected investment share by fuel type in 2050:

- **58%** to more advanced biofuel, e.g., FT, pyrolysis, alcohol-to-jet
- **24%** to e-fuels (hydrogen reacted with carbon derived from direct air capture)
- **16%** to HEFA and HVO
- **<1%** to conventional biofuel (FAME, bioethanol)

Key investment factors

Energy security

- Provides **energy importers with new opportunities to establish domestic energy supply chains.**
  - 22 countries currently supply over 90% of global oil, may present new opportunities for major importers such as the EU and China, as well as other Asia-Pacific countries.
- Provides **opportunities to fully utilize local feedstock** (waste, crops, etc.) and create new jobs domestically.

Decarbon-ization

- Plays a **critical role in decarbonizing transport sector** as market share of EV and future share in aviation increase.
- Countries **crafting specific mandates** in the form of fuel standards and investment expectations.
- Provides **opportunities to create a circular crops and waste economy**, where the process of producing biomass feedstock also reduces emissions.

Agriculture

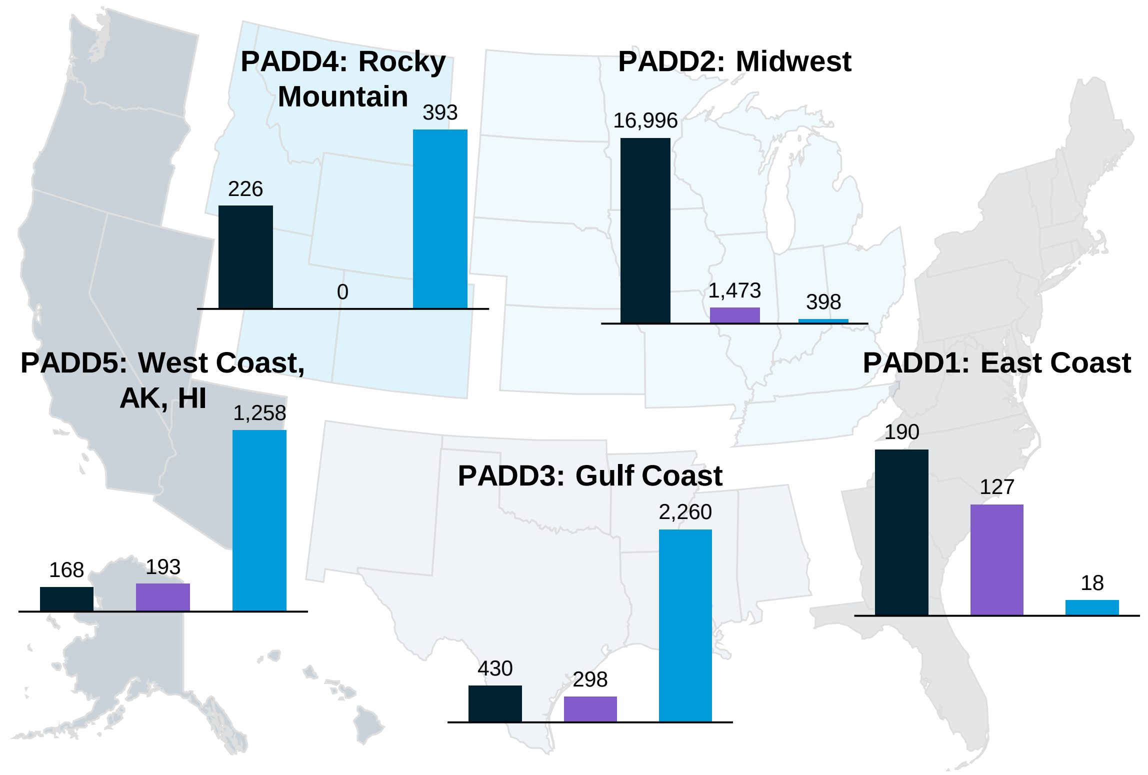
- Allows agricultural producers to use surpluses for fuel production.
  - Countries with structural supply surpluses like Indonesia (palm oil) and the U.S. (corn) are at the forefront of feedstock production.
- Municipal waste facilities, landfills, and animal waste collectors are becoming biofuel feedstock producers with an increase in the potential to reduce feedstock cost.

Sources: McKinsey, GEP 2023: Sustainable fuel outlook; Asian Sky Group, Shell Aviation Says $1.45 Trillion Investment Needed to Expand SAF Production (2022); S&P Global, Key Considerations in Financing Biofuels Investments (2025); Investopedia, World's 10 Biggest Oil Exporters (2024); Statista (KPMG), Crude oil importers (2023); OFI, Croplands for biofuels use (2023).

Gulf Coast states and California are the largest producers of renewable and other advanced biofuels

Biofuel production capacity, *million gallon/year*

PADD-level



State-level

1. **Louisiana 1,443**
2. California 1,143
3. Texas 537
4. Wyoming 209
5. North Dakota 192

1. **Iowa 473**
2. Missouri 257
3. Illinois 192
4. Texas 174
5. Washington 107

1. **Iowa 4,898**
2. Nebraska 2,399
3. Illinois 1,867
4. South Dakota 1,487
5. Minnesota 1,443

Observations

- Gulf Coast States and California lead in renewable and other advanced biofuel production with **Diamond Green Diesel** and **Martinez Renewables** being the largest producers in the country.
  - Green Diamond Diesel Norco Plant (LA, 982M gal/year)
  - Martinez Renewables Eagle Plant (CA, 731M gal/year)
  - Green Diamond Diesel Arthur Plant (TX, 537M gal/year)
- Midwestern states lead in both ethanol and biodiesel production from advantageous access to feedstock.

Sources: U.S. EIA, U.S. Fuel Ethanol Plant Production Capacity (2024); U.S. EIA, U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity (2024).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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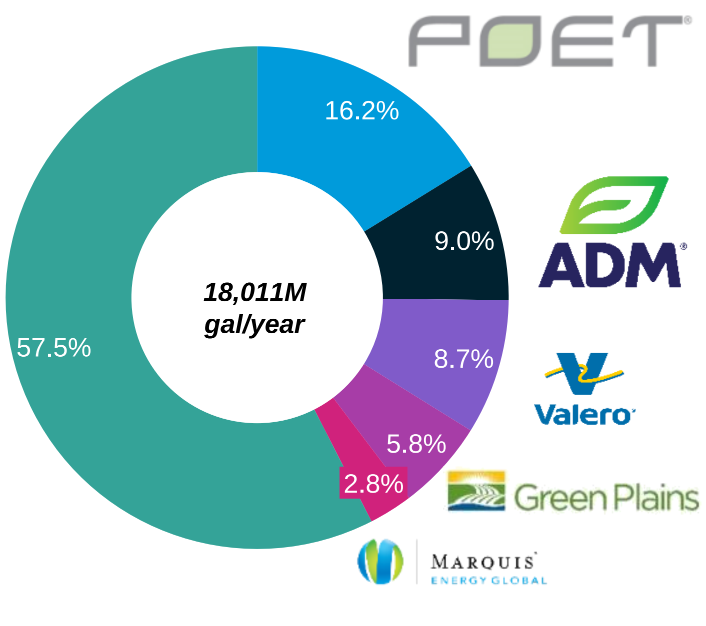
Climate Knowledge Initiative

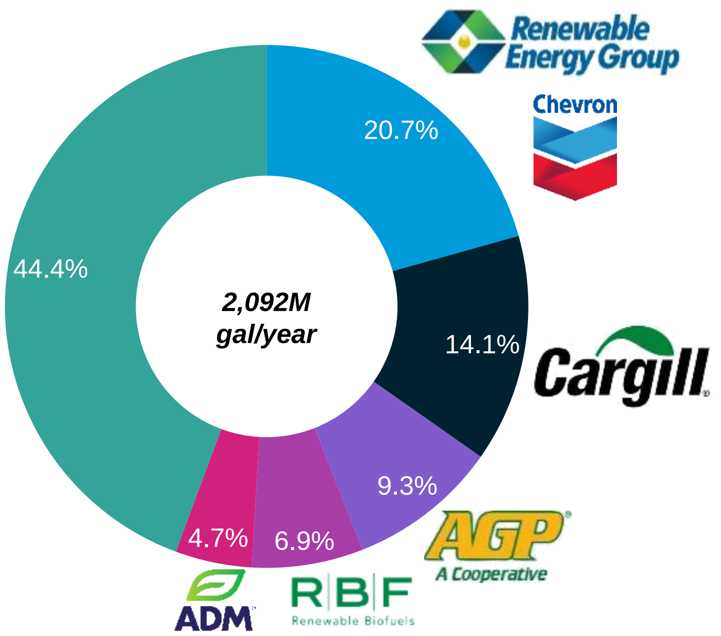
The biggest biofuels market players are producing ethanol and biodiesel

1. Ethanol (% of U.S. market share)



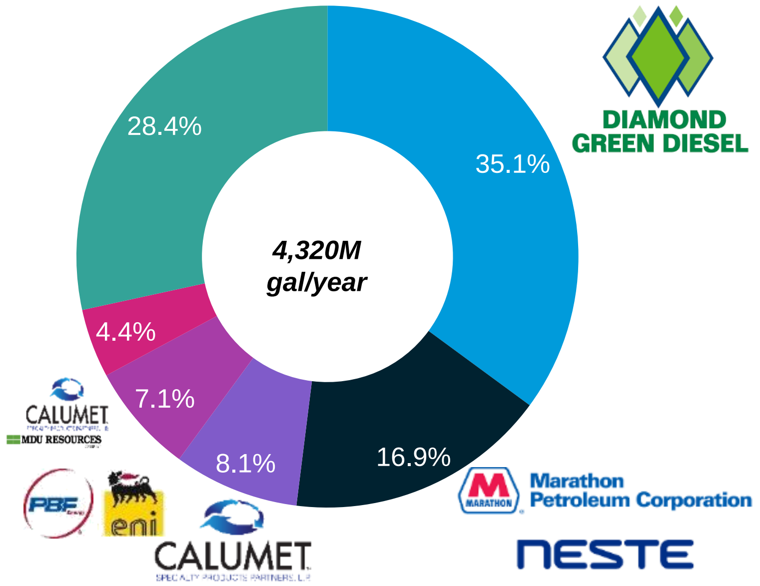
- **POET**, **ADM**, and **Valero Renewables** have been the top three ethanol producers during the past five years (2020-24).
- POET significantly increased production capacity in 2022 by adding 1,407M gal/year and became the leading producer of ethanol (2,918M gal/year).

