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Drop in decarbonization: Techno-economic benchmarks,  
hydrogen needs, and policy design of SAF and renewable  
diesel

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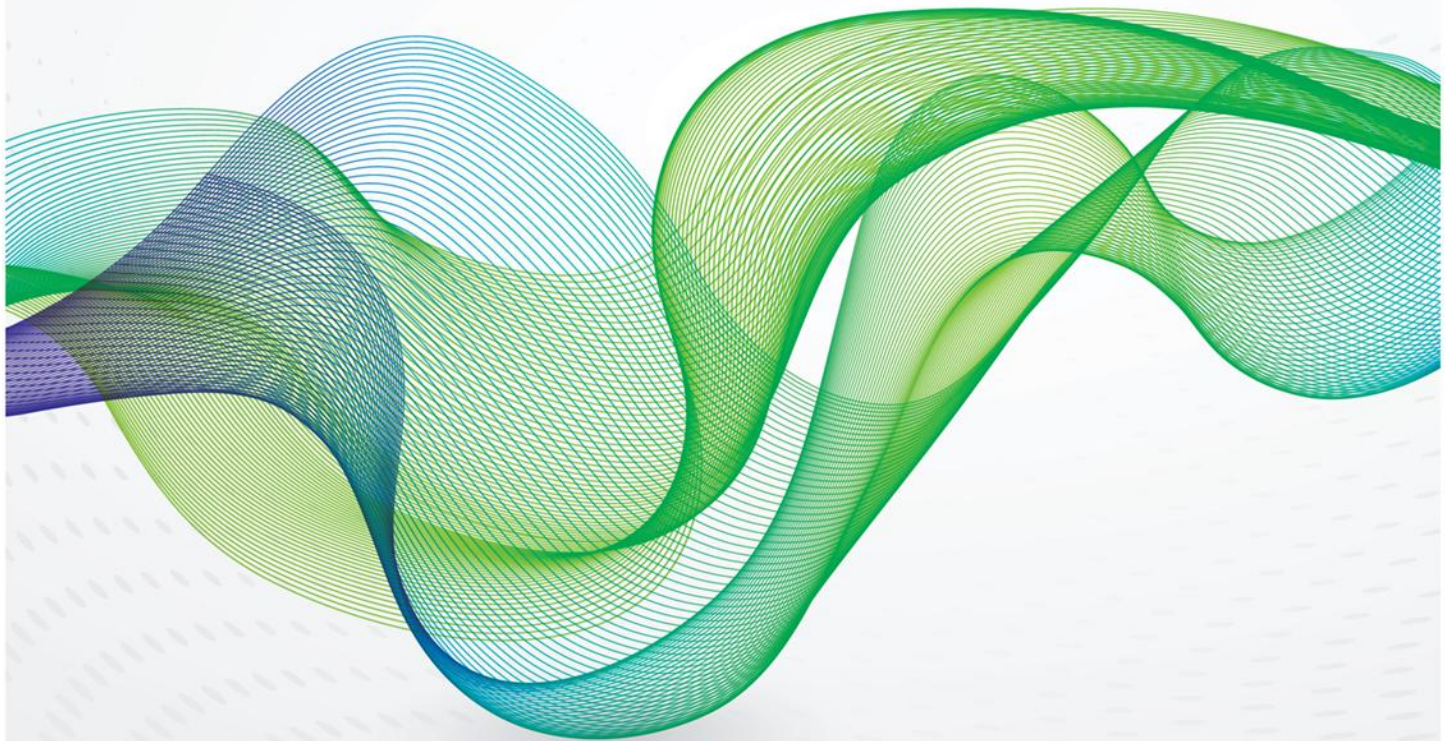
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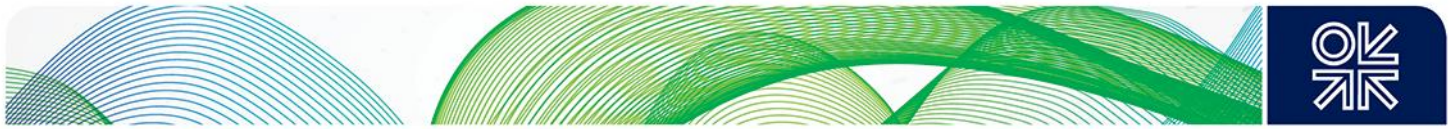
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December 2025

# **Drop In Decarbonization: Techno-Economic Benchmarks, Hydrogen Needs, and Policy Design of SAF and Renewable Diesel**





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## Abstract

Drop-in alternative liquid fuels—Renewable Diesel (RD) and Sustainable Aviation Fuel (SAF)—offer material, near-term abatement for hard-to-electrify transport segments, but their deployment depends on pathway-specific costs, hydrogen requirements, and policy design. The paper evaluates four production routes: Hydroprocessed Esters and Fatty Acids (HEFA), Fischer–Tropsch (FT), Alcohol-to-Jet (ATJ), and electro-Sustainable Aviation Fuel (eSAF) and co-processing options across the European Union, the United States, and Brazil.

Using a harmonized techno-economic model with Monte-Carlo uncertainty, the paper estimates factory-gate costs, decompose cost drivers, quantify hydrogen needs (internal vs. external), and compute 50% blend prices relative to fossil comparators; sensitivity analysis varies hydrogen and carbon prices.

The paper then maps the regulatory landscape and link instruments to the largest cost bars in each pathway. Results show a stable cost ranking:

- HEFA and FT cluster around \$1.3–\$1.7/kg
- ATJ at \$1.6–\$2.1/kg
- eSAF near \$5.0–\$5.3/kg

Decomposition highlights feedstock as the dominant lever for HEFA/ATJ, capital and site services for FT, and energy inputs (clean H<sub>2</sub> and power) plus CO<sub>2</sub> supply for eSAF. Hydrogen-price sensitivity is decisive only for eSAF. For 50% blends, parity expressed as carbon-price equivalents indicates ≈\$60–\$130/tCO<sub>2</sub> for HEFA/FT, ≈\$125–\$210/tCO<sub>2</sub> for ATJ, and ≈\$670–\$710/tCO<sub>2</sub> for eSAF.

The paper proposes a sequenced strategy: scale HEFA and FT now (with blending-credit architectures and feedstock/utility enablers), expand ATJ where alcohol logistics confer advantage, and unlock eSAF as clean-hydrogen and CO<sub>2</sub> costs fall—aligning instruments to pathway-specific cost drivers.

## Nomenclature

Term	Definition
ASTM	ASTM International (formerly American Society for Testing and Materials)
ASTM D1655	Aviation turbine fuel specification
ASTM D7566	Aviation turbine fuel containing synthesized hydrocarbons specification
ATJ	Alcohol-to-Jet
ATJ-SPK	ATJ-based Synthesized Paraffinic Kerosene
BtL	Biomass-to-Liquids
CAPEX	Capital Expenditures
CBG	Compressed Biogas
CBIO	Brazilian decarbonization credit (RenovaBio)
CNG	Compressed Natural Gas
CI	Carbon Intensity
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
COP21	2015 UN Climate Conference (Paris)
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
DCO	Decarbonylation
DCO <sub>2</sub>	Decarboxylation
DME	Dimethyl Ether
E20	20% ethanol gasoline blend
E85	85% ethanol gasoline blend
ED95	95% ethanol diesel
EIA	Energy Information Administration
EN 15940	European Norm 15940 (Paraffinic Diesel Fuel)
EU	European Union
EVs	Electric Vehicles
FT	Fischer–Tropsch
FT-SPK	FT-based Synthesized Paraffinic Kerosene
FFA	Free Fatty Acids
GHG	Greenhouse Gas
HDRD	Hydrogenation-Derived Renewable Diesel
HEFA	Hydroprocessed Esters and Fatty Acids
HEFA-SPK	HEFA-based Synthesized Paraffinic Kerosene
H/C	Hydrogen-to-Carbon (ratio)
HDO	Hydrodeoxygenation
HVO	Hydrotreated Vegetable Oil
HTFT	High-Temperature FT
ICAO	International Civil Aviation Organization



ILUC	Indirect Land-Use Change
IRA	Inflation Reduction Act
LBG	Liquefied Biogas
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LCOE	Levelized Cost of Energy
LNG	Liquefied Natural Gas
LTFT	Low-Temperature FT
MFSP	Minimum Fuel Selling Price
MOGD	Mobil Olefin-to-Gasoline/Distillate
MSW	Municipal Solid Waste
MTO	Methanol-to-Olefins
NREL	National Renewable Energy Laboratory
NZE	Net-Zero Emissions
OPEX	Operating Expenditures
OEM	Original Equipment Manufacturer
PPA	Power Purchase Agreement
PPAs	Power Purchase Agreements
PSA	Pressure Swing Adsorption
PtL	Power-to-Liquids
RD	Renewable Diesel
RFS	Renewable Fuel Standard
RED	Renewable Energy Directive
RED II	Renewable Energy Directive II
RED III	Renewable Energy Directive III
SIP	Synthesized Iso-Paraffins
SMR	Steam Methane Reforming
SPK	Synthesized Paraffinic Kerosene
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
UCO	Used Cooking Oil
UN	United Nations
UPM	UPM (Biofore)
USD	United States Dollar
WTWa	Well-to-Wake
ZSM-5	Zeolite Socony Mobil-5 (catalyst)



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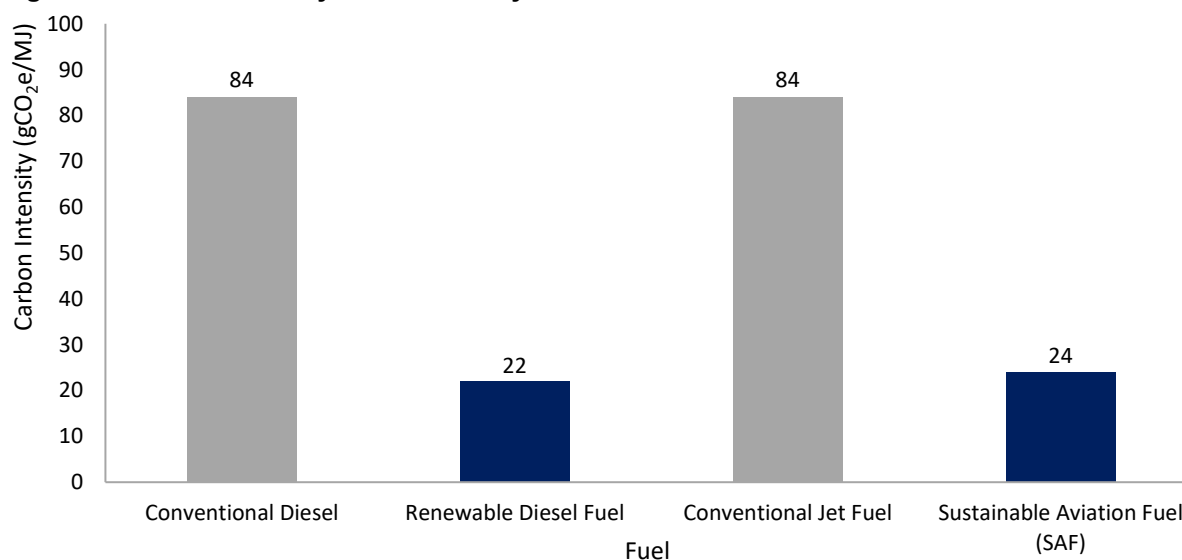
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## 1. Introduction

The energy transition has sharpened the search for practical alternative fuels in hard-to-abate segments of transport. Among the most promising options are drop-in alternative liquid fuels—Renewable Diesel (RD) and Sustainable Aviation Fuel (SAF)—which can be used in existing engines and distribution systems with minimal modification<sup>1</sup>. In contrast to first-generation biofuels derived from food crops, these fuels draw on non-food feedstocks (waste oils and fats, agricultural and forestry residues, the biogenic fraction of municipal solid waste, and lignocellulosic biomass), limiting indirect land-use change and improving lifecycle carbon performance<sup>2,3,4</sup>.

Transport is a major source of global Greenhouse Gas (GHG) emissions. Aviation contributes around 2–3% today and, absent strong policy intervention, its share could rise toward 20% by mid-century. Heavy-duty road transport accounts for roughly 8% and may grow in relative importance as passenger-vehicle emissions fall with electrification. With few immediately scalable decarbonization options in these segments, RD and SAF provide critical short- to medium-term abatement<sup>1</sup>. As Figure 1 illustrates, both fuels can reduce lifecycle carbon intensity by roughly three-quarters relative to their fossil counterparts, while remaining operationally compatible with today's fleets.

**Figure 1: Carbon intensity over the life cycle of fossil and renewable fuels**



Source: Adapted from<sup>1</sup>

Notwithstanding this potential, deployment at scale faces material constraints. Triglyceride feedstocks such as used cooking oil and tallow are limited and geographically uneven. Lignocellulosic biomass—structural plant material composed primarily of cellulose, hemicellulose, and lignin—includes residues (for example, straw, corn stover, and forest slash) and dedicated energy crops (such as miscanthus and switchgrass). Municipal solid waste refers here to sorted, pre-treated waste streams, with the biogenic fraction (food waste, paper, yard trimmings, textiles) most relevant for fuel production<sup>3,4</sup>. Mobilizing these feedstocks requires robust collection systems, pre-processing infrastructure, and clear sustainability rules<sup>2</sup>.

<sup>1</sup> Mu, K., Haris, I., Follette, C., Gordon, A., Boutin, N., & Whalen, R. (2022). *What It Will Take to Reap the Rewards of Renewable Fuels*. <https://www.bcg.com/publications/2022/what-it-will-take-to-reap-the-rewards-of-renewable-fuels>

<sup>2</sup> 1898 & Co. (2024). *The Feedstock Conundrum for RD and SAF*. <https://1898andco.burnsmcd.com/white-paper/the-feedstock-conundrum-for-renewable-diesel-and-sustainable-aviation-fuel?abm=true>

<sup>3</sup> IEA Bioenergy Task 39 (2021), *SAFs: Status, challenges and prospects*.

<sup>4</sup> IEA Bioenergy Task 43 (2025), *Review of feedstock supply for bioenergy in IEA Bioenergy*



Hydrogen plays a central role across the principal production pathways considered in this paper:

- In Hydroprocessed Esters and Fatty Acids (HEFA), waste oils and fats are deoxygenated and hydro-isomerized; hydrogen is consumed during hydrotreating and in upgrading to meet diesel and jet specifications<sup>3,5</sup>.
- In Fischer–Tropsch (FT) pathways, gasification of lignocellulosic biomass or the biogenic fraction of municipal solid waste yields syngas Carbon Monoxide (CO) and Hydrogen (H<sub>2</sub>); the H<sub>2</sub>/CO ratio is adjusted—via the water-gas shift and, where required, supplementary hydrogen—to synthesize long-chain hydrocarbons that are subsequently hydrocracked and distilled to diesel and jet ranges<sup>3,5</sup>.
- In Alcohol-to-Jet (ATJ), bio-alcohols (for example, ethanol or isobutanol produced from residues or waste) are dehydrated, oligomerized, and then hydroprocessed; hydrogen is required during the saturation and finishing steps to meet ASTM jet-fuel properties<sup>5,6</sup>.

Depending on facility design, hydrogen can be sourced internally (for example, reforming of process off-gases) or procured externally via natural-gas reforming or electrolysis; the choice materially influences lifecycle emissions and cost<sup>3,5</sup>.

Against this backdrop, this paper pursues three objectives. First, it provides a comparative techno-economic and environmental assessment of leading pathways for SAF and RD—HEFA, FT, ATJ, and electro-Sustainable Aviation Fuel/power-to-liquid (eSAF/PtL) – including co-processing options, across the European Union, the United States, and Brazil. The analysis quantifies lifecycle GHG performance, hydrogen requirements (distinguishing internal vs. external supply), factory-gate costs, and 50% blend outcomes, with Monte-Carlo uncertainty and sensitivities to hydrogen and carbon prices. Second, it maps the policy and regulatory instruments that shape commercialization—standards, mandates, credits, and market-creation tools—and links them to the dominant cost drivers for each pathway and region. Third, it translates the evidence into actionable guidance for investors, offtakers, refiners, and policymakers by identifying pathway-specific levers (feedstock mobilization for HEFA/ATJ, capital and utilities for FT, clean H<sub>2</sub> and CO<sub>2</sub> supply for eSAF), by proposing region-appropriate sequencing, and by indicating parity ranges (expressed as \$/tCO<sub>2</sub>) needed to close residual premiums.

## 2. Market Status and Investments in Alternative Liquid Fuels

Global biofuel demand has shown moderate but steady growth, rising from approximately 2 million barrels per day (mb/d) in 2022 to a projected 2.22 mb/d in 2024—an increase of around 11%<sup>7</sup>. As illustrated in Figure 2, this demand is predominantly driven by four key regions: the United States, Brazil, the European Union, and Indonesia. These regions collectively account for the majority of global biofuel consumption, reflecting both their supportive policy environments and access to large-scale feedstock supply chains.

Global investment in alternative liquid fuels has surged in recent years, particularly in 2022, driven by the expansion of RD production capacity. This growth was supported by favourable policy environments, particularly in the U.S. and Europe. Biorefineries producing RD saw significant expansion, with global capacity increasing by 7%, marking the largest annual growth in a decade<sup>7</sup>. Key investments included projects such as the \$1.2 billion Marathon-Neste partnership in California, a \$720 million Imperial project in Canada, and Neste’s \$2.2 billion expansion of its Rotterdam plant, which focused on SAF production<sup>7</sup>. These investments signal a growing interest in SAF, especially as the aviation sector seeks to decarbonize its operations.

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<sup>5</sup> U.S. Department of Energy, Bioenergy Technologies Office (2023), *SAF: Review of Technical Pathways*.

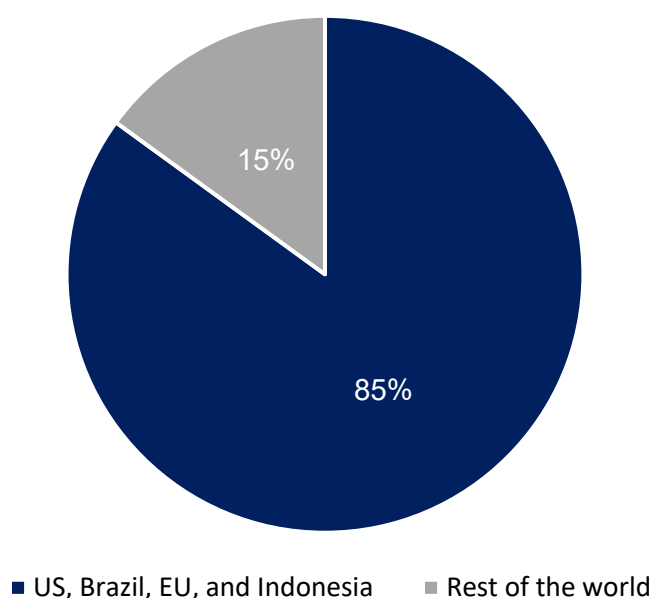
<sup>6</sup> ASTM International (latest edition), *ASTM D7566 – Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*.

<sup>7</sup> IEA. (2024). *Biofuels. Low-Emission Fuels*. <https://www.iea.org/energy-system/low-emission-fuels/biofuels>

Despite this progress, SAF still represents a small fraction of total jet fuel use. While over 200,000 flights have already used SAF blends, the fuel remains significantly more expensive than fossil jet fuel, primarily due to stringent safety standards and the high costs associated with its production.<sup>8</sup> HEFA biojet fuel is currently the most common form of SAF, but its adoption is hindered by many factors including the high capital costs for refineries. In the marine sector, biofuels account for less than 1% of total fuel consumption, with their use largely restricted to short-sea and inland shipping due to retrofitting challenges and cost barriers. While the European Commission has introduced incentives for biofuel adoption in shipping, uptake has remained limited.<sup>8</sup>

Looking forward, investment in alternative liquid fuels must increase more than sevenfold to meet Net-Zero Emissions (NZE) targets by 2050. The U.S., supported by the Inflation Reduction Act (IRA), which allocates \$9.4 billion in fiscal incentives for biofuels, is likely to lead this growth. Europe, with over 30 operational advanced biorefineries and 10 more expected by 2025, is also poised to play a significant role in the biofuel sector's expansion. However, sustained investment is critical to scaling up production, improving technologies, and lowering costs to make SAF and RD commercially viable on a large scale<sup>7</sup>.

**Figure 2: Global biofuels demand**



Source: Adapted from<sup>7</sup>

### 3. Alternative Liquid Fuels: Characteristics, Production Methods, and Environmental Impacts

#### 3.1 Renewable Diesel (RD) and Sustainable Aviation Fuel (SAF)

RD and SAF are drop-in, paraffinic fuels that can be produced on overlapping process platforms yet are designed to meet different end-use specifications (road diesel vs. aviation kerosene). In practice, the same lipid hydroprocessing platform (HEFA/HVO) can be tuned—via hydrotreating severity, hydroisomerization, and fractionation cut points—to bias the product slate toward diesel-range (C<sub>15</sub>–C<sub>18</sub>) or jet-range (C<sub>8</sub>–C<sub>16</sub>) hydrocarbons. Feedstock mix (e.g., tallow vs. Used Cooking Oil (UCO)) and target cold-flow properties further shape this split. Gas-to-liquids such as FT and ATJ pathways similarly produce paraffinic product streams that must be cut and finished to meet their respective fuel standards.

<sup>8</sup> Panoutsou, C., et al. (2021). *Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies*. Energy Strategy Reviews, 34. <https://doi.org/10.1016/j.esr.2021.100633>



Thus, it is important to note that for the subsequent analysis to follow, the technical analysis of this paper will treat RD and SAF as distinct specifications rather than distinct chemistries with the emphasis that process controls allow producers to shift marginal barrels between road diesel and jet fuel, as well as showing how hydrogen requirement, electricity use, and carbon price exposure differ by pathway and specification, affecting both costs and feasible blend ratios.

### 3.1.1 Renewable Diesel

RD—also called green diesel, second-generation diesel, bio-hydrogenated diesel, or Hydrotreated Vegetable Oil (HVO)—is produced from vegetable oils, waste oils, and animal fats.<sup>9</sup> Its composition is straight-chain and branched saturated hydrocarbons (C<sub>15</sub>–C<sub>18</sub>), closely mirroring petroleum diesel and allowing use without engine modifications or blend limits (e.g., RD20 or neat HVO100/RD100).<sup>10</sup> As Table 1 shows, RD typically delivers very high cetane (75–90), near-zero sulfur, excellent oxidative stability, and favorable cold-flow after isomerization. These attributes underpin its drop-in performance in existing engines and infrastructure.<sup>11</sup>

**Table 1: Crude-based diesel and RD fuel properties**

Properties	Crude-based diesel	RD
Cetane#	40–55	75–90
Energy density, MJ/kg	43	44
Density, g/ml	0.83–0.85	0.78
Cloud point, °C	-5	-10
Oxidative stability	Baseline	Excellent
Cold flow properties	Baseline	Excellent
Lubricity	Baseline	Baseline
Sulfur	<10 ppm	<10 ppm
NO <sub>x</sub> emissions	Baseline	-10 to 0

Source: Adapted from <sup>12</sup>

It is important to distinguish that biodiesel (FAME) is produced by transesterification and contains oxygen within the ester functional group. Its higher cloud point (especially from saturated feedstocks) and oxidative instability generally require blending into petroleum diesel to maintain operability and storage performance—hence the prevalence of B7/B10/B20 blends. By contrast, RD is produced via catalytic hydroprocessing (deoxygenation, hydroisomerization), yielding oxygen-free paraffins plus co-products (renewable naphtha and propane). Post-isomerization, RD achieves excellent cold-flow and storage stability without the blending constraints that apply to FAME<sup>14</sup>.

Table 2 shows a qualitative comparison between the two different chemistries of fuel.<sup>13,14</sup>

<sup>9</sup> Douvartzides, S. L., Charisiou, N. D., Papageridis, K. N., & Goula, M. A. (2019). *Green diesel: Biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines*. *Energies*, 12(5). <https://doi.org/10.3390/en12050809>

<sup>10</sup> U.S. Energy Information Administration. (2024, Feb 26). *Biofuels explained: Biodiesel, RD, and Other Biofuels*. <https://www.eia.gov/energyexplained/biofuels/biodiesel-rd-other-basics.php>

<sup>11</sup> Singh, V. (2023). *Current status and future outlook for RD industry*. In *RD: Value Chain, Sustainability, and Challenges* (pp. 103–122). Elsevier. <https://doi.org/10.1016/B978-0-323-91153-5.00005-4>

<sup>12</sup> Amin, A. (2019). *Review of diesel production from renewable resources: Catalysis, process kinetics and technologies*. *Ain Shams Engineering Journal*, 10(4), 821–839. <https://doi.org/10.1016/j.asej.2019.08.001>

<sup>13</sup> Agwu, O., Valera-Medina, A., Katrašnik, T., & Seljak, T. (2021). *Flame characteristics of glycerol/methanol blends in a swirl-stabilised gas turbine burner*. *Fuel*, 290. <https://doi.org/10.1016/j.fuel.2020.119968>

<sup>14</sup> Barla, R. J., Anand, A., Raghuvanshi, S., & Gupta, S. (2023). *Life cycle assessment of RD production*. In *RD: Value Chain, Sustainability, and Challenges* (pp. 65–86). Elsevier. <https://doi.org/10.1016/B978-0-323-91153-5.00003-0>



**Table 2: Comparison between biodiesel and RD**

Biodiesel	RD
Renewable and biodegradable, but higher cloud point requires blending with petroleum diesel.	Chemically similar to petroleum diesel, enabling use without pre-blending in existing infrastructure.
Produced via transesterification, yielding glycerol as a byproduct.	Produced via thermochemical hydroprocessing, yielding renewable naphtha and propane.

Source: Adapted from<sup>14</sup>

Moreover, when examining the other fuel type discussed in this paper—SAF—it becomes evident that certain chemical requirements necessitate the presence of aromatics to ensure safe operation. By extension, this consideration could also apply to RD, which, like SAF, lacks aromatics compared to its fossil fuel counterpart. Indeed, the aromatics consideration is an aviation issue only, not a diesel requirement. In jet fuel, a minimum level of ring-type hydrocarbons (achieved via blending with conventional kerosene or via approved synthetic aromatics) is needed to ensure elastomer seal swell and fit-for-purpose density; therefore, paraffinic SAF must adhere to ASTM D7566 blend limits. Diesel engines do not require aromatics for compatibility; in fact, low-aromatics paraffinic diesel is consistent with EN 15940 (paraffinic diesel fuel standard) and is valued for high cetane and cleaner combustion<sup>15,16</sup>.

When it comes to final demand, global RD production exceeded 5.5 billion liters in 2023, growing to 13 billion liters in 2024, led by North America, followed by Europe and Asia-Pacific.<sup>12</sup> This scale, coupled with product-slate flexibility in HEFA/HVO units, is why RD availability and marginal cut-point adjustments matter when it comes for producing other fuels, such as SAF, as the process can be adjusted to optimize for the production for one fuel over the other.

### 3.1.2 Sustainable Aviation Fuel

Conventional aviation turbine fuels are produced by crude oil distillation and treating, yielding kerosene-range (C<sub>8</sub>–C<sub>16</sub>) hydrocarbons with a boiling range of roughly 150–275 °C.<sup>17, 18</sup> SAF encompasses several paraffinic families—SPK (Synthesized Paraffinic Kerosene) from HEFA, FT, and ATJ routes, and SIP (Synthesized Iso-Paraffins). To ensure drop-in compatibility, SAF is blended with conventional jet and certified under ASTM D7566 (which cross-references to ASTM D1655 once the blend is qualified). These pathway-specific blend limits are designed to restore density, aromatics-related seal swell, and other fit-for-purpose properties that neat paraffins lack.<sup>15</sup>

Table 3 highlights the systematic differences emphasized in the analysis: paraffinic SAF has very low aromatics and sulfur, excellent cleanliness, and freezing points suitable for high-altitude operation; density is lower than Jet A-1, which is a primary reason for blending to meet energy-per-liter and material compatibility constraints.<sup>19,20</sup>

<sup>15</sup> ASTM D7566 — *Aviation Turbine Fuel Containing Synthesized Hydrocarbons: pathway annexes and blend-limit rationale* (density, aromatics/seal swell, fit-for-purpose).

<sup>16</sup> EN 15940 — *Automotive fuels—Paraffinic diesel fuel from synthesis or hydrotreatment—Requirements and test methods: neat use of paraffinic diesel and relevant property/compatibility framework*.

<sup>17</sup> Chuck, C. J., McManus, M., Allen, M. J., & Singh, S. (2016). *Feedstocks for Aviation Biofuels*. In *Biofuels for Aviation* (pp. 17–34). Elsevier. <https://doi.org/10.1016/B978-0-12-804568-8.00002-0>

<sup>18</sup> Kallio, P., Pásztor, A., Akhtar, M. K., & Jones, P. R. (2014). *Renewable jet fuel*. *Current Opinion in Biotechnology*, 26, 50–55. <https://doi.org/10.1016/j.copbio.2013.09.006>

<sup>19</sup> ICAO. (2025). *SAFs (SAF)*. <https://www.icao.int/environmental-protection/pages/SAF.aspx>

<sup>20</sup> Michaga, M. F. R., Michailos, S., Hughes, K. J., Ingham, D., & Pourkashanian, M. (2021). *Techno-economic and life cycle assessment review of SAF produced via biomass gasification*. In *Sustainable Biofuels: Opportunities and Challenges* (pp. 269–303). Elsevier. <https://doi.org/10.1016/B978-0-12-820297-5.00012-8>

**Table 3: Fossil jet fuel and SAF properties according to ASTM D7566**

Jet fuel properties	Jet A-1	HEFA-SPK	FT-SPK	ATJ-SPK
Flash point (°C)	38	38	38	38
Freezing point (°C)	-47	-40	-40	-40
Density at 15°C (kg/m <sup>3</sup> )	775–840	730–772	730–770	730–770
Net heat of combustion (MJ/kg)	42.8	--	--	--
Aromatics content	25% volume	0.5% mass	0.5% mass	0.5% mass
Sulfur content	0.30% mass	15 mg/kg	15 mg/kg	15 mg/kg

Source: Adapted from<sup>19,20</sup>

As defined by the International Civil Aviation Organization (ICAO), SAF is a renewable or waste-derived aviation fuel that meets sustainability criteria and delivers material lifecycle GHG reductions relative to fossil kerosene. In 2023, global SAF production reached ~600 million liters—a three-fold increase from 2022—yet still ~0.2% of total jet fuel consumption.<sup>21</sup> Looking ahead, SAF could contribute ~65% of aviation’s emission reductions by 2050, conditional on policy, technology maturation, and offset scarcity.<sup>22</sup> Table 4 summarizes advantages and obstacles.<sup>22</sup>

**Table 4: SAF: Advantages and obstacles**

Advantages	Obstacles
Derived from organic or waste-based sources.	Costs four times more than conventional jet fuel.
Compatible with existing aircraft when blended.	Represents <0.1% of global fuel consumption.
50% SAF blend reduces emissions by up to 40%.	Requires broader feedstock and production techniques.
Improves air quality and reduces contrails.	Needs favorable tax policies for production.

Source: Adapted from<sup>22</sup>

To summarize, the blending constraint is central to cost and deployment: paraffinic SAF’s very low aromatics necessitate ASTM-compliant blending with conventional jet or approved synthetic aromatics, whereas RD can be used neat under EN 15940. The techno-economic model discussed below reflects these spec-driven differences via hydrogen intensity (higher for certain SAF routes such as eSAF/PtL), electricity and carbon-price exposures, and the fossil comparator used in 50/50 blending (kerosene for SAF; diesel for RD).

### 3.2 Technical Production Routes (HEFA, FT, ATJ)

Three mature pathways—HEFA, FT, and ATJ—dominate the production landscape for RD and SAF. Although they draw on different feedstocks and unit operations, all three share a common technical objective: remove oxygen from biogenic intermediates and elevate the hydrogen-to-carbon (H/C) ratio so that the resulting hydrocarbons are fully “drop-in” and meet the same specifications as petroleum fuels.

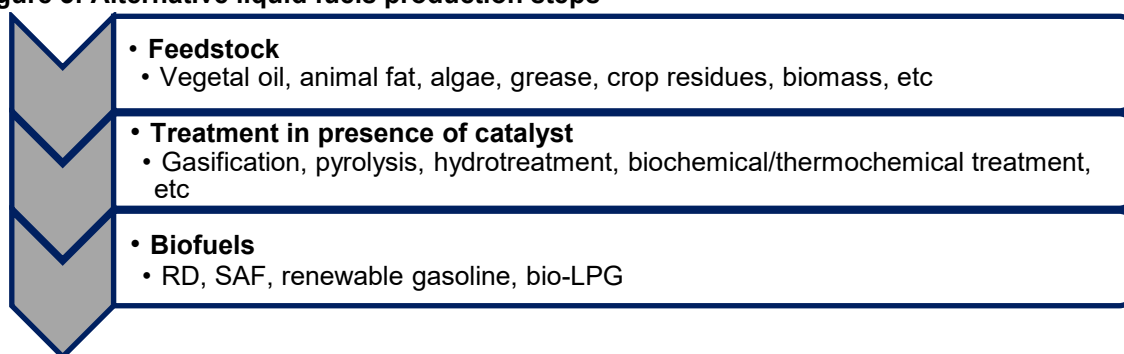
In practice, oxygen is removed as H<sub>2</sub>O, CO, and CO<sub>2</sub> through hydrodeoxygenation (HDO), decarboxylation (DCO<sub>2</sub>), and decarbonylation (DCO), respectively, with process hydrogen acting as a key reagent or, in the FT route, as a utility for downstream upgrading. This progression toward higher H/C is the thread that links lipid hydroprocessing (HEFA), synthesis-gas chemistry (FT), and alcohol upgrading (ATJ) into a coherent family of drop-in biofuel technologies.<sup>22</sup>

<sup>21</sup> IATA. (2023). *Net zero 2050: SAFs*. <https://www.iata.org/flynetzero>

<sup>22</sup> Walter, A., Seabra, J., Rocha, J., Guarenghi, M., Vieira, N., Damame, D., & Santos, J. L. (2021). *Spatially explicit assessment of the feasibility of SAFs production in Brazil*. *Energies*, 14(16). <https://doi.org/10.3390/en14164972>

The generic alternative liquid fuels production steps seen in Figure 3 present the conversion logic from feedstock pre-treatment (removal of water, metals, soaps, and heteroatoms) through oxygen removal and hydrocarbon upgrading, culminating in fractionation into jet- and diesel-range products. The schematic underscores two system-wide realities. Firstly, oxygen must be removed to achieve petroleum-like stability, energy density, and material compatibility. Secondly, hydrogen is consequential—either consumed directly (HEFA, ATJ finishing) or required in upgrading after synthesis (FT).<sup>11</sup>

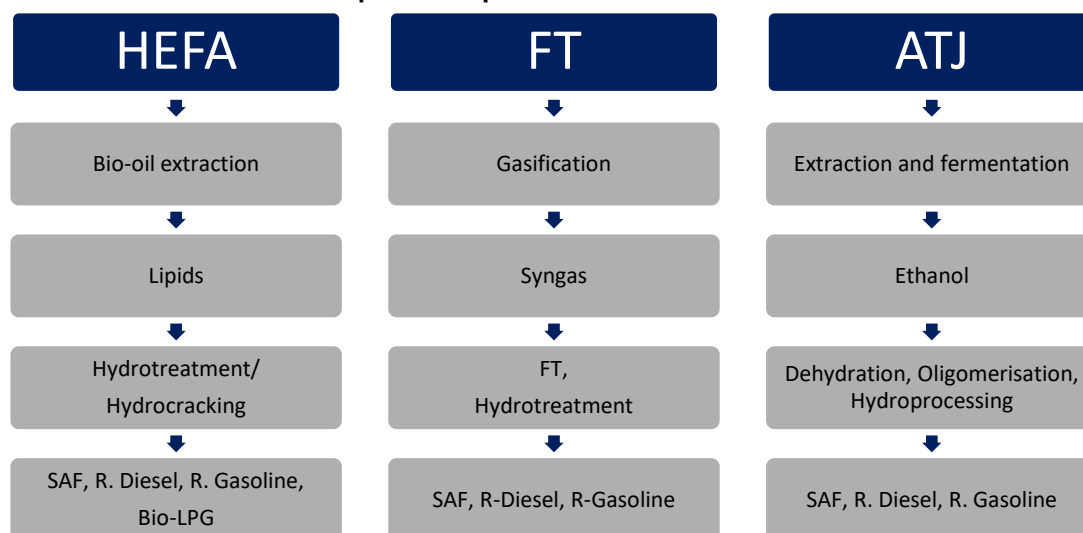
**Figure 3: Alternative liquid fuels production steps**



Source: Adapted from<sup>11</sup>

Taking the generic conversion logic from Figure 3 a step further in terms of detail shows three concrete value chains—HEFA, FT, and ATJ—showing representative feedstock inputs, core reactors, and principal co-products (e.g., naphtha, propane, wax), as seen in Figure 4. Read together, Figure 3 and Figure 4 move the discussion from process logic to route differentiation. Lipid-based molecules (HEFA) are already hydrocarbon-like and thus require mainly hydrogen-assisted deoxygenation and isomerisation; solid biomass or Municipal Solid Waste MSW (FT) must first be converted to synthesis gas and then to paraffinic waxes that are hydrocracked/isomerised; and alcohols (ATJ) are dehydrated and oligomerised before hydrogenation/isomerisation yields jet-range iso-paraffins.<sup>22,23,24</sup>

**Figure 4: The main alternative liquid fuels production routes**



Source: Adapted from<sup>22,23,24</sup>

<sup>23</sup> van Dyk, S., & Saddler, J. (2021). *Progress in Commercialization of Biojet/SAFs (SAF): Technologies, potential and challenges*.

<sup>24</sup> Haq, Z., & Kostova, B. (2017). *Biofuels in Defense and Aviation*.

These different pathways will be discussed in detail in the following subsections. However, at a quick glance, what distinguishes the three routes is the following:

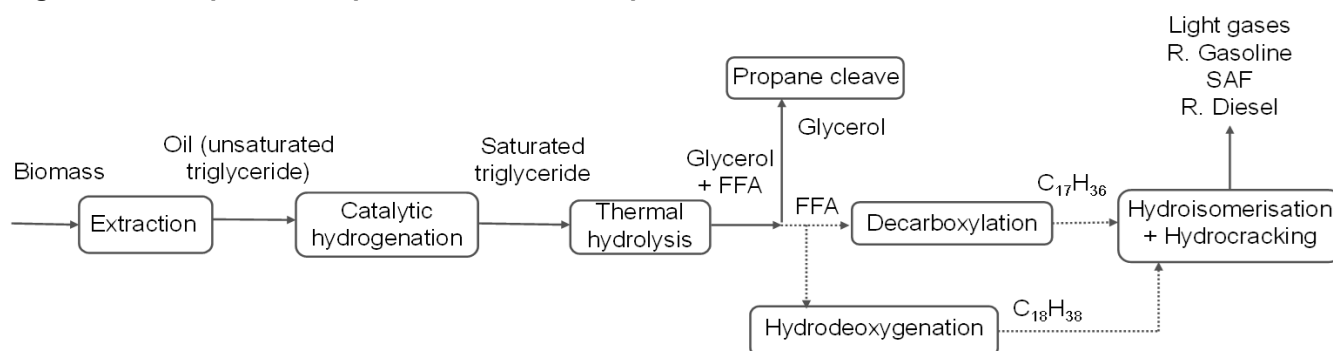
- HEFA (lipids → RD/SAF): Triglycerides/free fatty acids from oils, waste fats, and greases undergo HDO/DCO/DCO<sub>2</sub> and hydroisomerisation to produce normal and iso-paraffins. Cut-point selection (kerosene vs diesel) and isomerisation severity allow the operator to bias the product slate toward SAF or RD within the same refinery-style train. Propane and renewable naphtha are typical co-products.<sup>11,12,22,23,24</sup>
- FT (biomass/MSW → syngas → waxes → RD/SAF): Lignocellulosic or waste feedstocks are gasified to CO/H<sub>2</sub>, cleaned, and conditioned (e.g., water-gas shift). FT synthesis produces long-chain paraffinic waxes that are hydrocracked and isomerised, then fractionated. Tuning of cracking severity and fractionation adjusts the jet/diesel ratio.<sup>11,12,22,23,24</sup>
- ATJ (alcohols → olefins → iso-paraffins): Ethanol/isobutanol (from sugar/starch, cellulose, or gas fermentation) are dehydrated to olefins, oligomerised to jet-range molecules, and then hydrogenated/isomerised. The final product is a paraffinic kerosene (SAF) that meets ASTM D7566 via blending; any diesel-range co-product is route- and configuration-specific.<sup>11,12,22,23,24</sup>

Across all three routes, raising H/C while eliminating oxygen governs stability, cold-flow, and energy content, and it also shapes hydrogen demand and carbon efficiency (e.g., HDO tends to higher liquid yields but greater H<sub>2</sub> use; DCO/DCO<sub>2</sub> reduces H<sub>2</sub> demand but vents carbon as CO/CO<sub>2</sub>). These trade-offs become visible in techno-economic analyses and underpin the sensitivity to hydrogen price explored later in this section.

### 3.2.1 HEFA

The HEFA route is a versatile refinery-style pathway that converts vegetable oils, waste cooking oils, and animal fats into drop-in hydrocarbons by catalytic hydrotreating. In a single train, HEFA can yield SAF, RD, and renewable naphtha, with the slate tuned by reactor severity and cut-point selection. On average, ~1.2 t of vegetable oil feed is required per 1 t of total liquid fuels (product slate plus co-products), though actual yields depend on feedstock quality and operating conditions.<sup>25, 26</sup> Importantly, the same assets can be biased toward RD or SAF output as markets dictate, by adjusting hydroisomerisation/hydrocracking severity and fractionation. The overall flow is shown schematically in Figure 5.<sup>26</sup>

**Figure 5: HEFA process to produce alternative liquid fuels**



Source: Adapted from<sup>26</sup>

<sup>25</sup> Alenezi, R., Baig, M., Wang, J., Santos, R., & Leeke, G. A. (2010). *Continuous Flow Hydrolysis of Sunflower Oil for Biodiesel*. *Energy Sources, Part A*, 32(5), 460–468. <https://doi.org/10.1080/15567030802612341>

<sup>26</sup> Ng, K. S., Farooq, D., & Yang, A. (2021). *Global biorenewable development strategies for SAF production*. *Renewable and Sustainable Energy Reviews*, 150, 111502. <https://doi.org/10.1016/j.rser.2021.111502>

Multiple steps are observed in the figure and they are:

- Step 1 — Hydrogenation of unsaturates. Following oil extraction and pre-treatment, the first catalytic step saturates C=C bonds in triglycerides/free fatty acids to improve stability and prepare molecules for oxygen-removal chemistry. This hydrogenation is typically performed over nickel-based catalysts at moderate temperatures (~150–220 °C) and elevated hydrogen partial pressures (order 0.7–4 MPa, i.e., ~7–40 bar), as reported in the cited studies.<sup>25,26</sup>
- Step 2 — Triglyceride cleavage and propane formation. Thermal/catalytic hydrolysis cleaves triglycerides to glycerol + free fatty acids (FFA); under hydrotreating conditions glycerol is further converted (via dehydration/hydrogenation) to propane, a characteristic HEFA co-product.<sup>25,26</sup>
- Step 3 — Oxygen removal (HDO vs DCO/DCO<sub>2</sub>). Oxygen is then eliminated from FFA-derived intermediates via one of two families of reactions, yielding straight-chain paraffins (n-alkanes):
  - Hydrodeoxygenation (HDO): oxygen leaves primarily as H<sub>2</sub>O; typically operated at higher H<sub>2</sub> partial pressure and over sulphided NiMo/CoMo on alumina, with reactor temperatures commonly 300–600 °C depending on severity. HDO consumes more hydrogen but preserves carbon number.<sup>27,28,29</sup>
  - Decarboxylation/Decarbonylation (DCO/DCO<sub>2</sub>): oxygen leaves as CO (decarbonylation) and/or CO<sub>2</sub> (decarboxylation), generally at lower H<sub>2</sub> demand and somewhat lower pressure than HDO, but with one-carbon loss from the chain.<sup>27,28,29</sup>

These routes represent a classic hydrogen vs. carbon-efficiency trade-off: HDO favors liquid yield at higher H<sub>2</sub> use; DCO/DCO<sub>2</sub> reduces H<sub>2</sub> consumption but vents carbon as CO/CO<sub>2</sub>.