2. Biodiesel (% of U.S. market share)



- **Renewable Energy Group**, **Cargill**, and **AG Processing** have been the top three biodiesel producers during the past three years (2022-25).
- **World Energy**, a sustainable biofuel producer, is converting its biodiesel plant (250M gallons/year) into a SAF production plant.

3. Renewable/Other (% of U.S. market share)

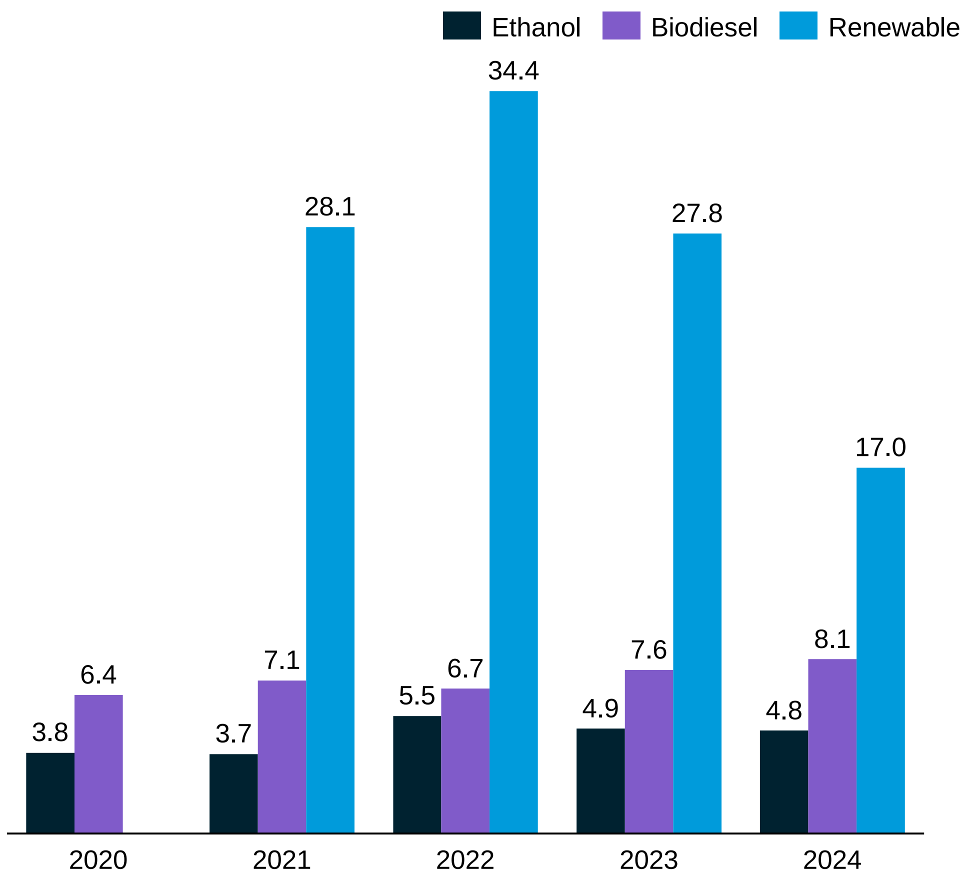


- **Diamond Green Diesel** and Martinez Renewables (Marathon-Neste JV) lead renewable biofuel production with a majority of the production capacity.

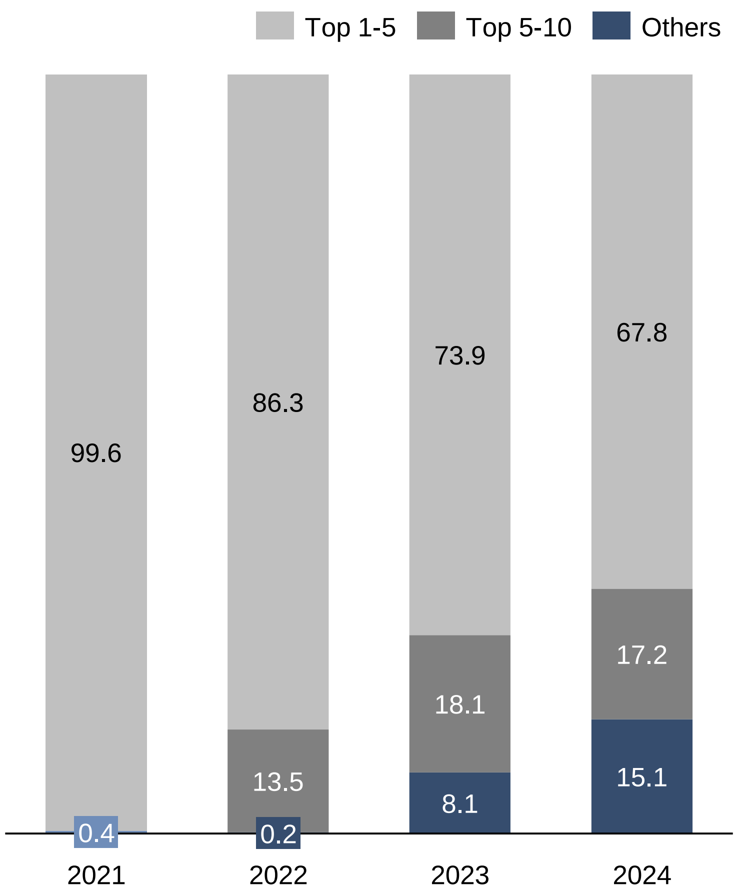
Sources: U.S. EIA, U.S. Fuel Ethanol Plant Production Capacity (2024); U.S. EIA, U.S. Biodiesel Plant Production Capacity (2024); U.S. EIA, U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity (2024).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Ethanol/biodiesel market has stayed relatively fragmented over the years, and the renewable biofuel market is becoming competitive

Biofuel market HHI trend



Renewable biofuel market share, %



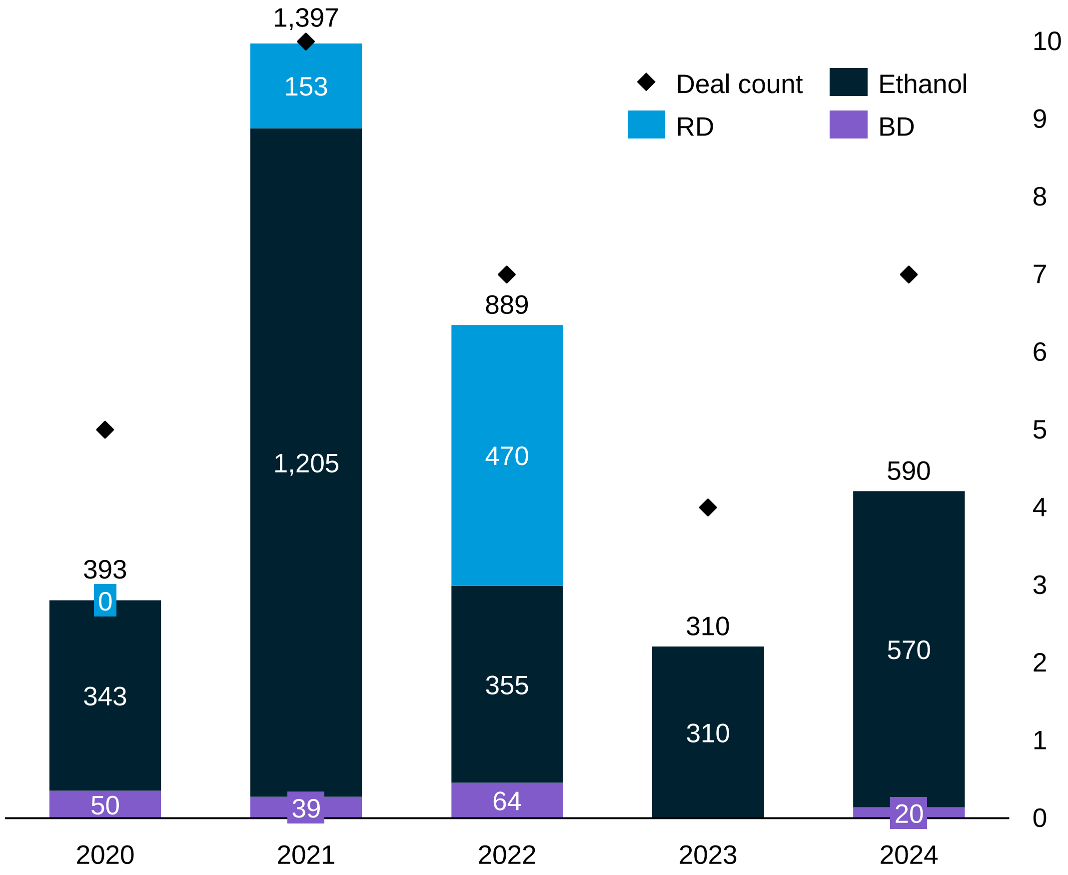
Observations

- The ethanol and biodiesel market has stayed relatively **fragmented** (HHI<15%, **non-concentrated**) with signs of slow consolidation.
  - Number of ethanol and biodiesel producers decreased from 125 to 109 and from 74 to 41, respectively.
- The renewable biofuel market is **moderately concentrated** (HHI>15%), although it is increasingly becoming competitive with new players aggressively entering the market.
  - Number of renewable biofuel producers increased from 6 to 19 over the past four years (2021-24).