- Step 4 — Isomerisation and cracking to jet/diesel range. The initial paraffinic product is normal-alkane-rich and, on its own, does not meet aviation cold-flow specifications. Consequently, HEFA includes hydroisomerisation (to create iso-paraffins that lower freeze point) and, as needed, hydrocracking (to trim chain length). The combination produces synthetic paraffinic kerosene (SPK) in the C<sub>9</sub>–C<sub>15</sub> range for jet fuel and C<sub>15</sub>–C<sub>18</sub> for diesel, alongside renewable naphtha; exact distributions depend on catalyst/temperature/space velocity and the selected cut points.<sup>30,31,26</sup>

As isomerisation severity and fractionation are tunable, a HEFA unit can be geared toward RD, maximising the diesel cut for road/marine markets, or toward SAF, prioritising kerosene cut and isomerisation severity to reach freeze-point targets, while co-producing propane and naphtha.<sup>25,26</sup>

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<sup>27</sup> Maggi, R. E., & Elliott, D. C. (1997). Upgrading Overview. In *Developments in Thermochemical Biomass Conversion* (pp. 575–588). Springer Netherlands. [https://doi.org/10.1007/978-94-009-1559-6\\_45](https://doi.org/10.1007/978-94-009-1559-6_45)

<sup>28</sup> Huber, G. W., Iborra, S., & Corma, A. (2006). Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysts, and Engineering. *Chemical Reviews*, 106(9), 4044–4098. <https://doi.org/10.1021/cr068360d>

<sup>29</sup> Marker, T. L. (2005). *Opportunities for Biorenewables in Oil Refineries*. <https://doi.org/10.2172/861458>

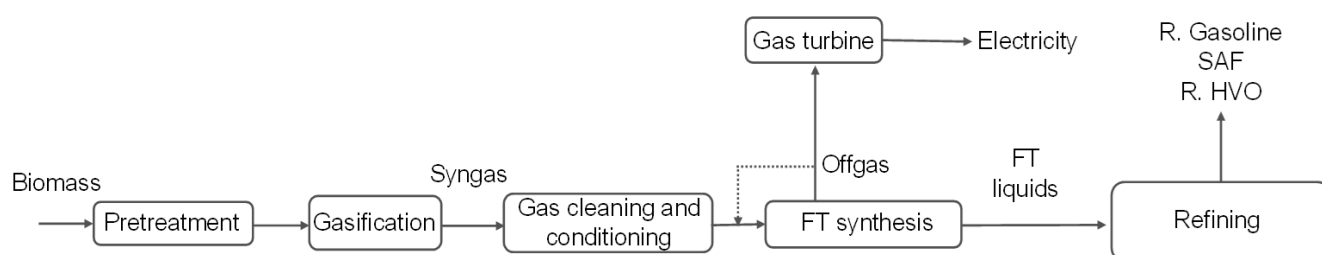
<sup>30</sup> Wang, W.-C. (2016). Techno-economic analysis of a bio-refinery process for producing Hydro-processed Renewable Jet fuel from Jatropha. *Renewable Energy*, 95, 63–73. <https://doi.org/10.1016/j.renene.2016.03.107>

<sup>31</sup> Wang, W.-C., Tao, L., Markham, J., Zhang, Y., Tan, E., Batan, L., Warner, E., & Biddy, M. (2016). *Review of Biojet Fuel Conversion Technologies*. [www.nrel.gov/publications](http://www.nrel.gov/publications).

### 3.2.2 FT

The FT route is a thermocatalytic platform that converts synthesis gas ( $\text{CO} + \text{H}_2$ )—produced upstream from coal, natural gas, or biomass—into long-chain hydrocarbons suitable for RD and, after upgrading and fractionation, SAF or RD. FT provides the hydrocarbon-forming step for syngas-based pathways.<sup>32,33,34,12</sup> A high-level process schematic is included in Figure 6.<sup>26</sup>

**Figure 6: FT process to produce alternative liquid fuels**



Source: Adapted from<sup>26</sup>

Two industrially relevant FT regimes are distinguished by temperature and catalyst: Low-Temperature FT (LTFT, typically cobalt-based) and High-Temperature FT (HTFT, iron-based). HTFT commonly operates at  $\sim 330\text{--}350^\circ\text{C}$ , producing a lighter product slate with excellent cold-flow properties, while LTFT favours heavier waxes that are subsequently cracked/isomerised to fuels.<sup>32,33,34,35,12</sup>

For biomass-to-liquids (BtL), gasification produces a  $\text{CO}/\text{H}_2$ -rich syngas that is cleaned, conditioned ( $\text{H}_2/\text{CO}$  ratio adjustment), and fed to the FT reactor. The FT product (a mixture of paraffinic hydrocarbons) is then hydrocracked and hydro-isomerised to meet diesel and jet specifications, followed by fractionation into naphtha, jet (kerosene cut), diesel, and light ends.<sup>36,37</sup> In practical yield terms, a commonly cited rule-of-thumb for BtL is  $\sim 5\text{--}6$  t of biomass per 1 t of FT liquid fuels, with actual conversion depending on gasifier/reformer efficiency and carbon losses.<sup>38,39,37</sup>

FT-derived RD exhibits very low sulfur and nitrogen, a high heating value, high cetane, and clean combustion, translating into lower  $\text{NO}_x$  and particulate emissions relative to conventional diesel. These fuels can be neat or blended in existing engines and infrastructure, mirroring the handling qualities of crude-based diesel.<sup>36,37</sup> Industrial activity underscores this readiness; for example, UPM (Biofore) has demonstrated RD production from paper/pulp/forestry residues via FT, targeting conventional diesel markets.<sup>40</sup>

When the kerosene cut is targeted and properly isomerised, the gasification–FT route underpins synthetic paraffinic kerosene (FT-SPK) production and is recognized as a pathway for SAF, contingent

<sup>32</sup> Collings, John. (2002). *Mind over matter: the Sasol story: a half-century of technological innovation*.

<sup>33</sup> Vosloo, A. C. (2001). *FT: a futuristic view*. *Fuel Processing Technology*, 71(1–3), 149–155. [https://doi.org/10.1016/S0378-3820\(01\)00143-6](https://doi.org/10.1016/S0378-3820(01)00143-6)

<sup>34</sup> Leckel, D. (2009). Hydroprocessing Euro 4-Type Diesel from High-Temperature Fischer–Tropsch Vacuum Gas Oils. *Energy & Fuels*, 23(1), 38–45. <https://doi.org/10.1021/ef800614p>

<sup>35</sup> Kamara, B. I., & Coetzee, J. (2009). Overview of High-Temperature Fischer–Tropsch Gasoline and Diesel Quality. *Energy & Fuels*, 23(4), 2242–2247. <https://doi.org/10.1021/ef800924z>

<sup>36</sup> Boerrigter, H., & Veringa, H. J. (2003). *Green' diesel production with FT synthesis*.

<sup>37</sup> Ng, K. S., & Sadhukhan, J. (2011). Techno-economic performance analysis of bio-oil based FT and CHP synthesis platform. *Biomass and Bioenergy*, 35(7), 3218–3234. <https://doi.org/10.1016/j.biombioe.2011.04.037>

<sup>38</sup> Ail, S. S., & Dasappa, S. (2016). *Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario*. *Renewable and Sustainable Energy Reviews*, 58, 267–286. <https://doi.org/10.1016/j.rser.2015.12.143>

<sup>39</sup> IATA. (2015). *SAF Roadmap* (Vol. 1).

<sup>40</sup> Norton, P., Vertin, K., Bailey, B., Clark, N. N., Lyons, D. W., Goguen, S., Eberhardt, J., & Francisco, S. (1998). *Emissions from Trucks using FT Diesel Fuel*.



on meeting blending and specification requirements.<sup>39,37</sup> In the visual logic of Figure 6, FT sits at the core of syngas-based liquid fuels, with downstream hydro-processing and cut-point selection dictating the split between jet and diesel fractions.

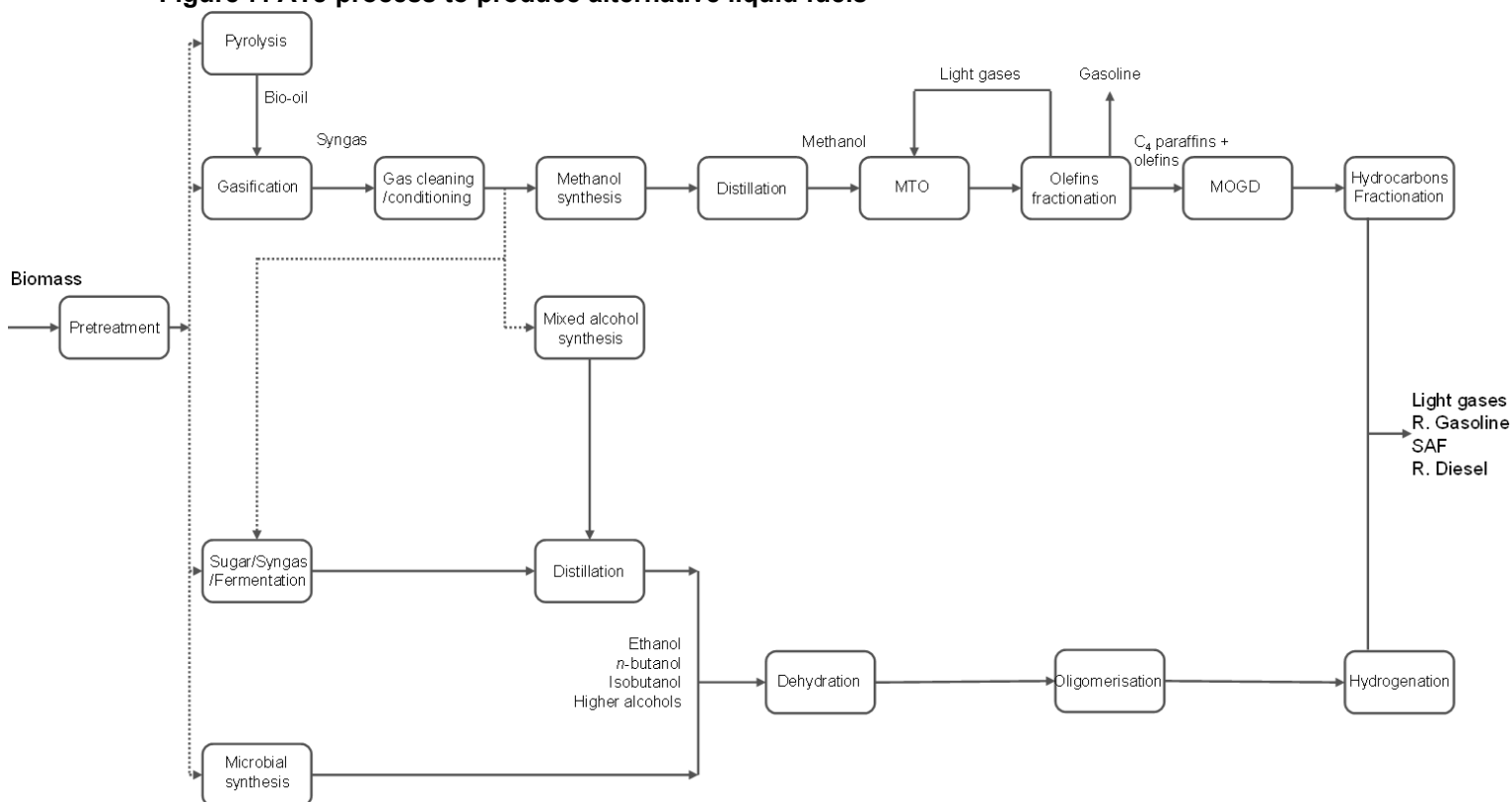
A central challenge for biomass gasification–FT is the stringent syngas purity required to avoid catalyst poisoning and equipment fouling. Robust particulate/tar removal, heteroatom cleanup, and process integration remain active development areas to ensure feed quality and cost-effective operation.<sup>36,41</sup>

### 3.2.3 ATJ

The ATJ pathway upgrades short-chain alcohols—most commonly methanol, ethanol, or isobutanol/butanol—into kerosene-range hydrocarbons ( $\approx C_8-C_{16}$ ) suitable for jet fuel blending. Two industrially relevant routes are distinguished by the intermediate chemistry:<sup>42</sup>

- Route A: MTO → MOGD. Methanol-to-Olefins (MTO) generates light olefins that are subsequently converted in Mobil’s Olefin-to-Gasoline/Distillate (MOGD) process to liquid fuels.<sup>42</sup>
- Route B: Alcohol oligomerization. Ethanol, isobutanol, or butanol undergo dehydration → oligomerization → hydrogenation to form paraffinic distillates.<sup>42</sup>

**Figure 7: ATJ process to produce alternative liquid fuels**



Source: Adapted from<sup>26</sup>

<sup>41</sup> Santos, R. G. dos, & Alencar, A. C. (2020). Biomass-derived syngas production via gasification process and its catalytic conversion into fuels by Fischer Tropsch synthesis: A review. *International Journal of Hydrogen Energy*, 45(36), 18114–18132. <https://doi.org/10.1016/j.ijhydene.2019.07.133>

<sup>42</sup> Soleimani, S. S., Adiguzel, A., & Nadaroglu, H. (2017). *Production of bioethanol by facultative anaerobic bacteria*. *Journal of the Institute of Brewing*, 123(3), 402–406. <https://doi.org/10.1002/jib.437>



The alcohol feedstock can be produced from biomass by thermochemical routes (e.g., gasification, pyrolysis with downstream synthesis) or biochemical routes (e.g., fermentation). Emerging microbial pathways are also under development for alcohol production.<sup>43,44</sup>

- For route A, as schematized in the figure for the MTO pathway (see Figure 7, ATJ–MTO), methanol is fed to an MTO reactor—typically a fluidized bed with ZSM-5 catalyst at ~482 °C and ~1 bar—producing a slate of methane, paraffins, olefins, and liquid biofuels. The reactor effluent is fractionated into light gases, renewable gasoline, and bio-olefins. Renewable gasoline emerges as the primary liquid cut, while bio-olefins are routed to MOGD, which further converts them to light gases and distillates—notably SAF-range kerosene and RD.<sup>45,26</sup>
- For route B, in the alcohol-oligomerization route, the alcohol is dehydrated to the corresponding olefin(s), oligomerized to build carbon number into the jet/diesel range, and then hydrogenated to yield paraffinic hydrocarbons. Downstream fractionation separates kerosene-range material for SAF blending and diesel-range material for RD.<sup>42</sup>

For both routes, saturation (hydrogenation) and cut management are used to deliver paraffinic distillates with properties appropriate for jet (kerosene cut) and diesel (heavier cut). The kerosene fraction from ATJ is intended for use as SAF blendstock, with blending undertaken to ensure fit-for-purpose properties alongside conventional jet fuel.<sup>45,26</sup>

### 3.3 Hydrogen Requirements in Production Pathways

Hydrogen is critical to producing drop-in fuels. Its role and sourcing, however, differ by pathway. Moreover, Hydrogen can be distinguished to be internal or external to the process. Where internal hydrogen is derived on site (e.g., syngas for FT, or steam-reforming of HEFA by-products/off-gas). Whilst external hydrogen is purchased or produced off-site (e.g., pipeline H<sub>2</sub>, external SMR, renewable electrolysis). With that mentioned, integration of hydrogen varies by plant, pathway, and even desired fuel produce (SAF, RD).

For HEFA (HVO/Hydroprocessed Esters & Fatty Acids), hydrogen is consumed during deoxygenation and, for jet fuel, more severe isomerisation/hydrocracking. Total purchased H<sub>2</sub> per tonne of finished fuel is typically ~36–48 kg/t for RD (RD-lean operation) and ~55–60 kg/t for SAF-lean operation. If a plant reforms its own by-products (propane/naphtha) or off-gas, a substantial fraction of this requirement can be met internally; without such integration it is entirely external.<sup>26,46,20</sup>

The FT step itself uses syngas (CO+H<sub>2</sub>) generated on site from biomass/natural gas and adjusted by water-gas shift; finishing (hydrocracking/hydrogenation) may require only “make-up” H<sub>2</sub>, often recovered from FT tail-gas or supplied in small quantities from SMR/PSA. In practice the external share is low (often 0–10 kg/t fuel; 0–5 %), with the balance effectively internal via syngas management and off-gas recycle.<sup>26,46</sup>

Finally, for ATJ (Alcohol-to-Jet), hydrogen is chiefly required to saturate oligomers after dehydration/oligomerisation. Reported values vary by route (isobutanol vs. ethanol/MTO-MOGD) and severity; literature indicates ~0.08 kg H<sub>2</sub>/kg jet, with lower figures reported in some designs. In all cases this H<sub>2</sub> is external.<sup>26,20</sup> A summary of this information can be seen in Table 5.

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<sup>43</sup> Martinez Hernandez, E., & Ng, K. S. (2018). Design of biorefinery systems for conversion of corn stover into biofuels using a biorefinery engineering framework. *Clean Technologies and Environmental Policy*, 20(7), 1501–1514. <https://doi.org/10.1007/s10098-017-1477-z>

<sup>44</sup> Lan, E. I., & Liao, J. C. (2013). Microbial synthesis of n-butanol, isobutanol, and other higher alcohols from diverse resources. *Bioresource Technology*, 135, 339–349. <https://doi.org/10.1016/j.biortech.2012.09.104>

<sup>45</sup> Baliban, R. C., et al. (2013). *Thermochemical Conversion of Duckweed Biomass to Gasoline, Diesel, and Jet Fuel: Process Synthesis and Global Optimization*. Ind. & Eng. Chem. Res., 52(33), 11436–11450. <https://doi.org/10.1021/ie3034703>

<sup>46</sup> Sotelo-Boyas, R., Trejo-Zarraga, F., & Jesus Hernandez-Loyo, F. de. (2012). *Hydroconversion of Triglycerides into Green Liquid Fuels*. In *Hydrogenation*. <https://doi.org/10.5772/48710>

**Table 5: Hydrogen requirements for key production pathways**

Pathway	Fuel type	Purchased H <sub>2</sub> (kg per tonne fuel)	Typical internal share	Typical external share
HEFA	RD	36–48	0–100%*	100–0%*
HEFA	SAF (HEFA-SPK)	55–60	0–100%*	100–0%*
FT	RD / SAF	0–10 (make-up)	~95–100%	~0–5%
ATJ	SAF (ATJ-SPK)	~80 (route-dependent; see notes)	0%	100%

Source: Adapted from<sup>47,48,49,50</sup>

Notes: (i) Values are normalised to kg H<sub>2</sub> per tonne of finished fuel. For HEFA, literature often reports kg H<sub>2</sub> per tonne of oil feed; we convert using ~1.2 t oil/t fuel unless a study provides a different yield. (ii) Route (isobutanol vs. ethanol/MTO-MOGD), catalyst, and severity of saturation/finishing drive the spread. \*Sites that steam-reform internal by-products (propane/naphtha/off-gas) can displace a large fraction—up to all—of purchased H<sub>2</sub>; without such integration, H<sub>2</sub> is fully external

### 3.4 Co-processing: Integration with Oil Refineries

Several energy companies have begun integrating alternative liquid fuels into their refining operations, leveraging their existing expertise in hydrotreating, co-processing, and hydrogenation technologies. Few are investing in full or partial refinery conversions, as well as co-processing methods that enable the gradual integration of renewable feedstocks into fossil fuel operations.

For RD production, oil refineries have implemented innovative strategies to simultaneously process triglyceride feedstocks with petroleum intermediates, such as straight run gas oil and vacuum gas oil, to generate RD. This co-processing method involves conducting hydrotreating on the triglycerides while simultaneously carrying out hydrodesulfurization of the gas oil within the same reactor, utilizing sulfided catalysts like Co-Mo/Al<sub>2</sub>O<sub>3</sub> and Ni-Mo/Al<sub>2</sub>O<sub>3</sub>.<sup>9,46,51</sup>

Operated typically at temperatures ranging between 350 to 450°C and pressures of 50 to 100 bar, this integrated process blends 5 to 20% vegetable oils with 80 to 95% gas oil. The resultant product stream comprises gas phase components including saturated hydrocarbons, green propane, CO, and CO<sub>2</sub>, alongside liquid phase hydrocarbons spanning from C<sub>5</sub> to C<sub>30</sub>, with notable yields of C<sub>15</sub> to C<sub>18</sub> RD,<sup>9,46,51</sup> as presented in Figure 8.

<sup>47</sup> van Dyk, S., Su, J., McMillan, J. D., & Saddler, J. (2019). *Potential synergies of drop-in biofuel production with further co-processing at oil refineries*. *Biofuels, Bioproducts and Biorefining*, 13(3), 760–775. <https://doi.org/10.1002/bbb.1974>

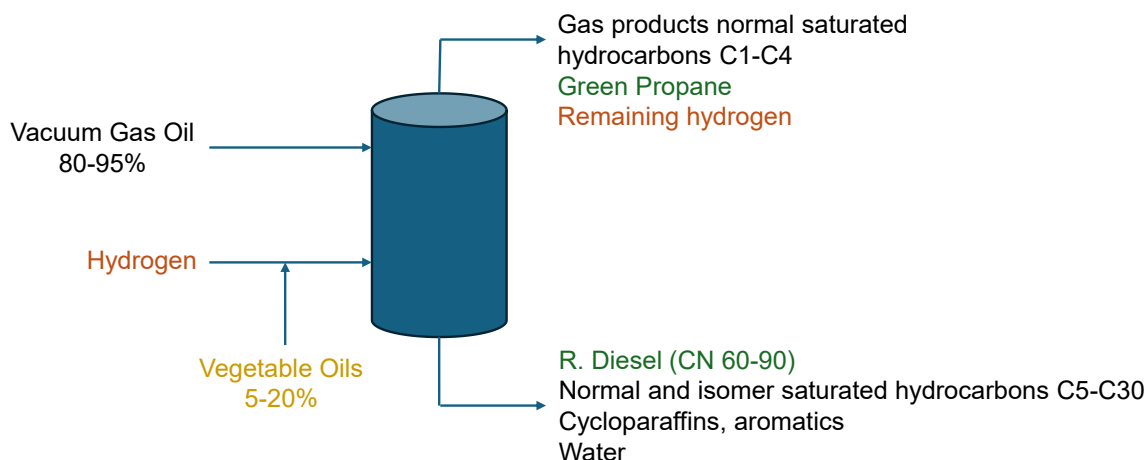
<sup>48</sup> Gogoi Saikia, M., Baratieri, M., & Menin, L. (2025). *Decarbonising SAF Pathways: Emerging Perspectives on Hydrogen Integration*. *Energies*, 18(21), 5742. <https://doi.org/10.3390/en18215742>

<sup>49</sup> Müller-Langer, F., Oehmichen, K., Dietrich, S., Zech, K. M., Reichmuth, M., & Weindorf, W. (2019). *PTG-HEFA Hybrid Refinery as Example of a SynBioPTx Concept—Results of a Feasibility Analysis*. *Applied Sciences*, 9(19), 4047. <https://doi.org/10.3390/app9194047>

<sup>50</sup> Ail, Snehesh Shivananda and Dasappa, S., (2016), *Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario*, *Renewable and Sustainable Energy Reviews*, 58, issue C, p. 267–286, <https://doi.org/10.1016/j.rser.2015.12.143>

<sup>51</sup> Kubička, D., & Tukač, V. (2013). *Hydrotreating of Triglyceride-Based Feedstocks in Refineries* (pp. 141–194). <https://doi.org/10.1016/B978-0-12-386505-2.00003-1>

**Figure 8: Co-processing hydroprocessing plant for biomass and petroleum distillates**



Source: Adapted from<sup>26</sup>

Integration of alternative liquid fuels into refinery feedstock can present multifaceted advantages encompassing carbon emissions reduction, enhanced energy security, and promotion of circular economy principles. This integration taps into a diverse array of biomass sources, and represents a pivotal shift towards sustainable energy solutions, offering a renewable and carbon-neutral alternative to fossil fuels.

In another way, the challenges facing biorefineries and biofuels encompass a wide array of factors including food security, feedstock diversity, logistics for biomass collection and transportation, seasonal variations, land usage, integration with existing refinery infrastructure, market viability, economic sustainability, and consistent investments in research and development.<sup>52</sup> It is imperative for biomass upgrading facilities to achieve optimal socio-economic performance while minimizing environmental impact. To address these challenges effectively, strategies such as waste stream minimization, diversification of the energy matrix, utilization of multiple feedstocks, and proposition of new products must be thoroughly examined and integrated into a holistic approach to enhance biorefinery sustainability.<sup>53</sup>

There are three primary approaches regarding production facility configurations for processing renewable feedstocks:

- Constructing entirely new plants,
- Fully converting traditional fossil-based refineries, or
- Partially converting them through a method known as coprocessing.

Currently, the most prevalent industry projects involve either full or partial conversions of existing refineries into biorefineries capable of handling renewable raw materials.

In cases of full refinery conversion, several operations are modified, such as the installation of new pre-treatment units for biogenic feedstock and steam reformers. Partial conversion, on the other hand, involves co-processing, where renewable and fossil oils are processed together within the same refinery unit. This approach results in final products that contain carbon from both renewable and fossil sources.

<sup>52</sup> Maity, S. K. (2015). Opportunities, recent trends and challenges of integrated biorefinery: Part i. In *Renewable and Sustainable Energy Reviews* (Vol. 43, pp. 1427–1445). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2014.11.092>

<sup>53</sup> Solarte-Toro, J. C., & Cardona Alzate, C. A. (2023). Sustainability of Biorefineries: Challenges and Perspectives. *Energies*, 16(9). <https://doi.org/10.3390/en16093786>



While constructing entirely new plants carries the risk of making conventional refinery assets obsolete, the two conversion options offer the advantage of adapting and repurposing existing infrastructure.<sup>54,47</sup>

Adaptation of conventional refineries allows for the utilization of processing units and external structures, including utilities, storage tanks, and distribution systems. Moreover, expertise in petroleum refining can be leveraged in these adaptive processes. Co-processing, specifically, is viewed as a readily applicable solution in existing facilities.<sup>55,56</sup>

The layout of oil refineries can differ significantly, but there's less diversity when the primary focus is on producing transportation fuels, especially concerning the crude oil source. A recent trend involves running more integrated refineries that produce petrochemicals to fully utilize the lighter fractions of crude oils.<sup>57</sup>

Several companies have shown that while repurposing a refinery for RD and SAF production is feasible, processing biogenic feedstocks such as soy oil, palm oil or waste cooking oil, poses unique challenges and often entails a steep learning curve. For instance, Neste has managed to incorporate biogenic feedstocks into some of its refineries, but adapting to the characteristics of various biogenic feedstocks in plant design and operation has proven challenging, adding complexity and cost. Unlike crude oil, which is transported via pipelines, biogenic feedstocks are typically delivered by rail, truck, or barge. This necessitates careful consideration of the size and frequency of feedstock supply, as well as storage requirements, especially if lipid feedstocks vary in grade.<sup>57,58</sup>

Co-processing biogenic feedstocks such as lipids or biocrudes within existing petroleum refineries introduces notable changes in operational demands, particularly in terms of energy and utility consumption.

The introduction of oxygenated and more reactive feedstocks into hydroprocessing units, especially hydrotreaters, increases the consumption of hydrogen, power, and heat, often beyond baseline levels observed in conventional fossil-only operations.<sup>59</sup>

However, the quantification of these increases is technically challenging due to the need to isolate the incremental demand attributable to the biogenic portion of the feed. Factors such as feedstock variability (e.g., sulfur and nitrogen content) and unstable baseline conditions further complicate this measurement. As co-processing ratios rise beyond current commercial practices (e.g., >5%), refiners are likely to face greater utility demands and may need to invest in additional hydrogen production capacity or improve process integration to maintain efficiency.<sup>59</sup>

The increase in utility demand associated with co-processing directly contributes to higher process emissions, which must be accounted for in any Life Cycle Assessment (LCA) of the resulting fuels. While co-processing aims to reduce the carbon intensity of fuels by incorporating renewable carbon, the emissions associated with additional hydrogen consumption and heat generation can offset some of these benefits.<sup>59</sup>

Moreover, the complexity of emissions accounting is heightened by the need to distinguish between fossil-derived and biogenic carbon, as well as by chemical interactions that may occur between the two

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<sup>54</sup> IBP. (2022). O setor de Óleo e Gás brasileiro em um contexto de emissões líquidas nulas (net zero emissions)

<sup>55</sup> Al-Sabawi, M., Chen, J., & Ng, S. (2012). Fluid catalytic cracking of biomass-derived oils and their blends with petroleum feedstocks: A review. In *Energy and Fuels* (Vol. 26, Issue 9, pp. 5355–5372). <https://doi.org/10.1021/ef3006417>

<sup>56</sup> Han, X., Wang, H., Zeng, Y., & Liu, J. (2021). Advancing the application of bio-oils by co-processing with petroleum intermediates: A review. *Energy Conversion and Management: X*, 10. <https://doi.org/10.1016/j.ecmx.2020.100069>

<sup>57</sup> Su, J., van Dyk, S., & Saddler, J. (2022). Repurposing oil refineries to “stand-alone units” that refine lipids/oleochemicals to produce low-carbon intensive, drop-in biofuels. In *Journal of Cleaner Production* (Vol. 376). Elsevier Ltd. <https://doi.org/10.1016/j.jclepro.2022.134335>

<sup>58</sup> Keyriläinen, J., & Koskinen, M. (2011). Renewable fuels and biofuels in a petroleum refinery. *Health & Environmental Research Online (HERO)*, 16(1), 1–8.

<sup>59</sup> van Dyk, S., Su, J., & Saddler, J. (2022). *Recent progress in the production of low carbon-intensive drop-in fuels - Standalone production and coprocessing.*



feed types during processing - particularly in catalytic cracking units. These interactions can invalidate simpler mass balance approaches, making precise attribution of emissions more difficult. Thus, although co-processing offers a pathway to lower-carbon fuels, its full climate impact is highly dependent on feedstock type, process configuration, and the development of more robust and standardized emissions quantification methods.<sup>59</sup>

As a benchmark in Italy, a notable biorefinery adaptation leveraged existing refinery infrastructure, significantly reducing costs to about one-fifth or one-fourth of what it would cost to build a new facility. By using existing hydrotreaters and a naphtha reformer as the core components, the same technology and capacity were retained. To address limited hydrogen production, a steam reformer was added, along with other improvements such as catalyst upgrades, new heat exchangers, adjustments in acid gas treatment, product recycling, and reactor interconnectivity refinements.<sup>60,61</sup>

### 3.5 Technology Readiness Level

With the conventional biofuel sector already well-established, particularly in ethanol from sugarcane or corn and biodiesel from soybeans and other traditional oilseeds, there is a growing imperative to evaluate the suitability of standard refining plants to produce alternative liquid fuels such as RD, and SAF. In this context, a recent study explored various pathways assessing technological maturity using the TRL (Technology Readiness Level) framework in conventional refinery production routes that can be used as biorefineries.<sup>62,54</sup>

Presently, pathways utilizing oilseeds, oils, or residual fats—such as RD production and co-processing options—are poised to capitalize on refining assets, boasting a TRL 9 (proven current system in an operational environment). This offers distinct advantages, including immediate access to substitute products and the utilization of mature technologies. However, they are not without their challenges, contending with competition from other sectors like food and biodiesel, along with concerns regarding shifts in land use, availability of feedstock and scalability.<sup>54</sup>

HEFA uses feedstocks such as waste oils (e.g., used cooking oil, animal fats) and crops like jatropha and camelina. These feedstocks undergo a hydrogenation process to remove oxygen, resulting in hydrocarbon fuel components. Currently, HEFA is the only SAF in commercial use, with a TRL of 8-9.<sup>63</sup> However, its supply potential is limited due to competition for sustainable feedstocks with other sectors, like road transport.

ATJ technology, with a TRL of 7-8, converts processed lignocellulosic materials (such as agricultural and forestry residues), as well as sugar and starch crops like corn and wheat, into SAF via fermentation.<sup>63</sup> Some ATJ pathways can produce SAF with aromatic content, which is crucial for certain aircraft components. Although reducing aromatics benefits the environment, eliminating them could affect aircraft engine components like rubber seals. This makes ATJ a candidate for future 100% SAF certification, beyond current blending limits.

FT pathway uses biogas or syngas, derived from gasifying feedstocks such as agricultural residues or municipal solid waste, which is then processed in a FT reactor. The route generally rests at a TRL 7. Like ATJ, this method is classified as an advanced biofuel under the EU Renewable Energy Directive (RED II) if derived from specific feedstocks, offering significant emissions reductions. However, neither pathway has yet been commercialized within the EU.<sup>63</sup>

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<sup>60</sup> ENI. (2014). *Green Refinery: reinventing petroleum refineries*.

<sup>61</sup> Fernando Rispoli, G., Prati, C., Amoroso, A., & Pollesel, P. (2017). *Method for revamping a conventional mineral oils refinery to a biorefinery*.

<sup>62</sup> IRENA. (2017). *Biofuels for aviation: Technology brief*.

<sup>63</sup> EASA. (2024). *What are SAFs?* European Aviation Environmental Report.

<https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/what-are-sustainable-aviation-fuels>

Notably, pathways utilizing oilseeds, oils, and residual fats as feedstocks boast the highest maturity level (TRL 9), making them primary choices for repurposed refineries in the short term.<sup>54</sup> Data life cycle emissions from alternative liquid fuels production are presented in the next section.

#### 4. Environmental Impacts and Life Cycle Assessment (LCA)

The main stages of value chain - production, harvest, processing, and distribution - are integral to the life cycle of alternative liquid fuels. While they contribute to GHG emissions, they also present opportunities for emission reduction. Efficiencies in harvesting, cleaner technologies in processing, and optimized distribution are key to making biofuels a viable, sustainable alternative to crude-based fuels.<sup>64</sup> LCA studies are instrumental in evaluating the environmental performance of these biofuels by assessing their entire life cycle, from feedstock production to end-use.

A significant contributor to GHG emissions in the production chain is the choice of feedstock. The transportation, cultivation, and fertilization processes associated with feedstock procurement can significantly elevate the global warming impact of advanced biofuel production. Recent analysis revealed that biomass provision and transport accounted for 30% to 50% of the total GHG emissions. Similarly, other studies identified feedstock cultivation, H<sub>2</sub> production, and conversion inputs as the primary contributors to life cycle GHG emissions in the advanced biofuel production pathways.<sup>65,66,20</sup>

One notable study investigated the production of RD using different feedstocks, including lignocellulosic biomass, sunflower oil, and palm oil.<sup>14</sup> The study specifically examined Hydrogenation-Derived RD (HDRD) derived from lignocellulosic biomass and revealed that GHG emissions from this process can range from 39% to 47% of those emitted by crude-based diesel alternatives. Additionally, the analysis highlights a CO<sub>2</sub> emission rate of 3.18 kg per kg of crude-based fuel, with a RD yield of 0.71 kg.<sup>14</sup> These findings underscore the significant potential for alternative liquid fuels production from diverse feedstock sources, offering promising opportunities for reducing emissions and enhancing sustainability in the transportation sector.

In a case study analyzing RD co-processing with used cooking oil (UCO) and fossil light gas oil in a diesel hydrotreater at an industrial refinery, two scenarios were compared: (1) the conventional hydrodesulfurization of light gas oil for ultra-low sulfur diesel production (the reference scenario), and (2) the co-processing of pretreated UCO with fossil feedstock at a 5/95% volume ratio (the retrofit scenario).<sup>67</sup> The LCA results show that crude-based diesel production results in net GHG emissions of 103.41 gCO<sub>2</sub>eq/MJ, while the RD blend reduces emissions to 95.42 gCO<sub>2</sub>eq/MJ, achieving a 7.7% reduction.<sup>67</sup> Additionally, establishing a facility dedicated solely to UCO-based RD could further reduce emissions by up to 93%, highlighting the potential environmental benefits of sustainable fuel production.<sup>67</sup>

The assessment of GHG emissions from SAF vis-à-vis conventional crude-based jet kerosene often relies on LCA methodologies. A study associated with HEFA route analyzed various feedstocks, including jatropha (*Jatropha curcas*), pennycress (*Thlaspi arvense*), castor (*Ricinus communis*), energy tobacco (*Nicotiana tabacum*, Solaris), and Salicornia (*Salicornia bigelovii*) oils.<sup>68</sup> The analysis revealed that HEFA pathways exhibit significant GHG emissions reductions (ranging from 34% to 65%) compared

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<sup>64</sup> Rial, R. C. (2024). *Biofuels versus climate change: Exploring potentials and challenges in the energy transition*. *Renewable and Sustainable Energy Reviews*, 196. <https://doi.org/10.1016/j.rser.2024.114369>

<sup>65</sup> de Jong, S., et al. (2017). *Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production*. *Biotechnology for Biofuels*, 10(1), 64. <https://doi.org/10.1186/s13068-017-0739-7>

<sup>66</sup> Neuling, U., & Kaltschmitt, M. (2018). Techno-economic and environmental analysis of aviation biofuels. *Fuel Processing Technology*, 171, 54–69. <https://doi.org/10.1016/j.fuproc.2017.09.022>

<sup>67</sup> Kourkoumpas, D.-S., Sagani, A., Vallianatos, A., Kiartzis, S., Karellas, S., Dedoussis, V., & Grammelis, P. (2024). Life cycle GHG emission reduction of hydrotreated vegetable oil integration in an industrial petroleum refinery. *Green Technologies and Sustainability*, 2(2), 100076. <https://doi.org/10.1016/j.grets.2024.100076>

<sup>68</sup> Seber, G., Escobar, N., Valin, H., & Malina, R. (2022). Uncertainty in life cycle greenhouse gas emissions of SAFs from vegetable oils. *Renewable and Sustainable Energy Reviews*, 170. <https://doi.org/10.1016/j.rser.2022.112945>



to fossil jet kerosene, particularly, without accounting Direct Land Use Change (DLUC) emissions. Importantly, DLUC emissions nullify any GHG savings achieved through HEFA fuels if forests or natural shrublands are displaced. This underscores the critical importance of considering land use change dynamics in assessing the sustainability of SAF pathways.<sup>68</sup>

Different studies conducted a comprehensive assessment comparing HEFA, FT, and ATJ technologies in terms of well-to-wake (WTWa) GHG emissions. Their findings indicate substantial GHG emissions reductions across all technologies relative to crude-based fuels, with FT showcasing the highest performance, achieving reductions ranging from 86% to 100%, concluding that route technology offers superior GHG emissions reductions compared to others processes.<sup>20,65,66</sup>

LCA studies focusing on the ATJ pathway remain relatively limited in scope. However, the initial stage of the ATJ process, namely alcohol synthesis, has garnered considerable attention in numerous assessments. Consequently, there exists a body of LCA studies examining alcohol production from sugar or starch, as well as from lignocellulosic biomass. Despite this, LCAs addressing syngas fermentation and methanol-to-olefins (MAS) processes are notably scarce in the existing literature.<sup>69,70,71</sup>

**Table 6: GHG emissions of SAF production pathways**

Pathway	Feedstock	GHG emissions (gCO <sub>2</sub> eq/MJ)
HEFA	Mixed Animal Fats	28.6
	Soybean oilseed	40.4
	Corn oil	17.2
Coprocessing HEFA	Used cooking oil	16.7
FT	Poplar	12.2
	Miscanthus	10.4
	Switchgrass	10.4
	Municipal solid waste	5.2
ATJ	Sugarcane	24.1
	Corn grain	65.7
	Agricultural residues	24.6
	Waste gases	42.4
Fossil	Crude-based source	94

Source: Adapted from<sup>72,73</sup>

Although LCAs examining ATJ pathways utilizing alcohol derived from fermentation are more prevalent in the literature, assessments of thermochemical pathways remain relatively scarce. A study undertook a comparative analysis of various ATJ pathways for SAF production from sugarcane derivatives,

<sup>69</sup> Kim, S., & Dale, B. E. (2008). Life cycle assessment of fuel ethanol derived from corn grain via dry milling. *Bioresource Technology*, 99(12), 5250–5260. <https://doi.org/10.1016/j.biortech.2007.09.034>

<sup>70</sup> Mu, D., Seager, T., Rao, P. S., & Zhao, F. (2010). Comparative Life Cycle Assessment of Lignocellulosic Ethanol Production: Biochemical Versus Thermochemical Conversion. *Environmental Management*, 46(4), 565–578. <https://doi.org/10.1007/s00267-010-9494-2>

<sup>71</sup> Tao, L., Tan, E. C. D., McCormick, R., Zhang, M., Aden, A., He, X., & Ziegler, B. T. (2014). Techno-economic analysis and life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-butanol. *Biofuels, Bioproducts and Biorefining*, 8(1), 30–48. <https://doi.org/10.1002/bbb.1431>

<sup>72</sup> ICAO. (2025). *Carbon Offsetting and Reduction Scheme for International Aviation (CORSA)*. <https://www.icao.int/environmental-protection/CORSA/Pages/default.aspx>

<sup>73</sup> Mu, K., Haris, I., Follette, C., Gordon, A., Boutin, N., & Whalen, R. (2022). *What It Will Take to Reap the Rewards of Renewable Fuels*. <https://www.bcg.com/publications/2022/what-it-will-take-to-reap-the-rewards-of-renewable-fuels>

encompassing sugar and bagasse. Through an attributional LCA, the pathway involving ethanol production via syngas fermentation demonstrated the most substantial GHG emissions reductions, accounting for 90% of crude-based jet fuel emissions, albeit constrained by the high energy demands of the gasification step.<sup>74,20</sup> Detailed GHG emission values, with comparative cases between HEFA, FT and ATJ routes for SAF, are provided in Table 6.