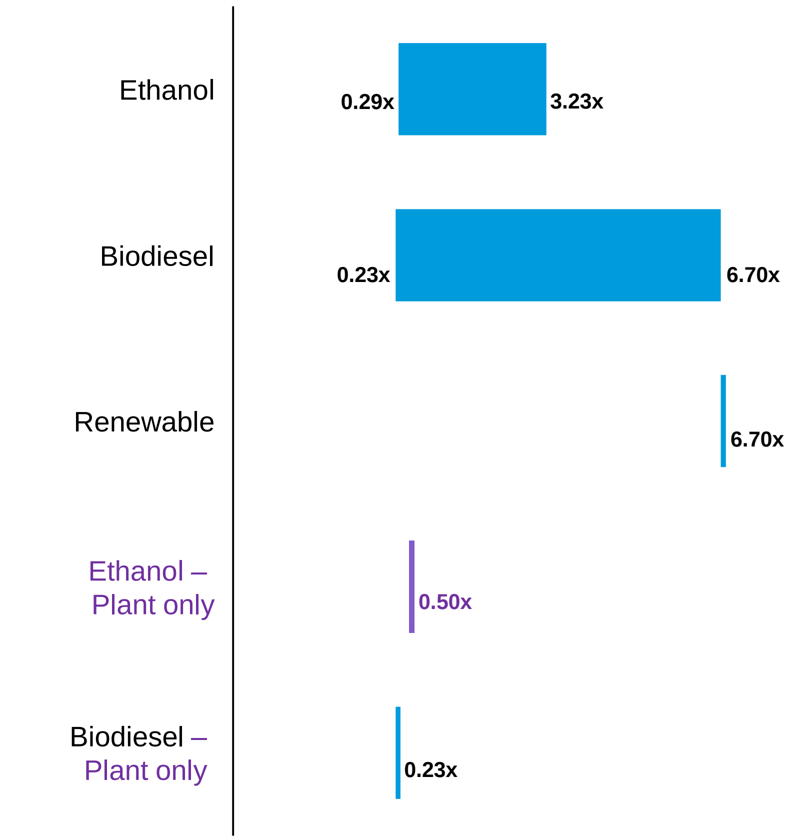
Note: Total may not sum exactly due to rounding.
Sources: U.S. EIA, U.S. Fuel Ethanol Plant Production Capacity (2024); U.S. EIA, U.S. Biodiesel Plant Production Capacity (2024); U.S. EIA, U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity (2024).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Biofuels M&A market has been largely driven by small-scale ethanol plant acquisitions with $/gallon multiple of 0.5x

Biofuel deal volume by capacity, *million gal/year*



Biofuels market M&A multiples, *$/gallon*



Observations

- Most biofuel M&A has been focused on ethanol plants, particularly in 2021, due to favorable macroeconomic conditions (e.g., low cost of financing).
- Acquisition multiples for **plant-only deals** tend to be lower (0.23-0.5x) **compared with those for integrated assets**, which include advanced technologies such as carbon capture and other sustainable solutions.

Sources: Ocean Park (Investment Bank), 2020 Review and Outlook (2021), 2021 Review and Outlook (2022), 2022 Review and Outlook (2023), 2023 Review and Outlook (2024), 2024 Review and Outlook (2025).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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Biofuel prices have increased over time, alongside traditional gasoline and diesel prices

Biofuel price trends from 2000-2024, *$/gallon*

Observations

- Biofuel prices closely resemble traditional fuel prices, maintaining a relatively stable difference.
- Although fuel prices have increased over the past 20 years, price increase growth has become increasingly stagnant since 2008.
- Notable events:

  1) 2008-2009: A decrease in oil prices due to deteriorating demand in the aftermath of the global financial crisis.

  2) 2011-2013: An increase in oil prices due to the crisis in the Middle East and a strong emerging market demand.

  3) 2014-2016: A plunge in oil prices due to U.S. oil production and lackluster demand.

  4) 2021-2022: A sharp increase in fuel prices from the COVID-19 supply shock.

Source: DOE, Fuel Prices (2025).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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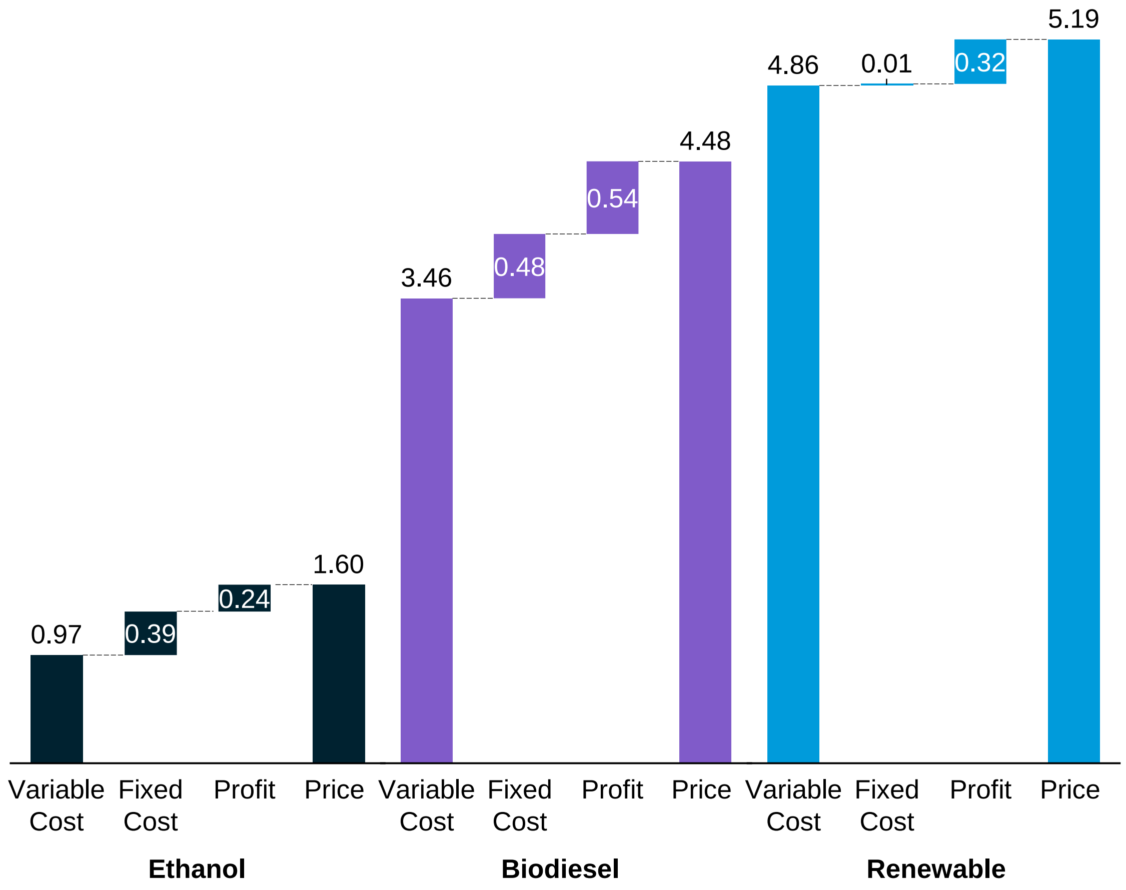
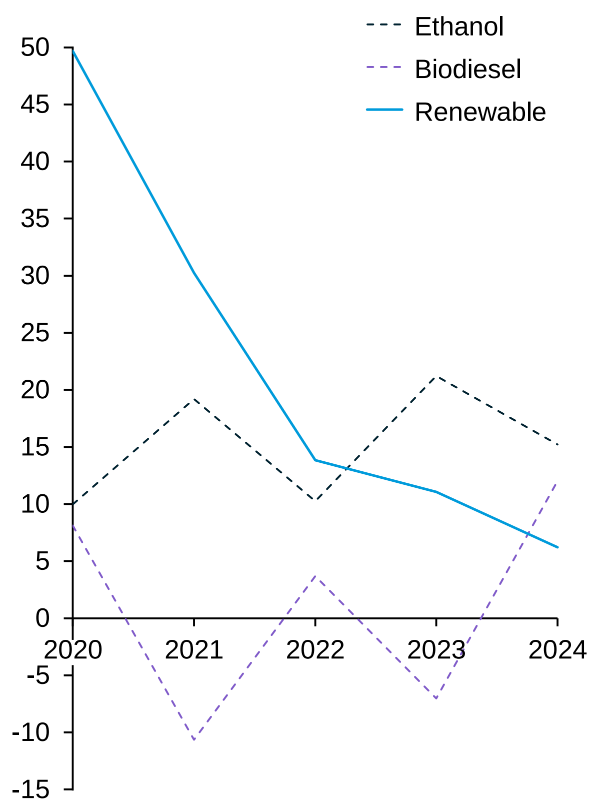
Ethanol production has consistently been profitable, while the margin for renewable biofuel has eroded significantly

Cost breakdown of biofuels in 2024, *$/gallon*



Operating profit margin, *%*



Observations

- **Ethanol** production has been consistently profitable, with operating margins of 10 to ~21% (2020-24).
- **Biodiesel** production has fluctuated between profit and loss, with operating margins of -11% to ~12% (2020-24).
- **Renewable** biofuel production has experienced a declining margin, from 50% to 6% (2020-24), due to increased competition and oversupply.
  - Net RIN generated has consistently exceeded the EPA requirement (RFS2 Advanced Biofuel Mandate) since 2020, negatively affecting RIN credit prices.