## 5. SAF and RD Techno-Economic Model Results and Analysis

This section compares four SAF and RD pathways—HEFA, FT, ATJ, and eSAF (PtL) or eSAF FT<sup>75</sup>—across the EU, the United States, and Brazil. We report factory-gate costs (the unit cost at the plant boundary, excluding distribution, taxes, and retail margins), disaggregate those costs by component, present the 50 % blend prices that end users face, and test sensitivity to hydrogen and carbon prices. Throughout, the fossil comparators are fixed by model input at \$0.767/kg for kerosene and \$0.784/kg for diesel (EIA spot prices converted to \$/kg). These elements together inform procurement choices, investment screening, and policy design by identifying the lowest-cost options today, the dominant cost drivers, and the levers with the greatest potential to shift competitiveness. The following analysis is based on the methodological approach seen in the appendices of this paper. Moreover, if not explicitly mentioned, results would refer to an SAF output rather than RD.

### 5.1 Simulated Factory-Gate Costs

Factory-gate costs exhibit a stable ranking with a moderate regional spread:

- HEFA and FT cluster at \$1.3–\$1.7/kg (EU high, Brazil low)
- ATJ lies at \$1.6–\$2.1/kg, and
- eSAF FT remains materially higher at ≈\$5.0–\$5.3/kg, as purchased hydrogen and captured CO<sub>2</sub> dominate its cost base.

For context, fossil kerosene and diesel benchmarks convert to ≈\$0.77–\$0.78/kg.

The error bars Figure 9 visualise different notions of risk: for SAF/RD/eSAF FT, the whiskers show Monte-Carlo  $\pm 1\sigma$ —one standard deviation from repeated simulations that vary correlated CAPEX and OPEX parameters—so they represent techno-economic parameter uncertainty. For fossil comparators, the whiskers show 2005–2025 monthly spot-price volatility converted to \$/kg—so they represent market price variability. Readers should not conflate these concepts when comparing bar heights and whiskers.

Across regions, the neat (unblended) gaps to the fossil comparator quantify the distance to parity: Relative to fossil jet, SAF-HEFA averages \$0.61/kg (≈80 %), SAF-FT \$0.72/kg (≈94 %), and SAF-ATJ \$1.07/kg (≈140 %). Relative to diesel, RD-HEFA averages \$0.46/kg (≈59 %).

eSAF sits much higher at \$4.37/kg (≈570 %) above fossil jet. To interpret the materiality of these premia, the model uses the symbol  $\sigma$  (sigma) to denote one standard deviation of historical monthly fossil fuel price movements (≈\$0.27/kg for jet; ≈\$0.24/kg for diesel over 2005–2025). Expressed in  $\sigma$ -terms, the neat premiums are ~2–3 $\sigma$  for HEFA/FT, ~2 $\sigma$  for RD-HEFA, ~4 $\sigma$  for ATJ, and well beyond historical swings for eSAF.

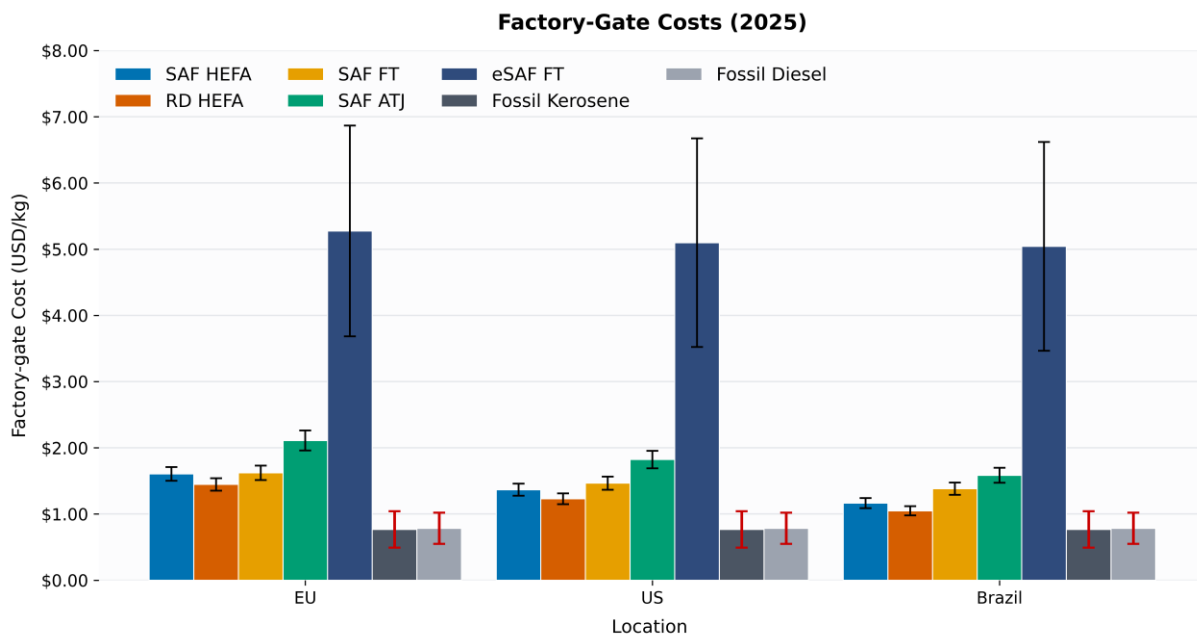
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<sup>74</sup> Capaz, R., Posada, J. A., Seabra, J. E. A., & Osseweijer, P. (2018). *Life Cycle Assessment of Renewable Jet Fuel from ethanol: an analysis from consequential and attributional approaches*. (ResearchGate preprint)

<sup>75</sup> In this paper, eSAF refers exclusively to fuels produced via PtL pathway that employs FT synthesis as the conversion technology for combining hydrogen and carbon feedstocks. Accordingly, in all figures, tables, and discussion that follow in this section, the terms eSAF, eSAF FT and eSAF PtL can be considered interchangeable, as no other eSAF conversion technology is considered within the analysis of this paper.



**Figure 9: Simulated factory-gate costs for HEFA, FT, and ATJ across locations**



Error bars: SAF/RD/eSAF = Monte-Carlo  $\pm 1\sigma$  (n=10,000), Fossil Kerosene/Diesel = 2005-2025 monthly spot price  $\pm 1\sigma$  (EIA) converted to USD/kg.

Source: Authors' contribution

**Table 7: Mean factory-gate costs (USD/kg) and standard deviations**

Technology	Location	Mean (USD/kg)	Std (USD/kg)
SAF HEFA	EU	1.61	0.1
	US	1.37	0.09
	Brazil	1.16	0.08
RD HEFA	EU	1.45	0.1
	US	1.23	0.08
	Brazil	1.05	0.07
SAF FT	EU	1.62	0.11
	US	1.47	0.1
	Brazil	1.38	0.09
SAF ATJ	EU	2.11	0.15
	US	1.82	0.13
	Brazil	1.58	0.11
eSAF FT	EU	5.27	1.59
	US	5.1	1.58
	Brazil	5.04	1.58

Source: Authors' contribution

This  $\sigma$  framing links today's premia to what end users have previously managed. Airlines have operated through multi- $\sigma$  jet-fuel episodes and can mitigate and pass through moderate fuel premia using tools that are structural to the business model: dynamic yield management (adjusting fare buckets in real time), network pricing and capacity (route mix, frequency, and aircraft size/capacity to match demand),

fuel surcharges and hedging, and growth in ancillary revenues. These mechanisms spread cost shocks across a global customer base and over time, which raises aviation's tolerance for moderate SAF premia—especially when premia fall in the 2–3 $\sigma$  range observed for HEFA/FT.

By contrast, heavy-duty diesel applications allow less pass-through. Many freight contracts calculate fuel surcharges from a public diesel price index and apply the index from a prior period (a one- to four-week lag), rather than today's price. Carriers also operate on thin margins and serve price-sensitive shippers. In this setting, even a ~2 $\sigma$  premium (as for RD-HEFA) is hard to absorb: unless contracts include explicit pass-through clauses or policy credits cover the spread, the premium tends to surface as higher freight rates, lower margins, or reduced service levels. Moreover, a lower average premium does not guarantee easier market uptake for RD. Adoption still hinges on procurement practice (lowest-price tenders versus value-based awards), credit/certificate volatility (which can shift the realised spread), specification and logistics (fuel-spec compliance, depot blending, terminal access), and OEM/warranty acceptance in specific duty cycles. Without stable policy signals (e.g., mandates, tradable credits with guardrails, or offtake contracts with indexed adders/floors), RD adoption is likely to track compliance obligations rather than expand through voluntary demand—even when its neat gap is smaller than aviation SAF.

## 5.2 Pathways Cost Decomposition by Location

The decomposition in Figure 10 (with numerical detail in Table 8) is directionally consistent with recent literature and industry assessments. For HEFA and ATJ, feedstock is the largest single cost component; multiple studies and stakeholder syntheses report that variability in lipid or alcohol feedstock pricing drives most of the movement in minimum selling price, with capital changes playing a secondary role.<sup>76,77</sup> NREL's 2024 HEFA state-of-industry report explicitly identifies feedstock price volatility and availability as the dominant economic lever, outweighing capital reductions once plants reach commercial scale.<sup>76</sup> This aligns with the ~40–45 % feedstock shares in Table 8 for HEFA/ATJ (the considered base year and price set); numerous Techno-Economic Analysis (TEAs) show higher shares when feedstock prices are elevated, reinforcing that magnitude depends on market conditions while the ranking of drivers remains stable.<sup>76</sup>

For FT from lignocellulosic biomass, decades of TEA work describe a capital- and site-services-intensive system (gasification, oxygen supply, gas cleanup, FT synthesis, hydroprocessing) with material maintenance and utilities burdens—consistent with Table 8 values of ~30–36 % CAPEX and ~30–40 % maintenance + utilities.<sup>80</sup>

For eSAF, independent assessments converge that electricity and hydrogen are first-order cost drivers and that CO<sub>2</sub> supply (especially DAC) adds a substantial but secondary bar; Figure 10 shows ~54–56 % energy (H<sub>2</sub> + power) and ~22–23 % carbon (CO<sub>2</sub> supply) in the EU case, in line with regional analyses that attribute most PTL cost to electricity for electrolysis and to CO<sub>2</sub> capture/logistics.<sup>78,79</sup>

Together, these comparisons indicate that the model's decomposition is aligned with current studies on the identity of dominant cost drivers; the exact percentages vary by input prices, scale, and system boundaries—an expected outcome when moving from general TEA to region- and year-specific assumptions.<sup>78,76,80</sup>

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<sup>76</sup> National Renewable Energy Laboratory. (2024). SAF state of industry report: HEFA pathway (NREL Technical Report).

<sup>77</sup> Transport & Environment. (2022). Hydrogen use in aviation: Analysis of power to liquids inputs and costs. T&E.

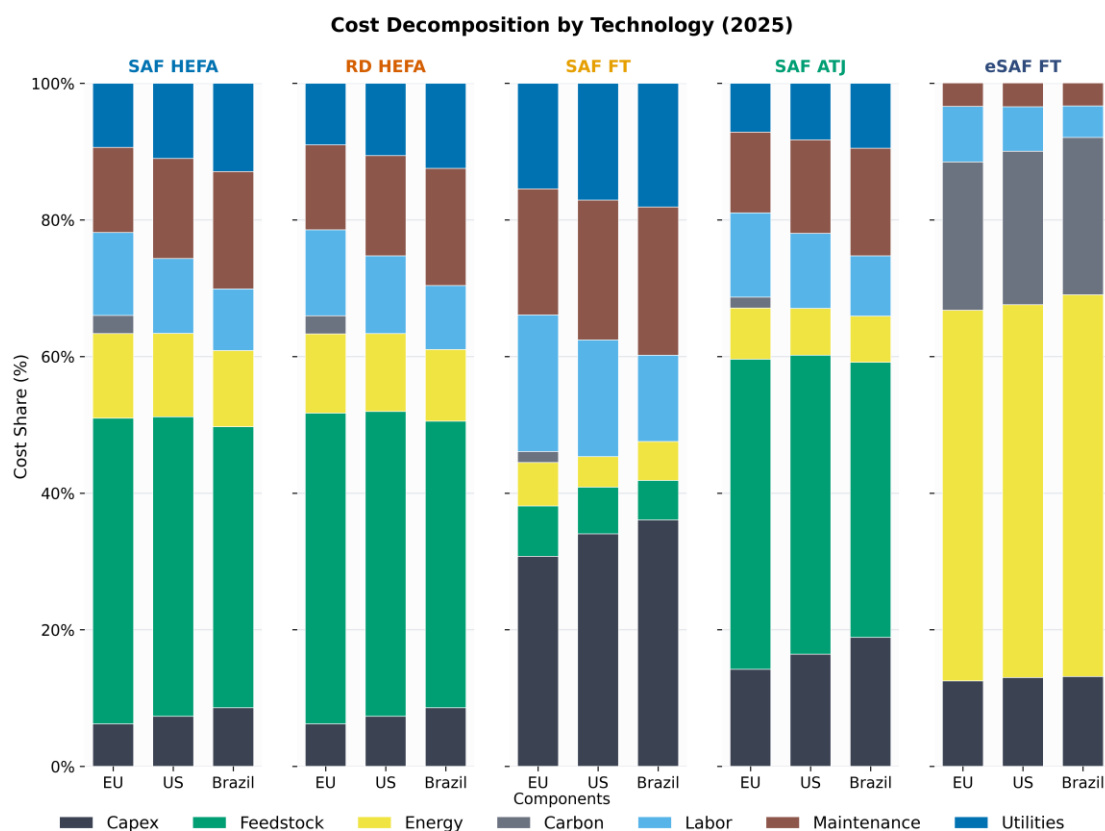
<sup>78</sup> International Council on Clean Transportation. (2022). Current and future cost of e kerosene in the United States and Europe (Working Paper 2022 14).

<sup>79</sup> U.S. Department of Energy. (2024). Clean hydrogen production cost: Proton exchange membrane (PEM) electrolysis. Office of Energy Efficiency and Renewable Energy.

<sup>80</sup> Swanson, R. M., Satrio, J. A., Brown, R. C., Platon, A., & Hsu, D. D. (2010). Techno economic analysis of biofuels production based on gasification (NREL/TP 6A20 46587). National Renewable Energy Laboratory.



**Figure 10: Technology pathways cost decomposition by location**



Source: Authors' contribution

These cost structures translate into distinct value-chain priorities for industry participants. For HEFA and ATJ, operators and offtakers should concentrate on feedstock system performance: contracting strategies that diversify feedstock baskets (e.g., used cooking oil, tallow, waste lipids or regionally advantaged alcohols), quality control and pre-treatment to improve yields, and logistics that reduce delivered-cost dispersion across seasons. Commercial teams can hedge exposure with indexed supply agreements and collars tied to published feedstock indices, while engineering teams focus on hydrogen efficiency and yield uplift that compound feedstock savings. This emphasis reflects the finding—also reported by NREL—that feedstock and policy credits dominate MFSP sensitivity for HEFA; CAPEX reductions help, but do not move the needle to the same extent once plants are at scale.<sup>76</sup>

For FT, the decomposition indicates that project design, uptime, and utilities procurement drive competitiveness. Developers should prioritise sites with reliable utilities (power, steam, oxygen) and industrial services, use modularisation and proven gasification/cleanup trains to lower installed cost, and invest in reliability engineering and maintenance regimes that deliver high capacity factors. Where available, co-location with industrial partners (e.g., pulp and paper, steel residues, MSW supply chains) can reduce feedstock handling costs while leaving the main lever—capital and site services—squarely addressed. Public tools that lower the cost of capital (e.g., loan guarantees) or industrial tariffs for utilities map directly to the largest bars in Table 8 for FT and thus offer high policy efficiency. This mirrors long-standing TEA conclusions that FT solutions are feasible but capital-constrained and sensitive to balance-of-plant costs rather than biomass prices alone.<sup>80</sup>

**Table 8: Decomposed CAPEX and OPEX contributions (%)**

Technology	Location	CAPEX (%)	Feedstock (%)	Energy (%)	Carbon (%)	Labor (%)	Maintenance (%)	Utilities (%)
SAF HEFA	EU	6.2	44.7	12.4	2.7	12.1	12.5	9.4
	US	7.3	43.9	12.2	0	11	14.6	11
	Brazil	8.6	41.1	11.2	0	9	17.2	12.9
RD HEFA	EU	6.2	45.5	11.6	2.7	12.6	12.4	9
	US	7.3	44.6	11.4	0	11.4	14.7	10.6
	Brazil	8.6	41.9	10.5	0	9.4	17.2	12.4
SAF FT	EU	30.7	7.4	6.4	1.6	20	18.5	15.4
	US	34	6.8	4.5	0	17.1	20.5	17.1
	Brazil	36.1	5.8	5.7	0	12.6	21.7	18.1
SAF ATJ	EU	14.2	45.4	7.5	1.6	12.3	11.8	7.1
	US	16.4	43.8	6.9	0	11	13.7	8.3
	Brazil	18.9	40.3	6.8	0	8.8	15.8	9.5
eSAF FT	EU	12.5	0	54.3	21.7	8.1	7.3	6.3
	US	13	0	54.6	22.5	6.5	7.6	6.5
	Brazil	13.2	0	55.9	23	4.6	7.7	6.6

Source: Authors' contribution

For eSAF, the pathway is governed by energy input economics. Producers should secure long-tenor, low-cost renewable PPAs matched to electrolyser duty (to keep utilisation high), optimise electrolyser selection and sizing, and develop bankable CO<sub>2</sub> sourcing (early from point sources; increasingly biogenic or DAC as standards tighten). As hydrogen cost is decisive, market instruments or tax credits that directly reduce delivered \$/kg H<sub>2</sub> can change viability more than broad carbon pricing at current cost levels; several recent policy designs explicitly target delivered H<sub>2</sub> cost for this reason. Similarly, CO<sub>2</sub> transport and storage networks and DAC cost-downs are pivotal to compress the “carbon” bar in Figure 10. These observations are consistent with regionally resolved PtL studies that attribute the majority of cost to electricity for hydrogen and highlight CO<sub>2</sub> supply as the next-largest component.<sup>78,79,77</sup>

The decomposition also implies region-specific strategies for stakeholders:

- European Union. Higher average electricity prices and evolving CO<sub>2</sub> logistics mean eSAF economics hinge on renewable power procurement and CO<sub>2</sub> offtake infrastructure. Investors should favour projects with secured PPAs, grid access that minimises curtailment, and proximity to emerging CO<sub>2</sub> hubs; policy makers can improve capital efficiency with contracts-for-difference (CfDs) for SAF output, targeted production credits for green H<sub>2</sub>, and support for CO<sub>2</sub> transport/DAC pilots, aligning instruments with Figure 10's energy and carbon bars.<sup>81,82,83</sup> For HEFA/ATJ, feedstock sustainability constraints and competition with RD

<sup>81</sup> European Union. (2023). Regulation (EU) 2023/2405 of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). Official Journal of the European Union.

<sup>82</sup> European Commission. (2024a). Industrial carbon management: Enabling CO<sub>2</sub> transport and storage infrastructure. Publications Office of the European Union.

<sup>83</sup> European Commission. (2024b). CO<sub>2</sub> transport infrastructure: Key to achieving climate neutrality by 2050. Joint Research Centre (JRC) Brief.



reinforce the value of waste-lipid mobilisation and certification frameworks; sensitivity analyses in recent NREL work underscore feedstock's primacy.<sup>76</sup> For FT, industrial-site integration and utility-tariff relief offer large effects as CAPEX and utilities dominate the stack.<sup>80</sup>

- **United States.** Lower delivered energy costs (in many grids) and active federal incentives tilt eSAF viability toward projects that capture hydrogen credits and maintain high electrolyser utilisation. The U.S. Section 45V clean hydrogen production credit can materially reduce effective H<sub>2</sub> cost where projects meet eligibility requirements, reinforcing the pathway's chief lever.<sup>84,85</sup> For HEFA/ATJ, investors should focus on feedstock-secure platforms (e.g., integrated rendering/UCO supply, ethanol basins) and on policy stacking (state LCFS, federal credits) that stabilises realised spreads. For FT, low-cost biomass catchments and access to industrial utilities remain decisive for bankability.<sup>80</sup>
- **Brazil.** Lower modelled feedstock and utility costs support near-term HEFA and FT deployment where sustainable feedstock mobilisation and certification remain credible. ATJ can benefit from ethanol integration, but Table 8 suggests it will still be feedstock-driven; thus, logistics and contract design outweigh CAPEX fine-tuning. For eSAF, regions with very low LCOE wind/solar (e.g., Northeast) and emerging CO<sub>2</sub> sources offer the best early-mover prospects, provided that long-tenor PPAs and CO<sub>2</sub> offtake are in place. These choices align with broader analyses that tie PtL cost to electricity and hydrogen, with CO<sub>2</sub> as the next-largest term.<sup>86,87</sup>

In sum, Figure 10 and Table 8 do more than explain why pathways rank as they do; they identify who can move each pathway down the cost curve and how. Feedstock levers (sourcing, quality, logistics, contracting) create the highest return for HEFA/ATJ. Capital, reliability, and utility-cost levers dominate for FT. Energy and CO<sub>2</sub> levers – renewable power price, electrolyser cost and utilisation, and CO<sub>2</sub> supply/logistics—determine outcomes for eSAF. Aligning project design and policy instruments with the largest bars in Figure 10 offers the most efficient route for industry, investors, and governments to close the competitiveness gap documented in the preceding section.<sup>78,76,80</sup>

### 5.3 Blending Effect for the Different Pathways Across the Considered Locations

A 50 % blend means the final fuel at the airport gate is half SAF (or RD) and half the fossil comparator (kerosene for SAF; diesel for RD). This view reflects what airlines and fuel buyers actually pay. Blending reduces dispersion across regions as half of the price is the same fossil benchmark in all locations, and it also dampens techno-economic uncertainty for the SAF portion: by construction, a 50 % blend roughly halves the Monte-Carlo spread from the neat SAF stack. For context, fossil reference prices used in the model are \$0.767/kg (kerosene) and \$0.784/kg (diesel), based on EIA spot series converted to \$/kg.<sup>88,89</sup>

In the EU, blending leads to ≈\$1.19/kg for HEFA and FT, ≈\$1.12/kg for RD-HEFA, \$1.29–\$1.44/kg for ATJ, and ≈\$3.0/kg for eSAF. Translating these into a “real” price gap—the premium above the fossil comparator at the same blend ratio—yields \$0.31/kg (≈40 %) for HEFA, \$0.36/kg (≈47 %) for FT, \$0.23/kg (≈29 %) for RD-HEFA, and \$0.54/kg (≈70 %) for ATJ; eSAF still shows \$2.18/kg (≈284 %). The percentage figures express the size of the premium relative to the relevant fossil benchmark (kerosene or diesel), which helps stakeholders judge materiality in budget or tariff terms.<sup>88,89</sup>

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<sup>84</sup> Internal Revenue Service. (2025). Clean hydrogen production credit (Section 45V): Guidance and FAQs. U.S. Department of the Treasury.