Sources: Iowa State University, Historical Biofuel Operating Margins (2025); Darling Ingredients, Diamond Green Diesel (10K) (2025).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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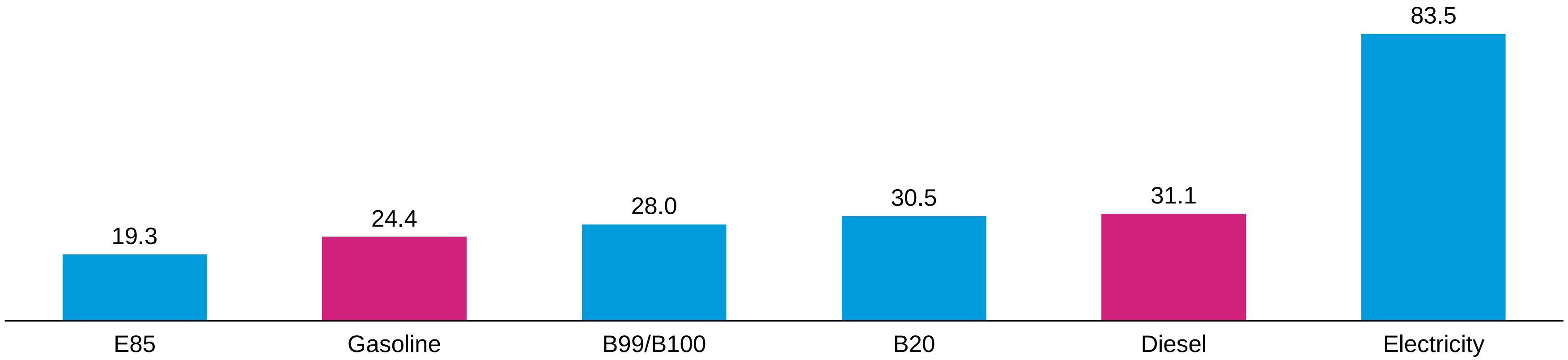
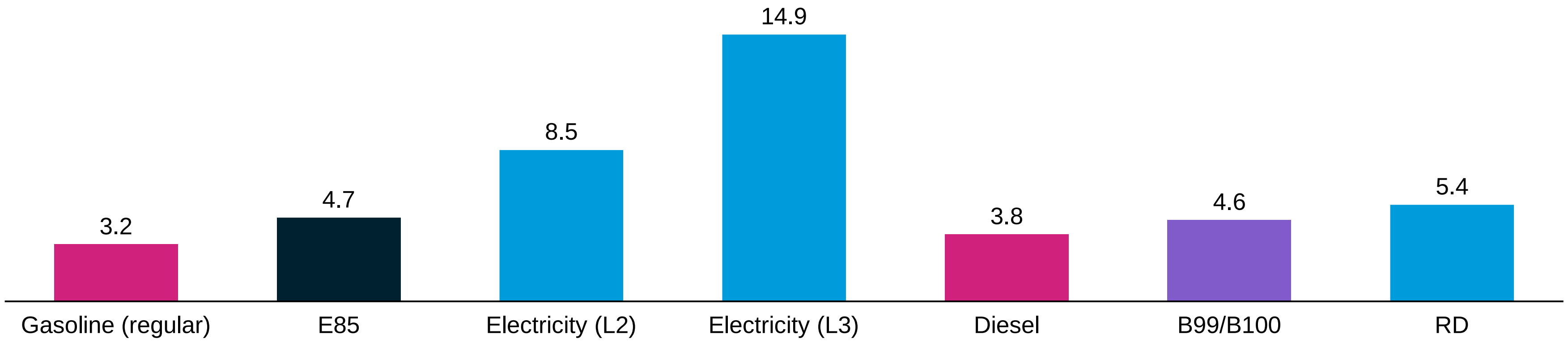
Fuel economics: Biofuels more costly, electricity most efficient

MPGe (miles per gallon equivalent)



Cost of energy per GGE (gasoline gallon equivalent) in 2024, *$/GGE*



Observations

- **Conventional fuels**
  - Cost per unit of energy (in GGE) is still lowest for conventional fuels (gasoline, diesel) and are more efficient in terms of fuel economy than biofuels.
- **Electricity (EV)**
  - Electricity is still the most expensive source of energy in terms of per GGE cost compared to other fuel sources.
  - However, electricity has a promising outlook because it is the most efficient, over 3x of conventional gasoline.

Sources: DOE, Fuel Economy (Ethanol), Fuel Economy (Biodiesel), Fuel Economy (Electricity), Fuel Economy (Gasoline), Fuel Economy (Diesel) (2025).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Biofuel adoption and technology development require a mix of funding sources to drive market innovation and adoption

	1 Direct Private Investment	2 Grants & Subsidies	3 Cross-Corporation Partnerships	4 Public-Private Partnerships	5 Corporate Fundraising
Entities	• Private equity • Venture capital • Bank financing	• Government agencies • State government	• Joint ventures • Long-term purchase/ contracts	• Federal and state government	• Biofuel producers
Description	• Long-term capital deployment without immediate pressure of repayment • Institutional investors to passively satisfy ESG mandates	• Systematically encourage industry participation by reducing cost or risk of production	• De-risking investments in technology development and new projects through risk/profit sharing	• Provides cost and risk buffers to industry players through strong systematic support (legislation, municipal contracts, etc.)	• Reduce corporate cost of capital compared with conventional loan/equity issuances • Attracts big institutional investors with ESG mandates
Examples	• **Bank of America**: $2B for SAF production, low-carbon technology • **MUFG**: $100M funding to LanzaJet (SAF technology)	• **Clean fuel production credit** (SAF tax credit) • **Advanced biofuel feedstock incentives** (producer incentive)	• **Green Diamond Diesel:** Valero Energy-Darling Ingredients JV • **Martinez Renewables:** Marathon Petroleum-Neste JV	• **Dupont-Nevada partnership** to develop a cellulosic ethanol plant • **RenovaBio:** Brazil's national biofuel policy	• **Neste:** Green bond issuance of €600M (2023) • **Clariant:** Green bond issuance of €175M for cellulosic ethanol plant construction (Romania)

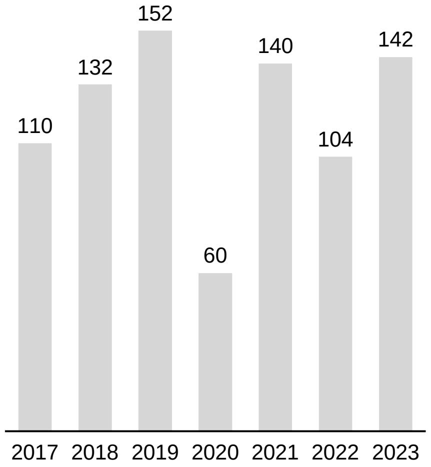
Sources: ETIP, ETIP 2022-2025 (2025); S&P Global, Key Considerations in Financing Biofuels Investments (2025); Waypoint 2050, Accelerating Adoption of Sustainable Aviation Fuel (2023); Bank of America, Bank of America Sets 2030 SAF Goal (2022); ESG Today, MUFG Invests in SAF (2024); PR Newswire, United Is First to Purchase SAF for O'Hare (2024); Bloomberg, Sunlight to SAF (2023); IATA, Creating a Virtuous Cycle of Investment in SAF (2023).

Credit: Yosafat Partogi, Sean Lee, Birru Lucha, Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Main investment challenges are fossil fuel investments, feedstock and technical challenges, and electrical vehicle competition

Biofuel investment challenges

Lack of divestment from fossil fuels

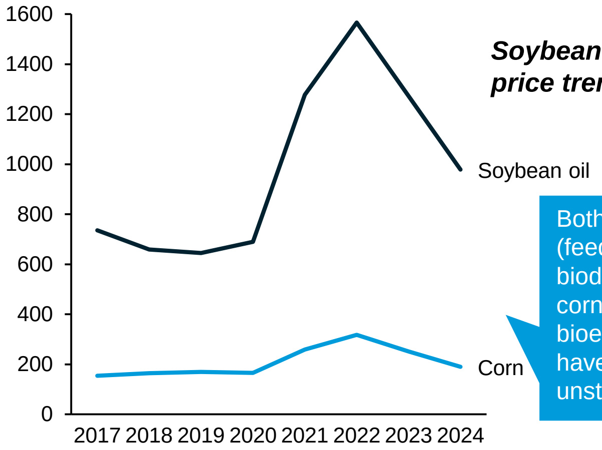


O&G CapEx trend ($B)

Oil and gas industry CapEx has stayed relatively stable despite consistent corporate divestment efforts.

- The **high cost of renewable** fuels and **lack of supply of** biofuels prevent further development of biofuels.
- **$1 trillion of public and private capital is dedicated to the fossil fuel industry.**
- Oil and gas companies spent only 5% of their investments in new renewable technologies.
- The risk-return ratio is still attractive for fossil fuels.

Feedstock availability and tech challenges

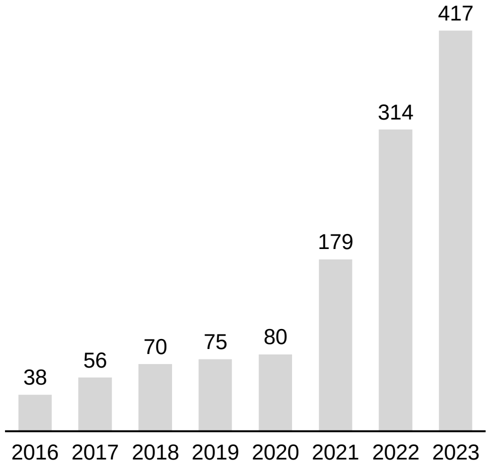


Soybean oil and corn price trends ($/ton)

Both soybean oil (feedstock for biodiesel) and corn (feedstock for bioethanol) prices have been unstable.

- **Feedstock availability** and **price volatility** remain the largest challenges for long-term expansion and market deployment of new technologies.
- **Lack of technological readiness** hampers interest and development in the industry, as advanced technologies still require high capital and operational expenditures and are not yet commercialized.

Peak demand and EV competition



EV battery global demand (GWh/year)

EV global demand has increased dramatically since 2021.

- Due to the **rise of EVs**, European motor fuel demand has already hit its peak.
- **Gasoline** will make a temporary return due to unfavorable macroeconomic conditions but **will also be phased out** in the long term due to electrification.
- Traditional refining margins have deteriorated, and **biofuels** is a logical way for businesses to adapt. However, this will **likely serve as only a short-term solution.**

Sources: EY, US Oil and Gas Reserves, Production and ESG Benchmarking Study (2024), US Oil and Gas Reserves, Production and ESG Benchmarking Study (2022); ETIP, Investing in European Fuel Security (2025); S&P Global, Key Considerations in Financing Biofuels Investments (2025); Bank of America, Bank of America Sets 2030 SAF Goal (2022); IATA, Creating a Virtuous Cycle of Investment in SAF (2023); FRED, Global Price of Corn (PMAIZMTUSDM) (2025); FRED, Global Price of Soybeans Oil (PSOILUSDM) (2025); IEA, Electric Vehicle Battery Demand by Region (2024).