<sup>85</sup> U.S. Department of the Treasury. (2025). Final regulations for the Section 45V clean hydrogen production tax credit. Federal Register.

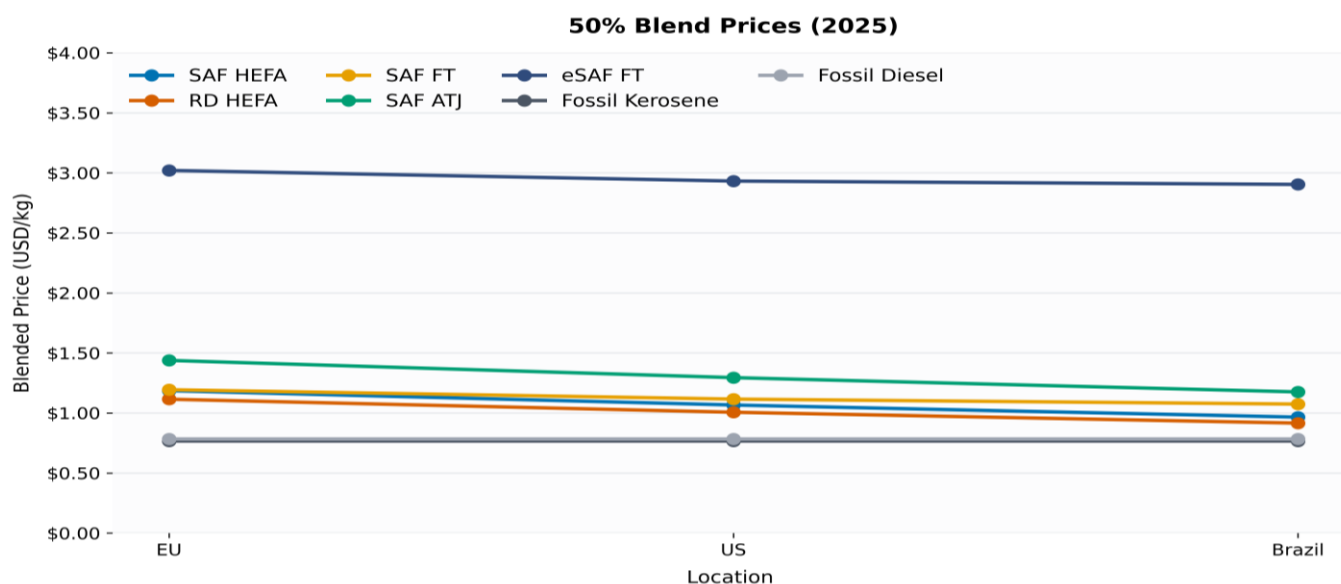
<sup>86</sup> Agora Industry. (2025). Hydrogen insights—Brazil: Cost, infrastructure, and deployment pathways. Agora Think Tank.

<sup>87</sup> International Renewable Energy Agency. (2024). Renewable power generation costs in 2023. IRENA.

<sup>88</sup> EIA/FRED. (n.d.-a). U.S. Gulf Coast Kerosene Type Jet Fuel Spot Price (USD/gal) (Series: WJFUELUSGULF). Federal Reserve Bank of St. Louis. <https://fred.stlouisfed.org/series/WJFUELUSGULF>

<sup>89</sup> EIA/FRED. (n.d.-b). Ultra Low Sulfur Diesel (NY Harbor) Spot Price (USD/gal) (Series: DDFUELNYH). Federal Reserve Bank of St. Louis. <https://fred.stlouisfed.org/series/DDFUELNYH>

**Figure 11: 50% blended prices for the different pathways across the considered locations**



Source: Authors' contribution. Note: Fossil Kerosene and Diesel designated here are not blended and are shown for average baseline representation

**Table 9: Fuels prices (USD/kg) at 50% blend ratio**

Technology	Location	Mean (USD/kg)	Std (USD/kg)
SAF HEFA	EU	1.19	0.05
	US	1.07	0.05
	Brazil	0.97	0.04
RD HEFA	EU	1.12	0.05
	US	1.01	0.04
	Brazil	0.92	0.03
SAF FT	EU	1.19	0.05
	US	1.12	0.05
	Brazil	1.07	0.05
SAF ATJ	EU	1.44	0.08
	US	1.29	0.07
	Brazil	1.18	0.06
eSAF FT	EU	3.02	0.8
	US	2.93	0.79
	Brazil	2.9	0.79

Source: Authors' contribution

As 50 % blends replace half of the fossil volume, it also delivers meaningful emissions cuts at the point of use. Using standard combustion factors— $\approx 3.15 \text{ kg CO}_2/\text{kg}$  for kerosene and  $\approx 3.21 \text{ kg CO}_2/\text{kg}$  for diesel—the 50 % blends reduce priced  $\text{CO}_2$  by  $\approx 42\%$  (HEFA),  $45\%$  (FT),  $44\%$  (ATJ),  $43\%$  (RD-HEFA)

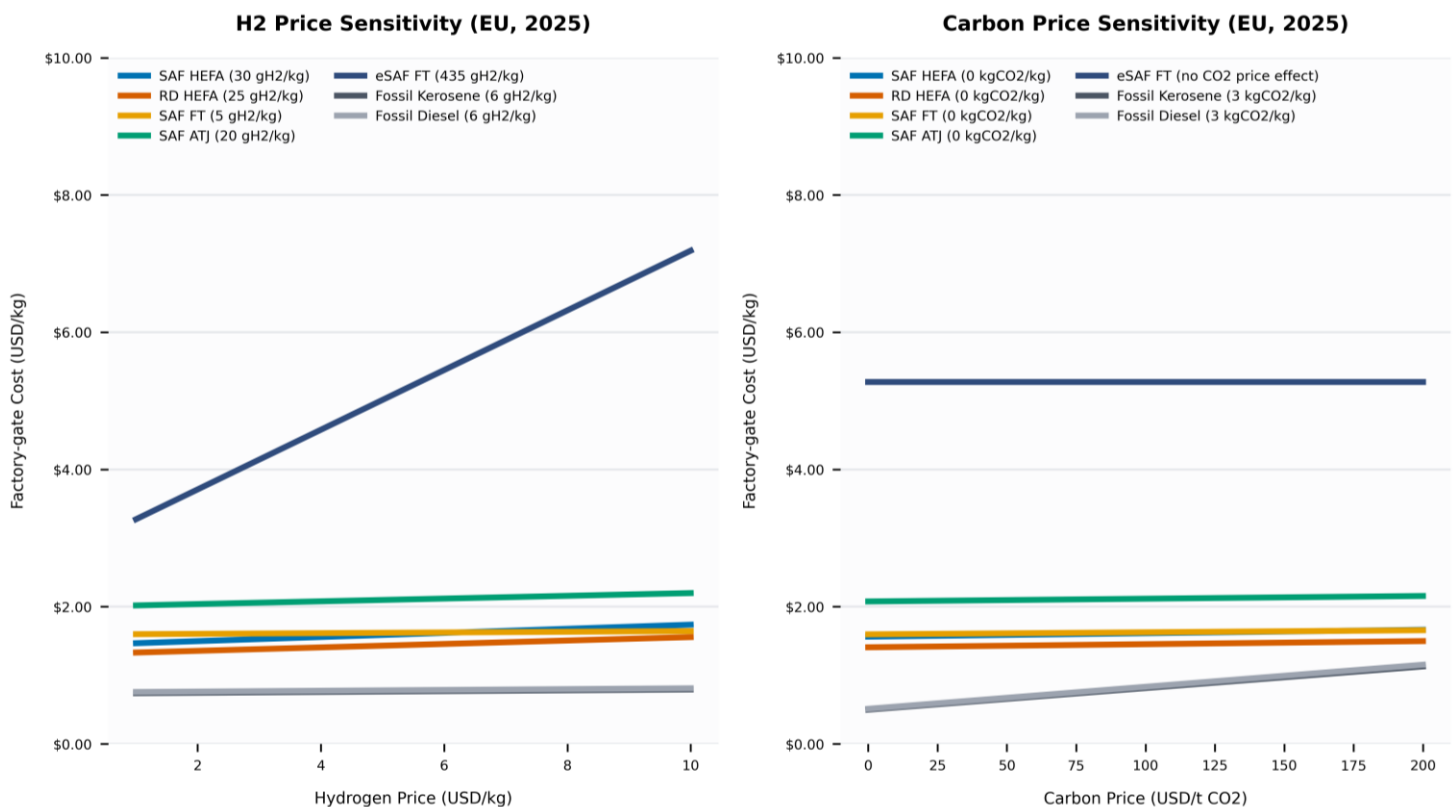


vs diesel), and 50 % (eSAF) relative to neat fossil fuel.<sup>90,91</sup> In practical terms, this combination—large emissions reductions with modest absolute \$/kg premia for HEFA/FT/RD-HEFA—explains why blending is an effective near-term offtake instrument while deeper cost reductions for ATJ and eSAF are pursued.

From a risk and contracting perspective, the 50 % blend also narrows cross-region dispersion and reduces exposure to SAF-specific uncertainties (feedstock for HEFA/ATJ; plant/utilities for FT; H<sub>2</sub>/CO<sub>2</sub> for eSAF) as only half of the price rides on the bio route. Airlines can incorporate these premia into long-term offtake contracts, hedging programs, and index-linked formulas alongside existing jet-fuel risk management. For RD buyers, blends help, but the ability to pass through the residual premium depends on surcharge formulas and policy credits; where tenders are strictly lowest-price, stable policy value (e.g., credit floors or CfDs) remains important to sustain demand (directionally consistent with the decomposition and sensitivity results discussed for Figure 10 and Figure 12).

## 5.4 Sensitivity Analysis and Implications

Figure 12: Hydrogen and carbon price sensitivity (EU case)



Source: Authors' calculation

<sup>90</sup> EUROCONTROL/ICAO. (2024). Standard inputs for cost benefit analyses: Amount of emissions released by fuel burn (Jet fuel EF ≈ 3.15 kg CO<sub>2</sub>/kg). [https://ansperformance.eu/economics/cba/standard-inputs/latest/chapters/amount\\_of\\_emissions\\_released\\_by\\_fuel\\_burn.html](https://ansperformance.eu/economics/cba/standard-inputs/latest/chapters/amount_of_emissions_released_by_fuel_burn.html)

<sup>91</sup> U.S. Environmental Protection Agency. (2023). Greenhouse gas equivalencies calculator: Calculations and references (Diesel CO<sub>2</sub> ≈ 10.21 kg/gal → ≈ 3.21 kg CO<sub>2</sub>/kg). <https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references>



Sensitivities clarify which exogenous levers matter most. Hydrogen slopes equal each pathway’s external H<sub>2</sub> intensity.

- eSAF’s intensity (~0.435 kg H<sub>2</sub>/kg fuel) implies that moving H<sub>2</sub> from \$2→\$10/kg shifts eSAF by ≈\$3.5/kg—a ≈66 % swing relative to its EU factory-gate mean and ≈460 % of the kerosene benchmark.
- HEFA (≈0.03), ATJ (≈0.02), and FT (≈0.005) move by tens of cents across the same span (≈4–9 % of the kerosene price).
- On the carbon axis, fossil kerosene/diesel increase by ≈\$0.32/kg per +\$100/t CO<sub>2</sub> (3.15/3.21 kg CO<sub>2</sub>/kg), while bio-routes move only a few cents per kg, consistent with their residual intensities. As these slopes indicate, carbon pricing narrows—but does not close—the gap for the lowest-cost bio blends at current inputs; H<sub>2</sub>/CO<sub>2</sub> input costs remain the make-or-break for eSAF.

A brief realism check follows. Using the following parity formula:

$$P_{CO_2} = (1000 \times (\Delta\$/kg)_{\text{pathway,location}}/EF), \text{ (in \$/t CO}_2\text{)}$$

Where EF denotes the fossil comparator’s tank-to-wake emission factor (kg CO<sub>2</sub> per kg of fuel), which converts the designated Δ\$/kg price gap into an equivalent carbon price.

The formula reveals that we get that neat eSAF parity in the EU implies >\$1,400/t CO<sub>2</sub>, which is not a credible policy pathway. Even at a 50 % blend, eSAF equalisation implies ≈\$670–\$710/t CO<sub>2</sub> in the EU and ≈\$680/t CO<sub>2</sub> in the US—well above typical policy ranges. By contrast, HEFA/FT blended gaps map to ≈\$60–\$130/t CO<sub>2</sub> in the US/Brazil and ≈\$100–\$130/t CO<sub>2</sub> in the EU—magnitudes that established instruments can plausibly deliver (e.g., mandates with tradable credits, contracts-for-difference).

An illustrative eSAF scenario underscores the point: starting from the EU factory-gate mean \$5.27/kg, lowering H<sub>2</sub> from \$5.6→\$1.0/kg reduces cost by (4.6 × 0.435) ≈ \$2.00/kg; replacing baseline DAC cost (≈21.7 % × \$5.27 ≈ \$1.14/kg) with \$50/t CO<sub>2</sub> (0.05 × 3.11 ≈ \$0.16/kg) saves another ≈\$0.99/kg. The implied factory-gate becomes ≈\$2.28/kg; a 50 % blend with fossil jet (\$0.767/kg) yields ≈\$1.52/kg and a residual gap of ≈\$0.76/kg (≈99 %), which still requires ≈\$240/t CO<sub>2</sub> to close. As this scenario already assumes very low H<sub>2</sub> and CO<sub>2</sub> costs, parity via carbon pricing alone remains unlikely; durable progress depends on structural reductions in clean H<sub>2</sub> and CO<sub>2</sub> costs plus risk-sharing instruments that bridge the remaining premium.

**Table 10: Requirements for Premiums and carbon prices of the considered pathways in a 50% blend type setting across the different regions to reach parity with the fossil comparator**

Incentive/Tax		Premium required to match SAF and RD with fossil comparator					Carbon price needed to match fossil comparator with SAF and RD				
		HEFA	RD-HEFA	FT	ATJ	eSAF	HEFA	RD-HEFA	FT	ATJ	eSAF
<b>Unit</b>		≈(Δ\$/kg <sub>fuel</sub> )					≈(\$/tCO <sub>2</sub> )				
<b>Location</b>	EU	0.41	0.34	0.41	0.67	2.25	130	106	130	210	711
	US	0.30	0.23	0.35	0.52	2.16	92	72	108	162	683
	Brazil	0.20	0.14	0.30	0.41	2.13	60	44	92	127	673

Source: Authors’ contribution

Note: Assuming fossil \$0.767/kg kerosene and \$0.784/kg diesel

Taken together, these findings support phased deployment with pathway-specific levers. In the short run, scale HEFA and FT where feedstocks and utilities are favourable, using blending mandates/credits or CfDs to bridge ≈\$60–\$135/t CO<sub>2</sub> gaps (typically ≈26–47 % blended premia in the US/Brazil and ≈55 % in the EU). Deploy ATJ where site integration or ethanol logistics confer advantage (typical blended requirements ≈\$125–\$210/t CO<sub>2</sub>, ≈54–88 % premium in the EU case). Advance eSAF through input-side interventions that move its dominant cost bars—renewable power price, electrolyser cost and utilisation, and CO<sub>2</sub> capture/transport—as parity via carbon pricing alone would imply politically and economically implausible levels.

## 6. Regulatory Framework and Policy Incentives for Alternative Liquid Fuels

Alternative liquid fuels are expected to play a central role in global decarbonization; however, their widespread adoption remains constrained by significant market barriers—most notably cost competitiveness, operational flexibility, and reliability. As highlighted by Panoutsou et al.<sup>8,92</sup>, the development of alternative liquid fuels is challenged across three principal dimensions: biomass supply, conversion pathways, and end use.

The techno-economic patterns documented in Section 5 imply that policy should be differentiated by pathway and region. In summary (Section 5.2):

- HEFA/ATJ are feedstock-exposed
- FT is capital/maintenance/utilities-intensive, and
- eSAF is governed by H<sub>2</sub> electricity and CO<sub>2</sub> supply. Instruments that do not target the largest bar in each stack (Figure 10) will deliver lower value than tailored measures.

### **Biomass**

In terms of biomass supply, issues such as soil quality degradation, land-use competition, and the mobilization of organic waste remain significant barriers. To address these challenges, policy interventions should focus on financial support for flagship and demonstration projects that enhance domestic biomass production while promoting sustainable agricultural practices and carbon farming. Additionally, the development of regional biomass supply hubs, clearer land classification frameworks, and incentives for utilizing organic waste streams can contribute to more efficient resource use and reduce land competition. Targeted financial mechanisms can also support land restoration efforts and encourage low-yield feedstock cultivation through sustainable methods like phytoremediation.<sup>8</sup>

For HEFA and ATJ, in which feedstock accounts for ~40–45% of cost (Table 8), the highest-leverage measures are:

- Waste-lipid and residue mobilization (collection logistics, certification throughput),
- Indexed offtake formulas that reference published feedstock indices to stabilize realized spreads, and
- Credit floors or CfDs sized to the blended gaps quantified in Table 9 and Table 10.

### **Conversion pathways**

In the conversion phase, high production costs, limited access to capital, and process inefficiencies hinder the competitiveness of alternative liquid fuels compared to fossil fuels. Supporting the scaling-up of innovative technologies, such as First-of-A-Kind plants, is essential to overcoming these barriers. Additionally, promoting financial integration through green funds and fostering public-private partnerships can help mitigate investment risks and enhance process efficiency. Encouraging collaboration between technology providers and major industry players can also facilitate the optimization of conversion pathways, making production more cost-effective and technologically viable.<sup>8</sup> Financial support for co-locating biorefineries with existing infrastructure can further reduce production costs, while targeted investments in biofuel distribution and storage facilities can strengthen supply chains and promote long-term industry sustainability.<sup>8</sup>

For FT, Section 5 shows ~30–36% CAPEX with material maintenance and utilities burdens; policy should therefore emphasize loan guarantees, concessional debt, accelerated depreciation, and utility tariff relief at industrial sites (mapping directly to Table 8's largest components). For eSAF, where energy (Hydrogen + power) ≈54–56% and CO<sub>2</sub> ≈22–23%, Hydrogen-cost and CO<sub>2</sub>-supply instruments

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<sup>92</sup> Ebadian, M., van Dyk, S., McMillan, J. D., & Saddler, J. (2020). *Biofuels policies that have encouraged their production and use: An international perspective*. Energy Policy, 147.



(renewable PPAs matched to electrolyser duty, production credits linked to delivered \$/kg-H<sub>2</sub>, and CO<sub>2</sub> transport/DAC support) will move the needle more than broad carbon pricing—consistent with Section 5.4’s sensitivity slopes.

**End Use**

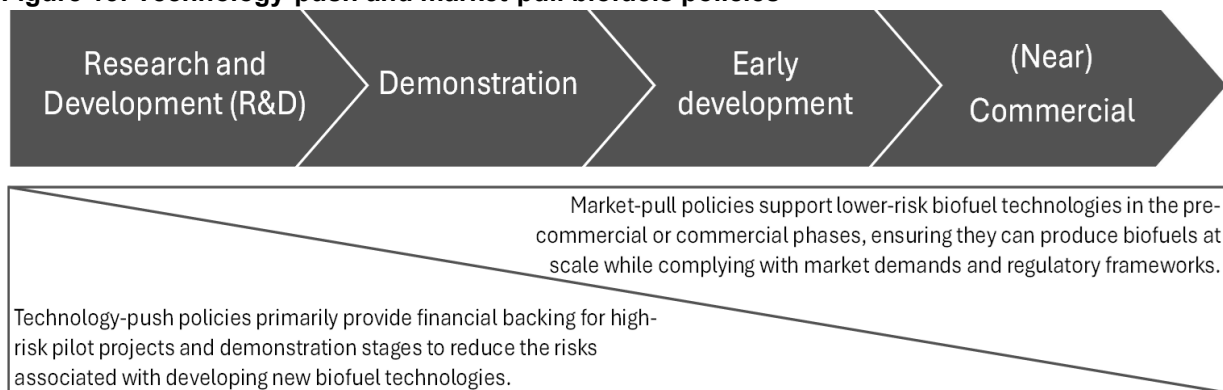
At the end-use stage, the primary impediments include the substantial price disparity with fossil fuels, limited downstream infrastructure, and the heterogeneity of local emissions regulations. Implementing carbon pricing mechanisms on fossil fuels can partially offset these disparities and improve alternative fuels competitiveness. Nevertheless, as demonstrated in Section 5 and Table 10, cost parity thresholds differ significantly by pathway. This suggests that differentiated carbon price points will be required to stimulate deployment across technologies, enabling a more efficient sequencing of policy.