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Appendix

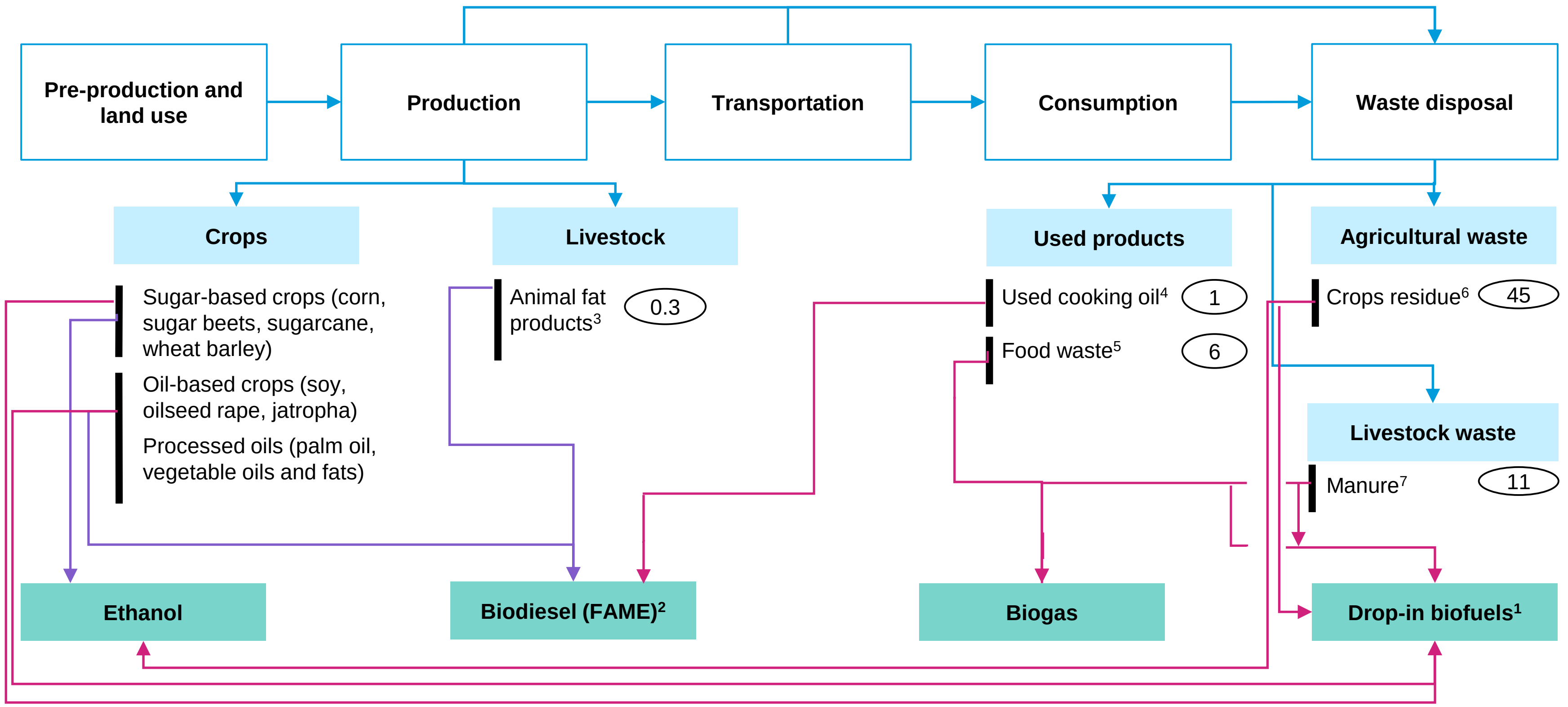
Glossary

AtJ	Alcohol-to-jet fuel
B(X)	Biodiesel blending rates with traditional fuels (B100, B85, etc.)
BEV	Battery electric vehicle
BOED/BPD	Barrels of oil equivalent per day / Barrels per day
BTL	Biomass-to-liquid
CAGR	Compound annual growth rate
CapEx	Capital expenditures
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2	Carbon dioxide
E(X)	Bioethanol blending rates with traditional fuels (E100, E85, etc.)
EJ	Exajoule
EU	European Union
EV	Electric vehicle
EVSP	Electric vehicle service provider
FAME	Fatty acid methyl ester
FT	Fischer-Tropsch
GHG(e)	Greenhouse gas emissions
GREET	Gases, Regulated Emissions, and Energy Use in Transportation
GT/MT	Gigaton/Megaton
GTL	Gas-to-liquid
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydrotreated vegetable oil
LCFS	Low Carbon Fuel Standard
MBOED	Million barrels of oil equivalent per day
MSW	Municipal solid waste
NZE	Net-zero emissions
O&M	Operating and management costs
OpEx	Operating expenses
PG(X)	Pyrolysis gas blending rates with traditional fuels (PG85, etc.)
R&D	Research and development
RFS	Renewable fuel standard
RIN	Renewable identification numbers
SAF	Sustainable aviation fuel
UCO	Used cooking oil
WEF CST	World Economic Forum Clean Skies for Tomorrow initiative

Biofuel feedstock is sourced from various stages of the food value chain; full potential could reach ~11% of global energy demand

Full potential to convert to energy, EJ | Main value chain | Food system's products | Biofuel end products | Gen 1 biofuels | Gen 2 biofuels

Food system value chain and corresponding biofuel end products (non-exhaustive)



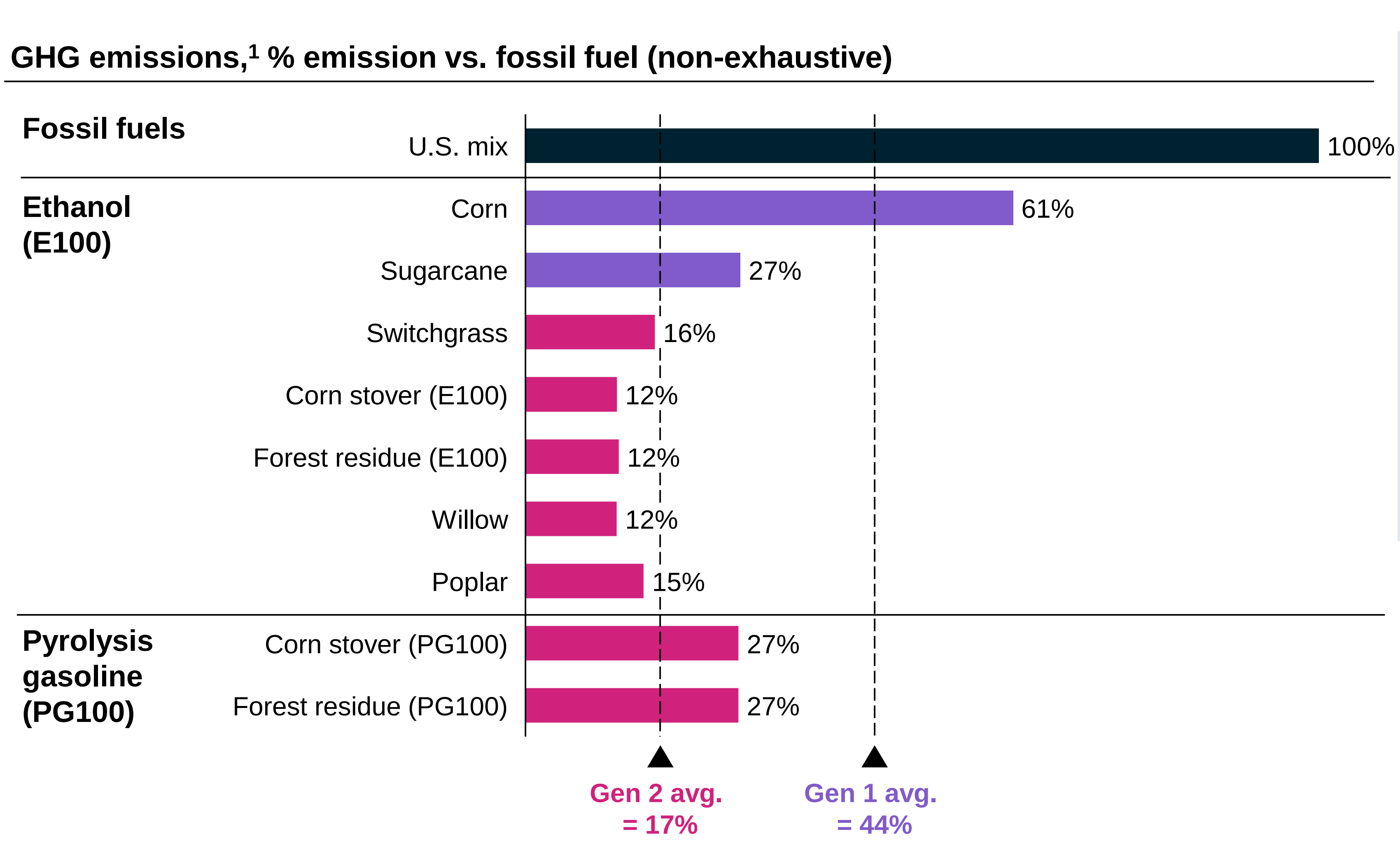
Observations

- **Current biofuel production still mainly relies on crops** to produce ethanol blending and FAME, with **4 EJ production** as of 2022.
- **Significant untapped potential exists from the non-crop** feedstock, equivalent to **~64 EJ (based on carbon content)** of energy production or ~**11% of global energy consumption** in 2022.
- Biofuel could play important role in decarbonization by **repurposing the food system's low-value output into fuels for the transport and power sectors.**

Note: Feedstock for Gen 3 biofuels, such as microalgal blooms and other lab-created products, is not a direct part of the food system and not a part of this chart.
1) Liquid bio-hydrocarbons that are functionally equivalent to petroleum fuels and fully compatible with existing petroleum infrastructure. 2) Fatty acid methyl esters. 3) 80% of global tallow oil production (~5.6M tons per year). 4) Based on global UCO potential for biodiesel production as of 2030. 5) Assumed 60% of total food waste that goes to landfill (~0.6B ton per year). 6) Based on total crop residue produced globally, and 100% goes to conversion into biofuels. 7) Based on global manure production in 2022 and assumed 100% goes to conversion into biogas for electricity generation (equals to ~3,000 TWh potential).
Sources: McKinsey, Sustainable Fuels Outlook (2024); Molecules, Second-Generation Biomass as Feedstock for Bioethanol Production (2024); UNEP, Food Waste Index (2024); GreenMatch, The Impact of Food Waste (2024); Clean Fuels Alliance America, Clean Fuels Releases Outlook (2023); World Biogas Association, Global Potential of Biogas (2019); Tallow Chandlers', Tallow (2015).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

A. Gasoline: Gen 2 feedstock consistently shows lower GHG emissions for both conventional and advanced technology

GHG emissions,[1] % emission vs. fossil fuel (non-exhaustive)



Observations

- **Bio-based gasoline fuels could result in a 40-88% reduction in GHG emissions** compared with conventional fossil-based fuel, depending on technology and feedstock.
- **Gen 1 ethanol (E100) production is significantly more emissions-heavy** than that for Gen 2 feedstocks; the main contributors are the farming process and energy consumption in the ethanol plant.
- Competition involving food crops could lead to **increased GHG emissions for Gen 1** due to changes in land use. Corn-based ethanol could have up to **90% higher GHG emissions compared** with fossil-based gasoline.

1) All emissions totals calculated in well-to-wheels framework, accounting for all steps in between crop production and use of the fuel in vehicles or other emissions-releasing capacities.
Sources: Argonne National Laboratory, GREET WTW Calculator (2022); Science, Increases in emissions from land use change (2008).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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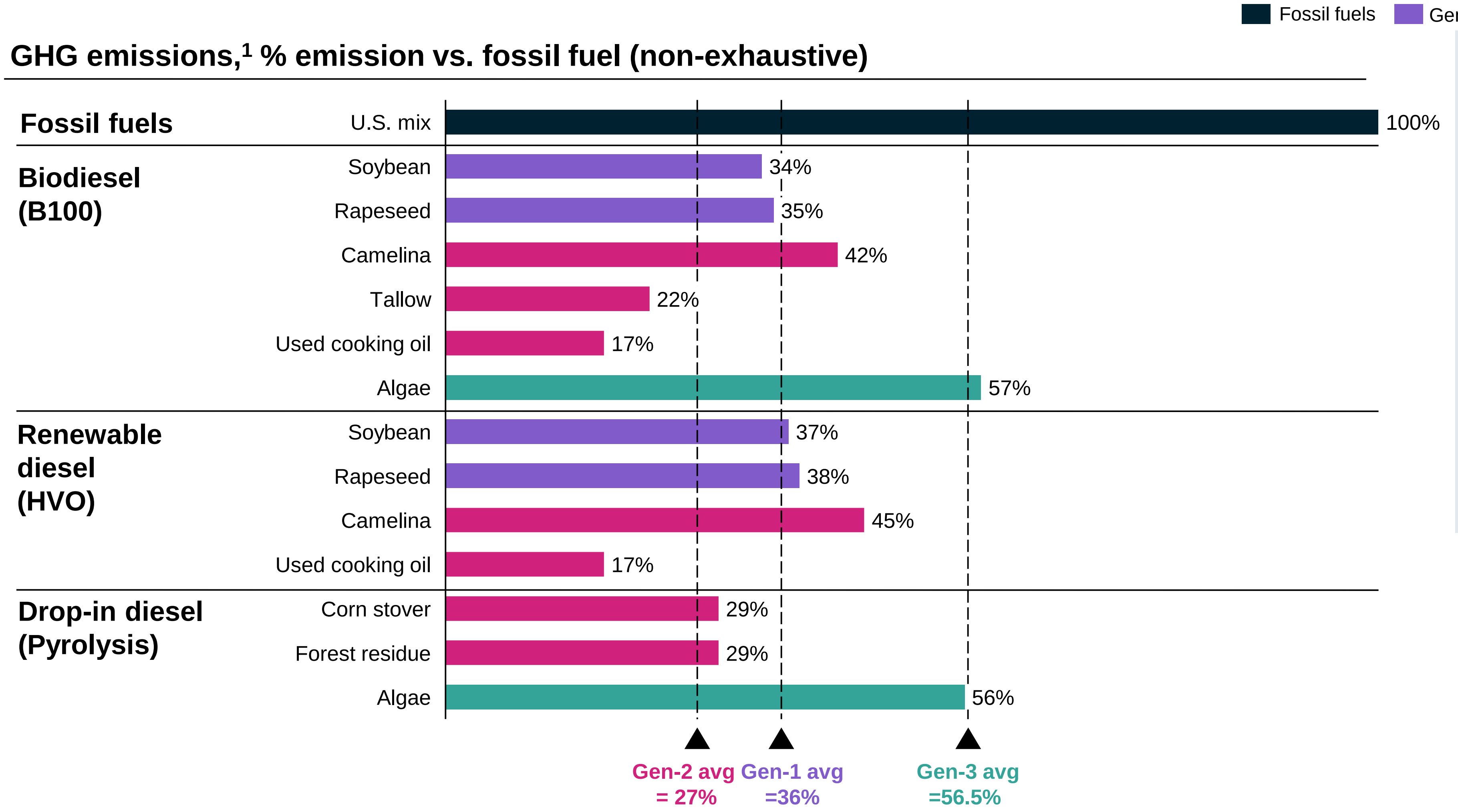
B. Diesel: Used cooking oil (UCO) and tallow result in the lowest emissions when used as feedstock for biodiesel and HVO

GHG emissions,[1] % emission vs. fossil fuel (non-exhaustive)



Observations

- **Fossil fuel diesels lead in greenhouse gas emissions**, followed by Gen 3 and a mix of Gen 1 and 2 fuels based on feedstock, **with a 42-78% reduction in emissions** (compared with conventional crude).
- **Gen 3 (algae-based)** diesel is still **very energy-intensive** and not yet scalable.
- **Gen 2** diesel in the form of used cooking oil and tallow is the **most promising** in terms of emissions reductions.

1) All emissions totals calculated in well-to-wheels framework, accounting for all steps in between crop production and use of the fuel in vehicles or other emissions-releasing capacities.
Sources: Argonne National Library, GREET WTW Calculator (2022); Environmental Science & Technology, Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel (2022).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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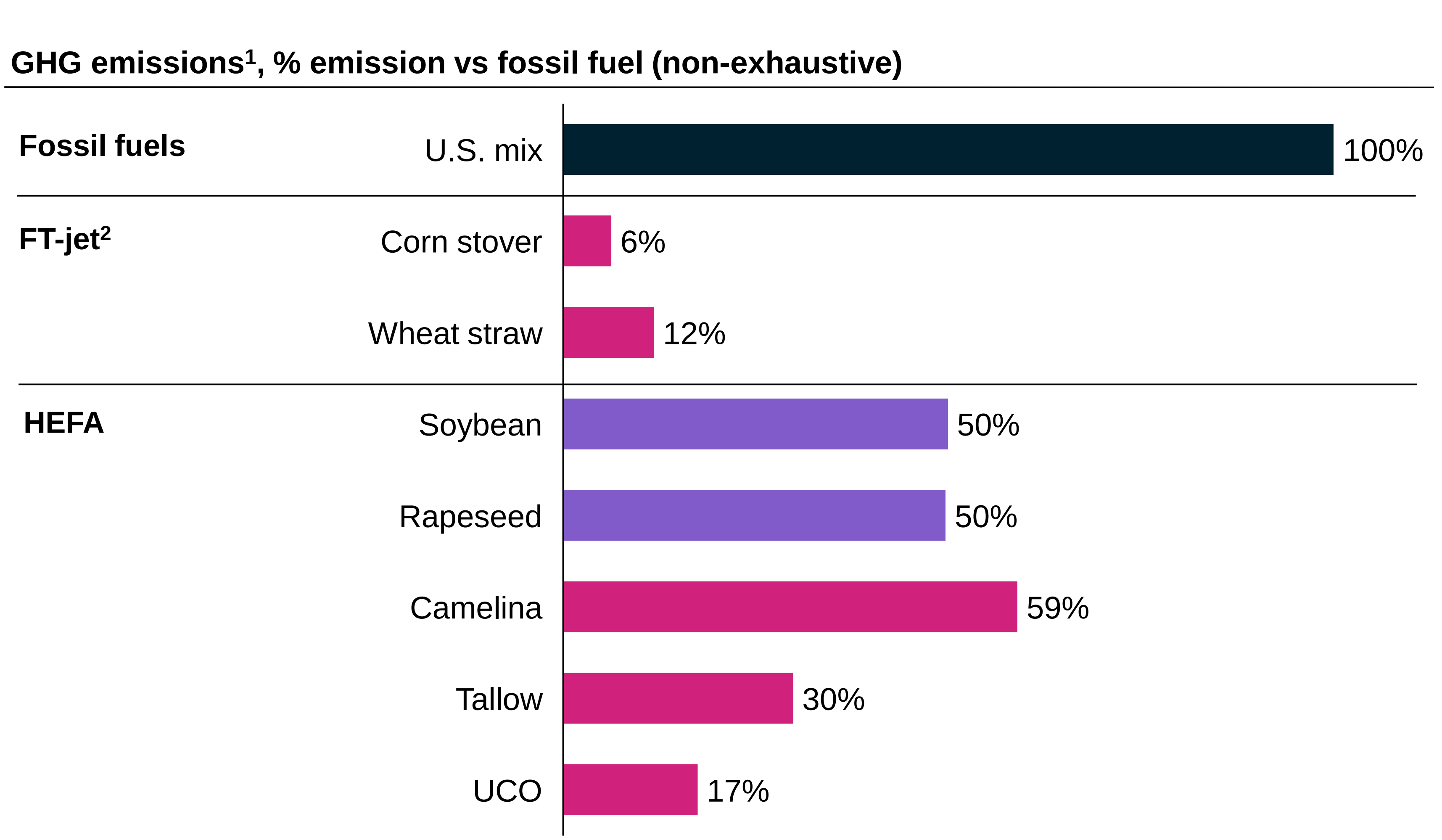
C. Jet fuel: Fischer-Tropsch is the most promising to reduce emissions in the aviation sector

GHG emissions[1], % emission vs fossil fuel (non-exhaustive)



Observations

- **Fischer-Tropsch jet fuel** is the **most promising** in terms of emissions reductions, with **a ~90% decrease in GHG emissions** in comparison to traditional fuels, mainly driven by:
  - **No upstream emissions from collection, recovery, and extraction** for feedstock from biomass (non-crops).
  - Low emissions throughout the feedstock-to-fuel conversion process, as **fuel uses syngas from biomass.**
- **For HEFA, UCO feedstock shows the lowest emission** among other feedstocks.