**6.1 Government Policy Landscape**

Governments worldwide are increasingly adopting greenhouse gas (GHG) reduction targets, blending mandates, carbon pricing mechanisms, and financial incentives to stimulate the deployment of bio- and synthetic fuels. More than eighty jurisdictions now maintain biofuel-supportive frameworks, with the majority of demand concentrated in the European Union, United States, Brazil, and Indonesia.<sup>92</sup>

Biofuel policies aim to boost production and usage through measures like blending mandates, tax incentives, and low carbon fuel standards. These policies, presented in Figure 13, can be grouped into technology-push strategies that encourage innovation and market-pull strategies that drive adoption.<sup>92</sup> R&D investments are equally vital to advancing the biofuels sector, particularly for second-generation biofuels derived from non-food materials like agricultural residues, forestry waste, or waste lipids. Countries such as Germany and India have focused on R&D for biofuels that minimize competition with food crops, aligning with broader sustainability goals. These countries are exploring second-generation biofuels that use innovative feedstocks, helping to reduce the environmental impact of biofuel production and aligning with the EU’s objectives under RED II, which prioritizes the use of sustainable feedstocks and advanced technologies.<sup>64</sup>

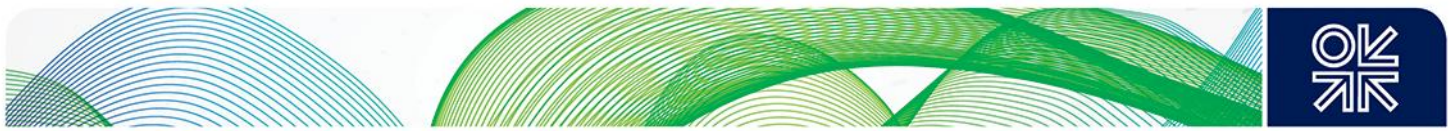
**Figure 13: Technology-push and market-pull biofuels policies**



Source: Adapted from<sup>92</sup>

One of the most significant policies fostering biofuel production has been the widespread use of biofuel blending mandates. Countries such as the U.S., the European Union, and Brazil have established blending mandates that require a minimum percentage of renewable fuels to be mixed with conventional fossil fuels in the transportation sector.<sup>64,92</sup> Indeed, given the narrower dispersion and reduced uncertainty of blends, mandates should be paired with tradable credits that have guardrails (price floors/ceilings, multi-year banking) to avoid the credit-volatility that otherwise deters long-term contracting—especially where RD pass-through is constrained.

Another effective policy mechanism in this area has been the Low Carbon Fuel Standard (LCFS), currently adopted in regions like California and British Columbia. LCFS policies focus on reducing the



carbon intensity of transportation fuels, offering incentives to produce biofuels with lower lifecycle GHG emissions. Under this framework, producers of low-carbon biofuels such as cellulosic ethanol and RD are rewarded with carbon credits, which can be sold or traded in carbon markets, thereby increasing the financial return on producing cleaner fuels.<sup>92</sup> This approach encourages continuous innovation and efficiency improvements in biofuel production, as producers seek to further reduce the carbon intensity of their fuels to maximize their economic benefits.<sup>92</sup>

### **United States**

In the United States, the Renewable Fuel Standards (RFS), along with state-level policies such as California's LCFS, set blending quotas for both conventional biofuels (such as ethanol) and alternative liquid fuels (such as RD and SAF), as well as tax credits, creating steady market demand. This policy prioritizes the profitability of the renewable fuels as well as the supply chain in an established bio-based fuel market.<sup>93,94</sup> Operationalising stacking of these credits could indeed make the pathways for the US seen in Table 10 reach the parity with their fossil comparator.

### **European Frameworks**

In Europe, the European Green Deal has laid the groundwork for achieving climate neutrality by 2050, emphasizing efficient resource use, biodiversity restoration, and pollution reduction. However, decarbonizing high-emission sectors, particularly transport, has been slow, with GHG emissions in European transport decreasing by only 3.8% since 2008, compared to an 18% reduction in other major sectors. Biofuel policy frameworks, initiated in 2003, incorporated advanced biofuel targets starting in 2009 to address these emissions gaps.<sup>8</sup> To further advance the role of biofuels, the European Commission adopted new rules in June 2023, regulating biofuels and biogas in co-processed fuels that blend bio-based and fossil-based raw materials. These rules, established through Delegated Regulation (EU/2023/1640), published in August 2023, define how such fuels contribute to the Renewable Energy Directive (RED) targets for renewable energy in transport.<sup>95,96</sup>

The Renewable Energy Directive requires EU member states to ensure that renewable energy constitutes at least 14% of total energy consumption in the transport sector by 2030, with a minimum of 3.5% coming from alternative liquid fuels.<sup>95,96</sup> Additionally, the Renewable Energy Directive II (RED II) mandates incremental sub-targets for alternative liquid fuels, beginning with 0.2% in 2022, rising to 1% in 2025, and ultimately 3.5% by 2030.<sup>95,96</sup> Fuel suppliers utilizing renewable electricity or renewable non-biological fuels may be exempt from these advanced biofuel requirements.

The revision of the Renewable Energy Directive, commonly referred to as RED III, represents a significant milestone in the European Union's energy transition strategy. Adopted by the European Parliament in September 2023, the directive aims to accelerate the deployment of renewable energy sources in line with the European Green Deal and the REPowerEU plan. RED III introduces streamlined permitting procedures for new renewable energy projects and retrofits, mandates an indicative target of at least 5% for innovative renewable technologies within new installations, and reinforces cross-border energy collaboration through a binding framework.<sup>97</sup> Additionally, it imposes stricter sustainability criteria for biomass utilization to prevent adverse impacts on soil quality and biodiversity, thereby ensuring that public subsidies do not support environmentally harmful practices. By establishing these measures, RED III seeks to enhance the EU's renewable energy share while maintaining environmental integrity.<sup>97</sup>

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<sup>93</sup> IEA. (2022). *Renewable Energy Market Update*. <https://www.iea.org/t&c/>

<sup>94</sup> OECD-FAO. (2020). *Agricultural Outlook 2020–2029*. <https://doi.org/10.1787/1112c23b-en>

<sup>95</sup> European Commission. (2024). *Renewable Energy – Recast to 2030 (RED II)*. [https://joint-research-centre.ec.europa.eu/.../renewable-energy-recast-2030-red-ii\\_en](https://joint-research-centre.ec.europa.eu/.../renewable-energy-recast-2030-red-ii_en)

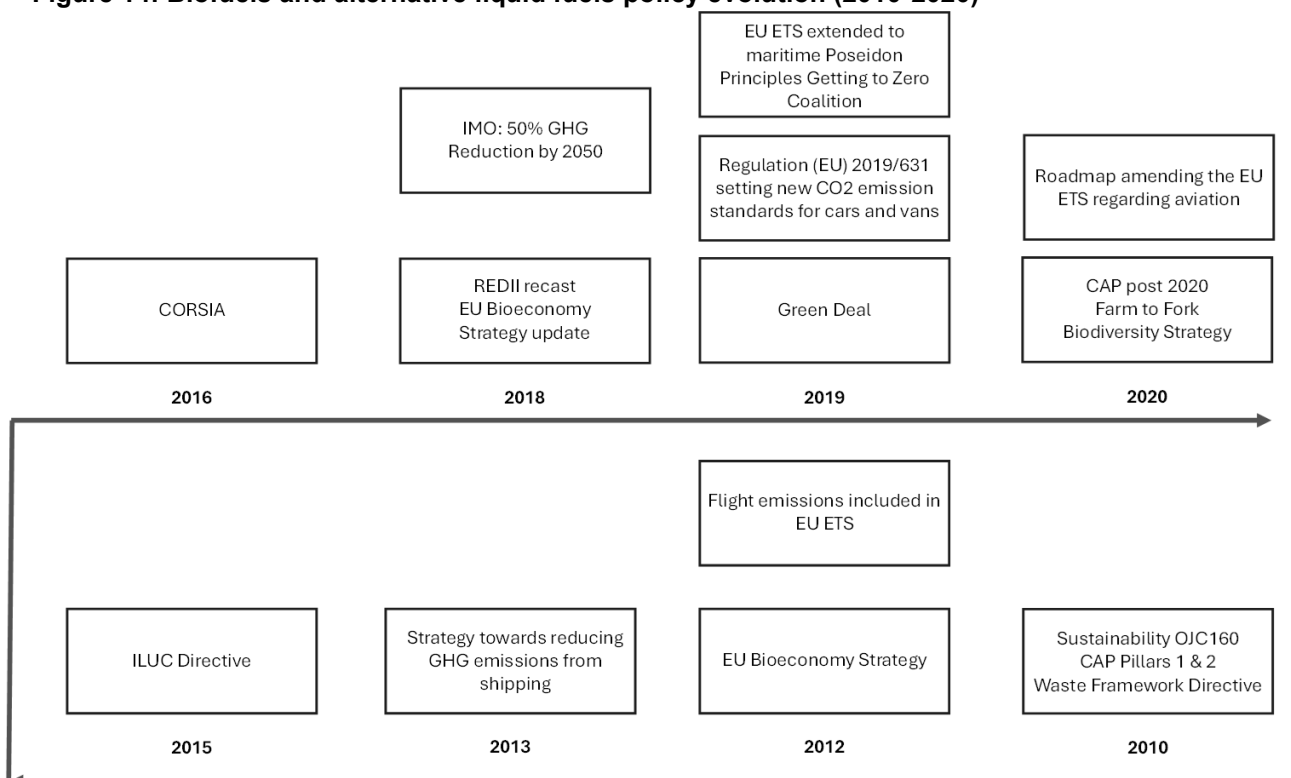
<sup>96</sup> European Commission. (2024). *Biofuels: ... advanced biofuels made from sustainable feedstock*. [https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biofuels\\_en](https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biofuels_en)

<sup>97</sup> EY. (2023). *Analysis of RED III Directive*. [https://www.ey.com/es\\_es/technical/alertas-fiscal-legal/analysis-of-red-iii-directive](https://www.ey.com/es_es/technical/alertas-fiscal-legal/analysis-of-red-iii-directive)



To close the EU blended gaps identified in Table 10, Member States can deploy SAF/RD CfDs indexed to kerosene/diesel benchmarks and—crucially for eSAF—pair ReFuelEU with hydrogen production incentives, long-tenor renewable PPAs for electrolysis, and CO<sub>2</sub> hub funding. This would focus scarce public funds on the make-or-break cost drivers highlighted in results of the previous section. Achieving the 2020–2030 targets also requires immediate, coordinated policy measures to enhance low-carbon fuel availability. Key efforts focus on minimizing Indirect Land Use Change (ILUC) impacts by prioritizing biofuel production on degraded or abandoned lands, as outlined in Delegated Regulation (EU) 2019/807.<sup>98</sup> Figure 14 shows the evolution of biofuels and alternative liquid fuels policies from 2010 to 2020.

**Figure 14: Biofuels and alternative liquid fuels policy evolution (2010-2020)**



Source: Adapted from<sup>8</sup>

### ReFuelEU Aviation

ReFuelEU Aviation, a key legislative component of the EU’s “Fit for 55” package, is designed to significantly increase the uptake of SAF across the European aviation sector. The regulation establishes mandatory SAF blending requirements for fuel suppliers at EU airports, with the goal of gradually reducing aviation-related CO<sub>2</sub> emissions and contributing to the EU’s overarching climate neutrality targets. According to the European Commission, the policy is expected to reduce aviation emissions by over 60% by 2050 compared to 1990 levels.<sup>98</sup> ReFuelEU also introduces harmonized EU-wide rules to eliminate national disparities, creating a level playing field for airlines and fuel providers while reducing compliance costs. Beyond emissions reductions, the policy is expected to boost innovation, support the development of SAF value chains, and stimulate economic growth by creating jobs through new SAF production facilities distributed across Member States. In doing so, ReFuelEU Aviation not only strengthens environmental goals but also promotes regional cohesion and sustainable industrial development within the EU.<sup>98</sup>

<sup>98</sup> European Commission. (2025). *ReFuelEU Aviation*. [https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation\\_en](https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en)



To match the blended premium levels quantified in Section 5.3, ReFuelEU implementation should include:

- airport-level SAF credit trading with price floors/ceilings,
- book-and-claim to connect scarce supply to distributed demand without distorting logistics, and
- blend-ratio glidepaths aligned with 2–3 $\sigma$  affordability for airlines (Section 5.1), keeping annual step-ups within manageable budget envelopes.

### **Brazil**

With Brazil's Low Carbon Framework advancing alongside the RenovaBio policy, a significant rise in RD production is anticipated, supported by long-term investment opportunities and abundant feedstock supply. Moreover, Brazil's commitment to COP21 targets reinforces RenovaBio's role in regulating carbon intensity (CI) through the trading of decarbonization credits (CBIOs), each representing one metric tonne of CO<sub>2</sub> emissions. While RenovaBio presents an innovative incentive mechanism for promoting biofuels, its current structure may not be sufficient to stimulate large-scale investments in more advanced or emerging technologies. Without complementary policies or stronger innovation-oriented financial instruments, the potential for fostering disruptive technological advancements in the Brazilian biofuel sector may remain limited.<sup>92,99</sup>

For Brazil, the results from Section 5, indicate that Brazil's lower modelled feedstock and utility costs lead to smaller parity ranges with the fossil comparators. Thus, a CBIO price floor or Brazil-specific CfDs at these levels could scale HEFA/FT quickly, while ATJ benefits where ethanol integration confers site advantage.

### **CORSIA**

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), established by the International Civil Aviation Organization (ICAO), represents the first global market-based mechanism targeting a specific sector. It plays a key role in supporting the decarbonization of international aviation by complementing in-sector mitigation measures, such as advancements in aircraft technology, operational efficiency improvements, and the adoption of SAF.<sup>72</sup> Under CORSIA, airlines are required to monitor, report, and offset emissions that exceed 2019 levels, thus promoting carbon-neutral growth from 2020 onward. Importantly, SAF plays a central role in achieving CORSIA compliance, as its lower life-cycle carbon intensity compared to fossil jet fuel allows airlines to reduce their offsetting obligations when SAF is used. Therefore, the scheme not only reinforces the need for scalable SAF production but also provides a regulatory incentive for its adoption within the aviation industry.<sup>72</sup>

Overall, the global push for alternative liquid fuels such as RD and SAF is being driven by a combination of economic incentives, market mechanisms, and sustainability certification schemes. As countries aim to decarbonize their transportation sectors, policies that promote innovation, investment, and sustainability in biofuel production will be critical. With continued support, alternative liquid fuels have the potential to play a key role in the global effort to achieve net-zero emissions and combat climate change.

## **6.2 Enablers for Policy Implementation**

### **6.2.1 Flexibility**

Flexibility is essential for biorefineries to handle diverse feedstocks and adjust processes based on market demand, while reliability depends on consistent feedstock supply and stable production processes. However, the primary obstacle is cost competitiveness, as alternative liquid fuels struggle to compete with cheaper fossil fuels and renewable electricity-based alternatives. Overcoming these barriers will require targeted policy interventions to support their adoption<sup>95,96</sup>.

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<sup>99</sup> Grangeia, C., Santos, L., & Lazaro, L. L. B. (2022). *The Brazilian biofuel policy (RenovaBio) and its uncertainties*. *Energy Conversion and Management*, X, 13. <https://doi.org/10.1016/j.ecmx.2021.100156>

### 6.2.2 Sustainability Certification

Sustainability certification schemes are another essential component of the advanced biofuel ecosystem, particularly in the EU. These schemes ensure that biofuel production adheres to strict environmental and social criteria, reducing the risk of deforestation, food insecurity, or other negative impacts associated with biofuel feedstock cultivation. Certification systems, such as those outlined under RED III or CORSIA, require biofuel producers to demonstrate that their products deliver significant GHG emissions reductions compared to fossil fuels, ensuring that biofuels contribute meaningfully to climate goals.<sup>100</sup>

### 6.2.3 Infrastructure Development

RD and SAF production face cost and adaptability challenges, which are mitigated by market-pull policies such as blending mandates and LCFS. These policies drive biofuel demand, promote decarbonization, and offer tax incentives to boost competitiveness with fossil fuels. LCFS programs also encourage innovation by promoting high-decarbonization technologies. Other incentives, such as excise tax reductions, further support both conventional and alternative liquid fuels, reducing production costs and improving feedstock availability. However, challenges such as high costs, limited biomass, and infrastructure readiness vary by region, influencing optimal biofuel pathways<sup>101</sup>.

Moreover, within the European Union market, the infrastructure supporting alternative liquid fuels is rated as "excellent" for only a few types, while for many others, it is classified as "medium" or even "poor." Similarly, the compatibility of certain biofuels with the existing vehicle fleet remains limited<sup>101</sup>.

According to Panoutsou et al.,<sup>8</sup> the availability of infrastructure varies significantly among different alternative liquid fuels. Fuels such as hydrogen, dimethyl ether (DME), methanol, butanol, ED95 (ethanol-based fuel for diesel engines), and MD95 (methanol-based diesel) have limited infrastructure support, making widespread adoption challenging. Medium infrastructure availability is observed for electric vehicles (EVs), liquefied natural gas (LNG) and liquefied biogas (LBG), ethanol blend E85 (85% ethanol, 15% gasoline), and compressed natural gas (CNG) or compressed biogas (CBG).<sup>8</sup> In contrast, HVO, fatty acid methyl esters (FAME) up to a 7% blend (B7) (in EU), renewable gasoline, and synthetic paraffinic kerosenes derived from (FT-SPK), HEFA (HEFA-SPK), and (ATJ-SPK) processes benefit from excellent infrastructure availability, facilitating their integration into existing fuel distribution and consumption networks.<sup>8</sup>

### 6.2.4 Fuel Compatibility

In terms of fuel compatibility with current fleets of vehicles, ships, and aircraft, significant variations exist. Certain fuels, including hydrogen, DME, methanol, EVs, ED95, and LNG/LBG, require dedicated engines, limiting their immediate adoption in conventional transportation systems.<sup>8</sup> Some fuels, such as ethanol blend E20 and FAME B10, require minor retrofitting to existing engines to ensure proper performance. Meanwhile, drop-in fuels—including HVO, FAME B7, renewable gasoline, FT-SPK, HEFA-SPK, and ATJ-SPK—are fully compatible with existing internal combustion engines, marine vessels, and aircraft, allowing for seamless integration without modifications to current fleets.<sup>8</sup>

### 6.2.5 Optimization

The production costs for SAF remain higher than those of fossil fuels. Alternative liquid fuels produced from waste generally have lower costs than those made from biomass due to cheaper feedstock and higher conversion efficiencies. Estimates ranging from EUR 0.37 to 1.08 per litre for technologies such as FT liquids, hydrotreated vegetable oils (HVO), bio-oil and coprocessing<sup>101</sup>. Reducing costs in the medium to long term is feasible as advanced biofuel technologies mature. Key areas for cost reduction

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<sup>100</sup> Usmani, R. A., Mohammad, A. S., & Ansari, S. S. (2023). *Comprehensive biofuel policy analysis framework*. *Renewable and Sustainable Energy Reviews*, 183. <https://doi.org/10.1016/j.rser.2023.113403>

include process optimization, better integration with other technologies, and increased by-product value. Scaling up production through larger facilities and gaining operational experience will further help reduce costs. Additionally, as technical risks decline and investor confidence grows, lower capital costs will contribute to making alternative liquid fuels more economically viable<sup>101</sup>. As shown in Table 11, advancements in processes and reductions in capital costs have been observed in specific cases.

**Table 11: Projected cost reductions for alternative liquid fuels (10–15 years)**

Production route	Process Improvement (%)	Process + Capital (%)	EU Cost (EUR/MWh)	EU Cost (EUR/litre)
FT liquids (biomass)	13.2–14.7	22.2–25.3	75–114	0.71–1.08
FT liquids (waste)	9.6–24.5	24–39.6	53–104	0.50–0.98
Bio-oil and coprocessing	5	14.4–16.5	79–139	0.37–0.66
HVO	—	2–3.3	51–91	0.48–0.86

Source: Adapted from<sup>101</sup>

In short, to increase the market share of alternative liquid fuels, future policies must address the entire value chain, ensuring compatibility with current engines, fuel infrastructure, and distribution networks. Aligning biofuel policies with global sustainability frameworks such as the UN’s SDGs can also support broader adoption by bridging technological and market gaps, promoting competitiveness, and scaling up the use of sustainable biofuels as viable alternatives to fossil fuels.

## 7. Conclusion

This study compares leading RD and SAF pathways—HEFA, FT, ATJ, and eSAF/PtL—across three regions and links their techno-economics to policy design. Three findings are robust.