1) All emissions totals calculated in well-to-wheels framework, accounting for all steps in between crop production and use of the fuel in vehicles or other emissions-releasing capacities.
Sources: Argonne National Laboratory, GREET WTW Calculator (2022); Corsia, Life Cycle Assessment (2020).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

1. Transesterification process converts vegetable oil and animal fats into biodiesel (FAME)

Process overview

Vegetable oils, animal fats (tallow), and used cooking oils (UCO) → Pre-treatment → Alcohol-catalyst mixing → Transesteri-fication → Separation & purification → **Biodiesel (FAME)**

Variation in specific feedstock used based on geographic availability of crops and oils

Pre-treatment

Removal of FFA[1] content in feedstock with high acid content, typically including animal fats, vegetable oil, and UCOs

Acid-catalyzed transesterification to remove fat, maintain low humidity, and reduce amount of saponifiable substances

Alcohol-catalyst mixing

Alcohol mixed with catalyst to create alkoxide mix until catalyst Is dissolved and anhydrous (free of water)

Catalysts can be classified as basic, acid, or enzymatic, with most popular enzymes being:

- Sodium and potassium hydroxides
- Sodium and potassium methoxides and methylates (used on an industrial scale)

Transesterification

Chemical reaction between alkoxide and pre-treated feedstock into fatty acid methyl esters (FAME) and glycerin

Reaction temperature is 50-60°C at atmospheric pressure

Separation & purification

Decantation process to separate FAME from glycerin

Other impurities (e.g., methanol, catalyst) removed through a water-washing process to comply with biodiesel quality standards

↓ **Byproduct: Glycerin** (~10% of total products)

Observations

- **Biodiesel** can be used in **unmodified diesel engines** with little or no changes to fueling infrastructure for **blends up to 20% (B20).**
- **Higher biodiesel blending** content **requires engine modification** due to moisture content, solid deposition, and lower heating value.
- U.S. production capacity **has fallen dramatically** since 2020 due to the rise of ”drop-in fuels” that can fully replace traditional fuels rather than being blended.
- Technical challenges include **the need for better catalysts** and **improved quality of diesel produced**, in addition to byproduct conversion and use of non-dirty solvents.

1) FFA = Free fatty acid.

Sources: Romano et al., Introduction to Biodiesel Production (2011); Farmdoc, Overview of Production Capacity (2023); IEA, Transport Biofuels (2022); OECD, Biofuels Outlook (2023).

Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport” (19 November 2025).

2. Hydrolysis and fermentation process converts sugar and starch into bioethanol

Process overview

Sugar-based crops

Lignocell-ulosic biomass

Algae

→ **Pretreatment** → **Hydrolysis** → **Fermentation** → **Distillation** → **Bioethanol**

Pretreatment

Complexity varies based on feedstock:

- **Sugar-based crops:** Sugar or starch extraction
- **Lignocellulosic biomass and algae:** Structure breaks down into simple fermentable sugars through physical, chemical, or biological processes, depending on feedstock

Hydrolysis

Uses water to break down polymers into monomers, and breaks down chemical bonds to release energy

Acids or enzymes used as catalysts (acids — less environmentally friendly but faster; enzymes — more environmentally friendly but slower process)

Fermentation

Metabolic process to break down simple sugars into ethanol

Types of fermentation processes:
- Batch
- Fed-batch
- Semi-continuous
- Continuous

Organisms facilitating:
- Bacteria
- Filamentous fungi
- Yeast

Distillation

Purifying liquid mixtures by heating, boiling, or condensation based on volatility of mixture, with goal of concentrating ethanol from fermentation broth

Observations

- Pretreatment and distillation are **extremely energy-intensive** processes, with distillation taking up 40% of total energy used in refining industries.
- **Gen 1 feedstocks still dominate bioethanol production**, although the crops vary:
  - U.S.: Mainly corn
  - Canada: Corn and wheat
  - Brazil: Sugarcane
  - Europe: Potatoes, wheat, and sugar beets
- **Gen 2 is becoming competitive**; current innovation focuses on **technical advancement** to lower cost (e.g., enzymes, energy) and increase yield and co-product utilization.

Sources: Molecules, Second-Generation Biomass for Bioethanol Production (2024); MDPI, Production of Biofuels Overview (2021); Bioengineered, A panoramic view of technological landscape of bioethanol production (2023).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

3. Anaerobic digestion converts wide range of waste into biogas

Process overview

Crop residues, livestock waste, municipal solid waste, and wastewater sludge

Municipal solid waste includes landfills and other industrial waste processing facilities

Deconstruction

Feedstock crushed into smaller pieces and slurrified (adding liquid to facilitate process)

Biowaste heated to around 37°C for microbes to be in ideal conditions

Anaerobic digestion

Series of biological processes where microorganisms break down biodegradable material into gaseous phase due to lack of oxygen

Technology includes:
- Complete mix digester
- Plug and flow digester
- Mixed plug flow digester
- Dry digester
- Open lagoon system

Purification

Removal of impurities (incl. CO_2 and H_2S) to meet purification standards

Processes include:
- Water scrubbing
- Pressure swing adsorption
- Use of amine solvents
- Membrane permeation

Byproduct: Digestate (repurposed into fertilizer)

Direct use

Renewable natural gas (for heating and power generation)

Liquefaction

Liquefaction process at low temperature and with pressurized system

Renewable liquefied natural gas

Observations

- Biogas comes in the form of **renewable natural gas** and can replace up to 10% of natural gas used in the U.S.
- Biogas has the potential to be **carbon neutral**, as it prevents methane emissions from many waste sources within food and waste system.
- There is a **lack of knowledge and ability to maximize** biogas extraction but potential to expand **small-scale digestion plants** for households and other smaller facilities.

Sources: EESI, Biogas Fact Sheet (2017); EIA, Biogas Explained (2023); National Grid, What Is Biogas? (2023); American Biogas Council, What Is Anaerobic Digestion? (2025); Gasum, How is Biogas Produced? (2025); Gazpack, How is Biogas Formed? (2025); Rotecna, Challenges and Opportunities of Biogas Production (2023).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

4. Hydrotreating process allows conversion of vegetable oils and animal fats into drop-in fuels

Process overview

Vegetable oils

Used cooking oils (UCO)

Animal fats (tallow)

→ **Pretreatment** → **Hydrotreatment** → **Catalytic isomerization** → **Distillation** →

- **Hydrotreated vegetable oil diesel**
- **HEFA kerosene**
- **Gasoline**
- **Naphtha fractions**

Pretreatment: **Aqueous acids and caustic wash** used to remove impurities like phosphorous, metals, nitrogen sulfur, and components containing chlorine

Chemical composition can separate into triglycerides and fatty acids

Hydrotreatment: **Hydrogen added into liquid feed** over a catalyst in temperatures of 300-450°C and 3-5 MPa to saturate double bonds of triglycerides and cleave fatty acids

Oxygen removed from glycerol in the form of water and transformed into propane

Fatty acids undergo hydrodeoxygenation (removing oxygen in form of water) or decarboxylation (removing oxygen in the form of CO2) depending on operating conditions

Catalytic isomerization: **Transforming compound into isomeric form** (different structure and configuration but identical chemical composition that creates varying properties), also known as **cracking**

Occurs at 300-400°C and results in change in hydrocarbon's molecular structure

Allows hydrocarbons to perform in varying weather conditions

Byproduct: Propane (can be repurposed for commercial use)

Distillation: **Distillation of fuel separates range of hydrocarbons produced**, and varying conversions occur to meet end-user criteria

Extra steps can be used to upgrade HVO into sustainable aviation fuel (SAF)

Observations

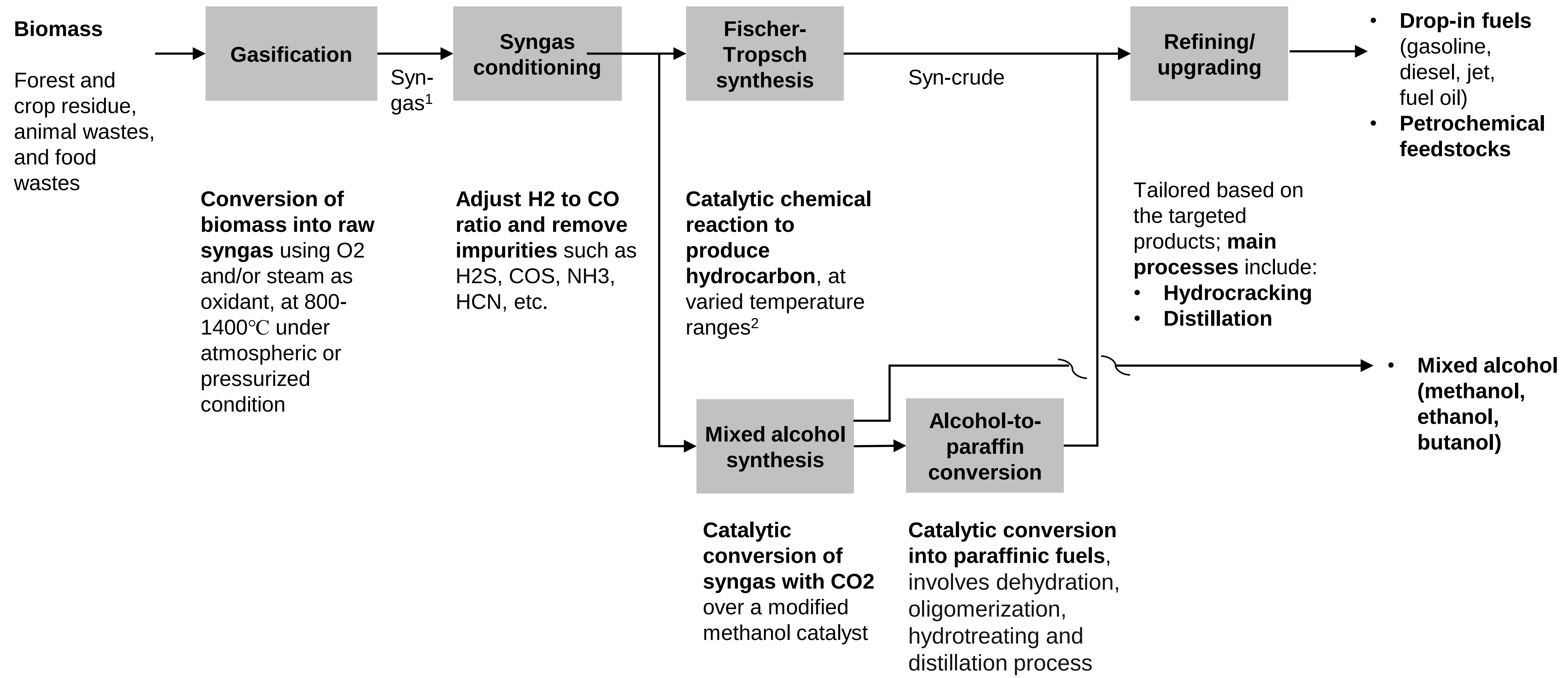
- Hydrotreated vegetable oil (HVO) fuel is a type of **"drop-in" fuel** that can be blended at high percentages or fully replace existing diesel without having to modify existing engines.
- HVO makes up the **majority of current sustainable fuel growth,** with the EU as a leading producer and the U.S. following behind.
- The production process is **energy-intensive** compared with traditional crude oil refining and poses **costs that are 15% higher** as well as **transportation barriers.**

Sources: ETIP, Hydrotreatment to HVO (2025); ETIP, HVO Fact Sheet (2020); BCC Research, A Green Fuel Solution (2024); McKinsey, Sustainable Fuels Outlook (2024); Rytter *et al.*, Thermochemical Production of Fuels (2020); DCD, HVO Supply Chains (2023); Biobased Diesel Daily, Requirements and Solutions for Pretreatment (2023).

Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

5. Gasification and Fischer-Tropsch process enables biomass conversion into drop-in fuels and mixed alcohols

Process overview



Observations

- The gasification process **could use many low-cost feedstocks**, depending on specific reactor design.
- Gasification and Fisher-Tropsch **technology are already established at a commercial scale for fossil feedstock** (coal, natural gas); development is still in progress for biomass due to high capital cost.
- **The alcohol to drop-in fuels route is not yet economically viable** due to process complexity and high capital cost.

1) Mixture of hydrocarbon gas, H2, CO, CO2, NH3, H2S, and other impurities depending on biomass content. 2) HTFT at 300-350℃, lighter products (naphtha, olefin), MTFT at 250-300 ℃, LTFT at 200-250 ℃; heavier products (diesel, wax).

Sources: ECN, Advanced liquid biofuel synthesis (2018); IRENA, Innovation Outlook: Advanced Liquid Biofuels (2016).

Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

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6. Pyrolysis is an alternative technology to convert biomass into bio-oil, as feedstock to produce drop-in fuels

Process overview

Ligno-cellulosic biomass → **Pre-treatment** → **Pyrolysis reaction** → **Separation** → **Refining** → Products

Ligno-cellulosic biomass

Forest and crop residue, animal wastes, and food wastes

Pre-treatment

Shredding and drying

Pyrolysis reaction

Thermal decomposition of biomass at high temperature (up to 500℃)

Types of pyrolysis (based on the duration):

- Slow (hours to days)
- Intermediate (10 min.)
- Fast (0.5-5 seconds)
- Flash(<1 second)
- Ultraflash (<0.5 second)

Separation

Physical separation process (via separator and distillation column), split into:

- Solid (char)
- Gas (syngas)
- Liquid (bio-oil)

Bio-oil (60-70%-wt)

Byproducts:

- **Char** (15-25% - wt)
- **Syngas**, used for heating and electricity generation (10-15% - wt)

Refining

Tailored based on the targeted products; **main processes** include:

- **Distillation**
- **Hydrotreatment**
- **Cracking**

Products

- **Biofuels** (gasoline, diesel, jet, fuel oil)
- **Petrochemical feedstocks**
- **Hydrogen**

Observations

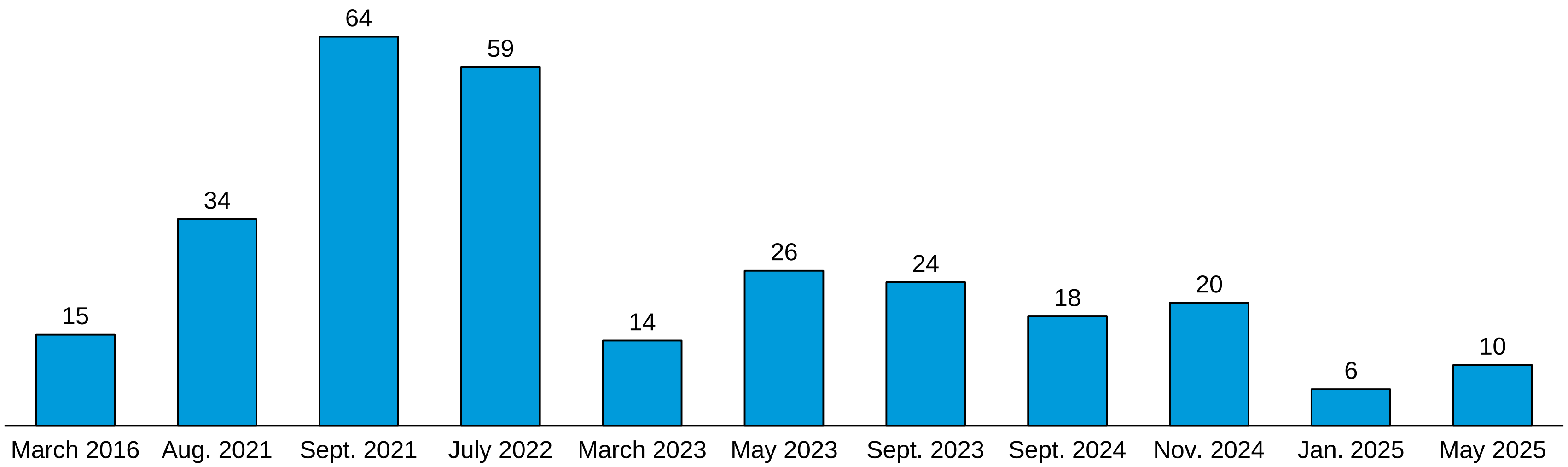
- Bio-oil is an **alternative to traditional fossil fuel oil** to produce liquid fuel and petrochemical products, with 50-70% heating value vs. petroleum-based fuels.
- The pyrolysis process is still **energy-intensive**; hence, the bio-oil price is not yet competitive with fossil-based oil.
- **Advancement of pyrolysis technology is still ongoing** to improve the yield, expand the feedstock's range, and lower the energy consumption, to give rise to a bio-circular economy.

Sources: USDA, What Is Pyrolysis? (2025); Technip Energies, Fast pyrolysis (2021); Energies, Pyrolysis of biomass (2023).
Credit: Sean Lee, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

Still in early stages, development of Gen 3 and 4 biofuels is led by private institutions and academic research with govt. funding

Since 2016, BETO has deployed $253M funding for the advancement of biofuels and related bioproducts

BETO funding, $M



Grant objective:	Advancement in algal biomass yield	Advance waste and algae bioenergy technology	Biofuels research to reduce transport emissions	Expand biofuels production and decarbonize transportation sector	Optimize production of affordable biofuels and biochemicals	Improve biofuels and bioproducts	Support production of low-carbon biofuels and bioproducts	Advance mixed algae development for low-carbon biofuels and bioproducts	Advance development of mixed algae for biofuels and bioproducts	Develop-ment of advanced biofuels	Algal systems R&D to expand U.S. bioenergy feedstock

Observations

- **The Bioenergy Technologies Office (BETO) under the DOE collaborates with industry and academia "advancing technology development and innovation across the entire biomass-to-bioenergy supply chain."**
  - Recipients of the Nov. 24 grant were 31% private and 69% academic.
  - Recipients of the Sept. 21 grant were 59% private and 41% academic.
- **11 grants have been deployed for the advancement of bioproducts.**
  - Bioproducts refers to biofuels and other products derived from biomass, such as bioplastics.
- **BETO's role in the DOE is to improve national energy security and reliability while fostering economic development.**

Source: DOE BETO, Bioenergy Technologies Office Funding Opportunities (2025).
Credit: Ariela Farchi Behar, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).

MPGe and cost of energy per GGE calculations [ref. Slide 69]

MPGe (miles per gallon equivalent)

	E85	B20	B99/B100	Electricity	Gasoline	Diesel
(a) MPG-average, gasoline (ratio)	0.79			3.42	1.00	
(b) MPG-average, diesel (ratio)		0.98	0.90			1.00
(c) MPG					24.40	31.11
MPGe (b)*(c), (a)*(c)	19.28	30.49	28.00	83.50		

Cost of energy per GGE (gasoline gallon equivalent) in 2024, *$/GGE*

	E85	B20	B99/B100	RD	Electricity	Gasoline	Diesel
(a) GGE/gal., kWh	0.78				0.03	1.00	
(b) DGE/gal.		0.99	0.93	0.96			1.00
(c) Price/gal. (2024)	3.66	3.39	4.25	5.20		3.19	3.76
Price/GGE (c/a)	**4.69**					**3.19**	
Price/DGE (c/b)		**3.42**	**4.56**	**5.41**			**3.76**
(d) Price/kWh (2024) (L2)					0.25		
(e) Price/kWh (2024) (L3)					0.45		
Price/GGE (L2) (d/a)					**8.47**		
Price/GGE (L3) (e/a)					**14.92**		

Sources: DOE, Fuel Economy (Ethanol), Fuel Economy (Biodiesel), Fuel Economy (Electricity), Fuel Economy (Gasoline), Fuel Economy (Diesel) (2025).
Credit: Heonjae Lee, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha et al., "Biofueling Transport" (19 November 2025).