- Cost: Factory-gate costs exhibit a stable hierarchy: HEFA and FT at \$1.3–\$1.7/kg, ATJ at \$1.6–\$2.1/kg, and eSAF materially higher at ≈\$5.0–\$5.3/kg. Fifty-percent blends compress dispersion and reflect prices faced by buyers: in the EU, HEFA/FT sit around \$1.19/kg, RD-HEFA near \$1.12/kg, ATJ \$1.29–\$1.44/kg, and eSAF ≈\$3.0/kg.
- Drivers: Decomposition clarifies why pathways respond differently to shocks: HEFA/ATJ are feedstock-dominated; FT is capital- and utilities-intensive; and eSAF is governed by delivered clean hydrogen and CO<sub>2</sub> supply. Sensitivity analysis confirms that hydrogen prices move eSAF by dollars per kilogram, but move HEFA/FT/ATJ only by tens of cents; carbon pricing narrows, but does not close, the premium for the lowest-cost blends.
- Implications: Expressing residual premia as carbon-price equivalents yields ≈\$60–\$130/tCO<sub>2</sub> for HEFA/FT blends, ≈\$125–\$210/tCO<sub>2</sub> for ATJ, and ≈\$670–\$710/tCO<sub>2</sub> for eSAF. Accordingly, the most efficient instruments are pathway-specific:
  - (i) waste-lipid and residue mobilization, indexed offtake, and certification throughput for HEFA/ATJ;
  - (ii) loan guarantees, utility-tariff relief, and reliability/uptime programs for FT; and
  - (iii) measures that cut delivered \$/kg-H<sub>2</sub> and secure bankable CO<sub>2</sub> offtake for eSAF (renewable PPAs matched to electrolyser duty, production tax credits, and CO<sub>2</sub> hub infrastructure).

<sup>101</sup> Spandagos, C. (2023). *Achieving decarbonization goals through biofuels: Policy challenges and opportunities in the EU and the US*. In *Advances in Biofuels Production, Optimization and Applications* (pp. 269–283). Elsevier. <https://doi.org/10.1016/B978-0-323-95076-3.00003-X>



A practical sequencing follows. In the near term, scale HEFA and FT using existing hydrotreating assets and co-processing where appropriate; anchor demand with blending mandates and tradable credits that include guardrails (floors/ceilings, banking). In the medium term, deepen cellulosic/waste FT and expand ATJ where alcohol supply chains are advantaged. In the longer term, deploy eSAF as clean-hydrogen and CO<sub>2</sub> costs structurally decline and as synthetic-aromatics work enables higher SAF blend ratios. For industry and investors, risk management should align with the dominant cost bar—feedstock basis risk for HEFA/ATJ, plant and utilities performance for FT, and input-commodity risk (H<sub>2</sub>, CO<sub>2</sub>, power) for eSAF. For policymakers, undifferentiated support is inefficient; aligning instruments to pathway-specific constraints is the most cost-effective route to scale.

While the model harmonizes assumptions across regions and reports uncertainty bands, future work should extend to additional regions and feedstock baskets, incorporate dynamic learning for first-of-a-kind plants, and test specification scenarios (e.g., synthetic aromatics) that affect feasible SAF blend ratios.

## Appendix A: SAF and RD Techno-Economic Model Code

This appendix presents the reproducible Python code used to quantify factory-gate costs and 50/50 blended prices for the considered fuels and technologies pathways as well as existing fossil fuel comparators under uncertainty analysis format, report cost-share decompositions (100% stacks), and generate price sensitivities to hydrogen and carbon prices. All figures (PNG) and tables (XLSX with CSV fallback) are produced automatically for inclusion in the main text.

```

#--- Start of code ---

"""
Executed in Spyder – Python 3.9.12 (64-bit), IPython 8.2.0.

Model author: Abdurahman Alsulaiman (OIES)

Disclaimer. The information in this document is provided by the authors through
OIES for general informational purposes only and does not constitute legal,
financial, tax, investment, engineering, or other professional advice. While
reasonable efforts have been made to ensure accuracy as of 31/October/2025, no
warranties or representations (express or implied) are made regarding
completeness, accuracy, timeliness, or fitness for any particular purpose. You
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losses or damages arising from reliance on this material to the fullest extent
permitted by law. Any forward-looking statements are subject to risks and
uncertainties; actual results may differ. References to third-party information
are provided for convenience and do not imply endorsement.

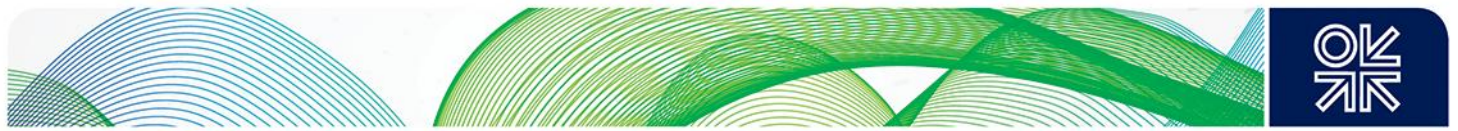
SAF and RD Techno-Economic Model (2025)
=====

Computes factory-gate and blended costs for multiple SAF pathways with Monte-Carlo
uncertainty, cost decomposition (100% stacks), and price sensitivities. Exports
PNG
figures and XLSX tables (CSV fallback).

Data notes
-----
• Each numeric input carries a bracketed citation [R#] to an open-access source
(or is a documented assumption grounded in that literature).
• “Fossil benchmarks” (jet/diesel) use EIA wholesale spot prices converted to
USD/kg; they appear in Figures 12, 14, and 15 and are not included in Figure 13.
[R1],[R2]
• eSAF_FT (PtL via RWGS+FT) hydrogen need is set by C12 stoichiometry (~0.435
kgH2/kg SAF), consistent with the PtL literature. [R7]

References (open-access)
-----
[R1] FRED/EIA – U.S. Gulf Coast Kerosene-Type Jet Fuel Spot (USD/gal)
https://fred.stlouisfed.org/series/WJFUELUSGULF

```



[R2] FRED/EIA – ULSD Spot, New York Harbor (USD/gal)  
<https://fred.stlouisfed.org/series/DDFUELNYH>

[R3] Eurostat – Electricity price statistics (non-household)  
[https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity\\_price\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics)

[R4] Eurostat dataset note (non-household)  
[https://ec.europa.eu/eurostat/cache/metadata/en/nrg\\_pc\\_205\\_esms.htm](https://ec.europa.eu/eurostat/cache/metadata/en/nrg_pc_205_esms.htm)

[R5] EIA – Average Price of Electricity to Industrial Sector (US)  
[https://www.eia.gov/electricity/monthly/epm\\_table\\_grapher.php?t=epmt\\_5\\_6\\_a](https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a)

[R6] GlobalPetrolPrices – Brazil business electricity price  
[https://www.globalpetrolprices.com/Brazil/electricity\\_prices/](https://www.globalpetrolprices.com/Brazil/electricity_prices/)

[R7] Transport & Environment (2022) – Hydrogen use in aviation (PtL inputs)  
[https://www.transportenvironment.org/uploads/files/H2-use-in-aviation-EE\\_TE-Update-Nov22.pdf](https://www.transportenvironment.org/uploads/files/H2-use-in-aviation-EE_TE-Update-Nov22.pdf)

[R8] ARCHES (2025) – Aviation whitepaper (HEFA H2 needs in practice)  
<https://archesh2.org/wp-content/uploads/2025/05/ARCHES-Aviation-Whitepaper-May-2025-1.pdf>

[R9] Müller-Langer et al. (2019, MDPI) – Hydrogen for lipid hydrotreating ranges  
<https://www.mdpi.com/2076-3417/9/19/4047>

[R10] NREL (2010) – TEA of biomass-to-liquids via FT (gasification)  
<https://docs.nrel.gov/docs/fy11osti/46587.pdf>

[R11] NREL (2024) – SAF State-of-Industry report (context for HEFA/FT/ATJ)  
<https://docs.nrel.gov/docs/fy24osti/87803.pdf>

[R12] DOE (2024) – Clean Hydrogen Production Cost, PEM  
<https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf>

[R13] ICCT (2024) – Green hydrogen costs (US/EU ranges)  
<https://theicct.org/the-price-of-green-hydrogen-estimate-future-production-costs-may24/>

[R14] Agora Industry (2025) – Brazil LCOH ranges  
[https://www.agora-industry.org/fileadmin/Projekte/2023/2023-24\\_IND\\_H2\\_Insights\\_BRA/A-IND\\_322\\_12-Insights-H2-Brazil\\_EN\\_WEB.pdf](https://www.agora-industry.org/fileadmin/Projekte/2023/2023-24_IND_H2_Insights_BRA/A-IND_322_12-Insights-H2-Brazil_EN_WEB.pdf)

[R15] EU ETS context – Carbon permits tracker  
<https://tradingeconomics.com/commodity/carbon>

[R16] EUROCONTROL/ICAO – Jet fuel EF  $\approx$  3.15–3.16 kg CO<sub>2</sub>/kg  
[https://ansperformance.eu/economics/cba/standard-inputs/latest/chapters/amount\\_of\\_emissions\\_released\\_by\\_fuel\\_burn.html](https://ansperformance.eu/economics/cba/standard-inputs/latest/chapters/amount_of_emissions_released_by_fuel_burn.html)

[R17] EIA – Mass CO<sub>2</sub> per gallon (fuel types)  
[https://www.eia.gov/environment/emissions/co2\\_vol\\_mass.php](https://www.eia.gov/environment/emissions/co2_vol_mass.php)

[R18] US EPA – Diesel CO<sub>2</sub>  $\sim$ 10.21 kg/gal (factor source)  
<https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references>

""

```
# --- Imports ---  
import numpy as np  
import pandas as pd  
import matplotlib as mpl
```

```
import matplotlib.pyplot as plt
from matplotlib.ticker import FuncFormatter, PercentFormatter
from pathlib import Path
from datetime import datetime

# --- Output ---
output_dir = Path("saf_cost_model_outputs")
output_dir.mkdir(parents=True, exist_ok=True)

# --- Typography / layout toggles ---
STYLE = {
    # global (figs 12-14)
    "legend": 12,
    "label": 12,
    "title": 14,
    "ticks": 11,
    # sensitivity only (fig 15)
    "sens_legend": 12,
    "sens_label": 13,
    "sens_title": 14,
    "sens_ticks": 12,
    # textual units
    "y_money_unit": "USD/kg",
    "x_loc_unit": "",
}

mpl.rcParams.update({
    'figure.dpi': 400,
    'savefig.dpi': 400,
    'figure.constrained_layout.use': False,
    'font.family': 'DejaVu Sans',
    'font.size': STYLE["ticks"],
    'axes.titlesize': STYLE["title"],
    'axes.titleweight': 'bold',
    'axes.labelsize': STYLE["label"],
    'axes.facecolor': '#FCFCFD',
    'axes.edgecolor': '#8E8E93',
    'axes.grid': True,
    'grid.color': '#E5E7EB',
    'grid.linewidth': 0.9,
    'grid.alpha': 1.0,
    'grid.linestyle': '-',
    'xtick.labelsize': STYLE["ticks"],
    'ytick.labelsize': STYLE["ticks"],
    'legend.frameon': False,
    'axes.axisbelow': True,
})
```

```

# --- Palette ---
TECH_COLORS = {
    'HEFA'      : '#0072B2', # deep blue
    'RD_HEFA'   : '#D55E00', # vermilion
    'FT'        : '#E69F00', # amber
    'ATJ'       : '#009E73', # green
    'eSAF_FT'   : '#2F4B7C', # indigo
}
DISPLAY_TECH = {
    'HEFA'      : 'SAF HEFA',
    'RD_HEFA'   : 'RD HEFA',
    'FT'        : 'SAF FT',
    'ATJ'       : 'SAF ATJ',
    'eSAF_FT'   : 'eSAF FT',
}
COMP_COLORS = {
    'capex'     : '#3B4252', # slate
    'feedstock' : '#009E73', # green
    'energy'    : '#F0E442', # yellow
    'carbon'    : '#6B7280', # gray
    'labor'     : '#56B4E9', # sky blue
    'maintenance': '#8C564B', # brown
    'utilities' : '#0072B2', # blue
}

# Fossil series formatting (used in Figs 12, 14, 15)
SERIES_LABEL = {
    'FOSSIL_JET'   : 'Fossil Kerosene',
    'FOSSIL_DIESEL': 'Fossil Diesel',
    **DISPLAY_TECH
}
SERIES_COLOR = {
    'FOSSIL_JET'   : '#4B5563', # dark gray
    'FOSSIL_DIESEL': '#9CA3AF', # mid gray
    **TECH_COLORS
}

def beautify_axes(ax, y_minor=False, y_percent=False):
    ax.spines['top'].set_visible(False); ax.spines['right'].set_visible(False)
    ax.spines['left'].set_visible(False); ax.spines['bottom'].set_visible(False)
    ax.grid(True, axis='y'); ax.grid(False, axis='x')
    if y_percent:
        ax.yaxis.set_major_formatter(PercentFormatter(100, decimals=0))

usd_fmt = FuncFormatter(lambda x, p: f'${x:,.2f}')
def save_figure(fig, basepath):
    fig.savefig(output_dir / f"{basepath}.png", dpi=400, bbox_inches='tight',
    facecolor=fig.get_facecolor())

```

```

def save_table(df: pd.DataFrame, base_name: str):
    """Write XLSX with openpyxl if available; otherwise CSV fallback (no
    xlswriter warning)."""
    xlsx_path = output_dir / f"{base_name}.xlsx"
    try:
        import openpyxl # noqa: F401
        df.to_excel(xlsx_path, index=False, engine='openpyxl')
    except Exception:
        csv_path = output_dir / f"{base_name}.csv"
        df.to_csv(csv_path, index=False)

np.random.seed(42)

# --- Fossil benchmarks (EIA spot → USD/kg; wholesale) ---
JET_USD_PER_GAL = 2.322 # [R1]
DIESEL_USD_PER_GAL = 2.493 # [R2]
GAL_TO_L = 3.785
RHO_JET_KG_PER_L = 0.80
RHO_DSL_KG_PER_L = 0.84
JET_USD_PER_KG = JET_USD_PER_GAL / (RHO_JET_KG_PER_L * GAL_TO_L) # ≈ 0.77
USD/kg
DSL_USD_PER_KG = DIESEL_USD_PER_GAL / (RHO_DSL_KG_PER_L * GAL_TO_L) # ≈ 0.78
USD/kg

# --- 20-year historical variability (monthly spot prices, ~2005–2025) ---
# Approximate 1σ in USD/gal; converted to USD/kg. [R1],[R2]
JET_STD_USD_PER_GAL_20Y = 0.83
DIESEL_STD_USD_PER_GAL_20Y = 0.75
JET_STD_USD_PER_KG_20Y = JET_STD_USD_PER_GAL_20Y / (RHO_JET_KG_PER_L * GAL_TO_L)
# ≈ 0.27 $/kg
DSL_STD_USD_PER_KG_20Y = DIESEL_STD_USD_PER_GAL_20Y / (RHO_DSL_KG_PER_L *
GAL_TO_L) # ≈ 0.24 $/kg

# Fossil CO2 emission factors for sensitivity behavior
FOSSIL_JET_EF_KGCO2_PER_KG = 3.15 # [R16]
EPA_DIESEL_KGCO2_PER_GAL = 10.21 # [R18]
FOSSIL_DSL_EF_KGCO2_PER_KG = EPA_DIESEL_KGCO2_PER_GAL / (RHO_DSL_KG_PER_L *
GAL_TO_L) # ≈ 3.21 kgCO2/kg

# --- Model ---
class AdvancedSAFCostModel:
    @staticmethod
    def _stoich_h2_req_alkane(n: int) -> float:
        return (6*n + 2) / (14*n + 2) # kg H2 / kg product

    @staticmethod
    def _stoich_co2_req_alkane(n: int) -> float:

```



```
        return (44*n) / (14*n + 2)    # kg CO2 / kg product

def __init__(self):
    self.n_simulations    = 10_000
    self.uncertainty_std  = 0.10
    self.jet_c_number     = 12
    self.esaf_h2_req      =
round(self._stoich_h2_req_alkane(self.jet_c_number), 3)  # ≈ 0.435
    self.esaf_co2_req     =
round(self._stoich_co2_req_alkane(self.jet_c_number), 2)  # ≈ 3.11

    # Exogenous H2 applies to any process that uses H2 (fossil defaults 6 g/kg
fuel)
    self.fossil_h2_req = {
        'FOSSIL_JET':    0.006,
        'FOSSIL_DIESEL': 0.006,
    }

    # Technology parameters (USD/kg fuel unless noted)
    self.tech_params = {
        'HEFA':
{'capex_base':0.10,'feedstock_base':0.60,'h2_req':0.03,'elec_req':0.20,

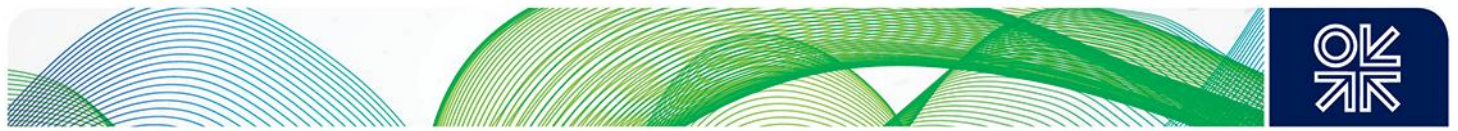
'labor_base':0.15,'maintenance_base':0.20,'utilities_base':0.15,
        'carbon_int':0.50,'fuel_type':'SAF'},
        'RD_HEFA':
{'capex_base':0.09,'feedstock_base':0.55,'h2_req':0.025,'elec_req':0.18,

'labor_base':0.14,'maintenance_base':0.18,'utilities_base':0.13,
        'carbon_int':0.45,'fuel_type':'RD'},
        'FT':
{'capex_base':0.50,'feedstock_base':0.10,'h2_req':0.005,'elec_req':0.50,

'labor_base':0.25,'maintenance_base':0.30,'utilities_base':0.25,
        'carbon_int':0.30,'fuel_type':'SAF'},
        'ATJ':
{'capex_base':0.30,'feedstock_base':0.80,'h2_req':0.02,'elec_req':0.30,

'labor_base':0.20,'maintenance_base':0.25,'utilities_base':0.15,
        'carbon_int':0.40,'fuel_type':'SAF'},
        'eSAF_FT':
{'capex_base':0.60,'feedstock_base':0.00,'h2_req':self.esaf_h2_req,'elec_req':0.60
,

'labor_base':0.30,'maintenance_base':0.35,'utilities_base':0.30,
        'carbon_int':0.00,'fuel_type':'eSAF'},
    }
}
```



```

        # Location parameters (2025). Electricity + H2 grounded in public ranges.
[R3-R6],[R12-R14]
        self.locations = {
            'EU' :
{'feedstock_mult':1.2,'h2_price':5.6,'elec_price':0.15,'carbon_price':85,

'labor_mult':1.3,'kerosene_price':JET_USD_PER_KG,'diesel_price':DSL_USD_PER_KG},
            'US' :
{'feedstock_mult':1.0,'h2_price':5.0,'elec_price':0.081,'carbon_price':0,

'labor_mult':1.0,'kerosene_price':JET_USD_PER_KG,'diesel_price':DSL_USD_PER_KG},
            'Brazil':
{'feedstock_mult':0.8,'h2_price':3.5,'elec_price':0.122,'carbon_price':0,

'labor_mult':0.7,'kerosene_price':JET_USD_PER_KG,'diesel_price':DSL_USD_PER_KG},
        }

        self.blend_ratio = 0.50
        self.timestamp = datetime.now().strftime("%Y%m%d_%H%M%S")

def run_simulation(self, technology, location, h2_range=None, dac_range=None):
    p = self.tech_params[technology].copy()
    loc = self.locations[location]

    feedstock_cost = p['feedstock_base'] * loc['feedstock_mult']
    labor_cost      = p['labor_base']     * loc['labor_mult']

    # Correlated uncertainties
    corr =
np.array([[1.0,0.7,0.6,0.6],[0.7,1.0,0.5,0.5],[0.6,0.5,1.0,0.4],[0.6,0.5,0.4,1.0]]
)

    L = np.linalg.cholesky(corr)
    z = np.random.normal(0, self.uncertainty_std, (self.n_simulations,4))
    uz = z @ L.T

    capex_sim      = p['capex_base']      * (1 + uz[:,0])
    feedstock_sim  = feedstock_cost       * (1 + uz[:,1])
    labor_sim      = labor_cost            * (1 + uz[:,2])
    maintenance_sim = p['maintenance_base'] * (1 + uz[:,3])
    utilities_sim  = p['utilities_base']   * (1 +
np.random.normal(0,self.uncertainty_std,self.n_simulations))

    # Energy & carbon
    if technology == 'eSAF_FT':
        h2_price = (np.random.choice(h2_range, self.n_simulations) if h2_range
else loc['h2_price'])
        h2_costs = h2_price * p['h2_req']
        dac_usd_per_kg_co2 = (np.random.choice(dac_range, self.n_simulations)

```

```

* 0.001) if dac_range else np.zeros(self.n_simulations)
    dac_costs = dac_usd_per_kg_co2 * self.esaf_co2_req
    elec_cost  = p['elec_req'] * loc['elec_price']
    carbon_cost = dac_costs
else:
    h2_costs    = p['h2_req'] * loc['h2_price']
    elec_cost   = p['elec_req'] * loc['elec_price']
    carbon_cost = p['carbon_int'] * (loc['carbon_price']/1000)

    factory = capex_sim + feedstock_sim + h2_costs + elec_cost + carbon_cost +
labor_sim + maintenance_sim + utilities_sim
    fossil_price = loc['kerosene_price'] if p['fuel_type'] in ['SAF','eSAF']
else loc['diesel_price']
    blended      = self.blend_ratio * factory + (1 - self.blend_ratio) *
fossil_price

    # Decomposition (energy = H2 + electricity; carbon = tax/DAC)
    energy_scalar = float(np.mean(h2_costs)) + elec_cost
    carbon_scalar = float(np.mean(carbon_cost))
    contrib = {
        'capex':capex_sim,'feedstock':feedstock_sim,
        'energy':np.full(self.n_simulations,energy_scalar),
        'carbon':np.full(self.n_simulations,carbon_scalar),

'labor':labor_sim,'maintenance':maintenance_sim,'utilities':utilities_sim
    }

    return {
        'factory_gate': {'mean':np.mean(factory),'std':np.std(factory),

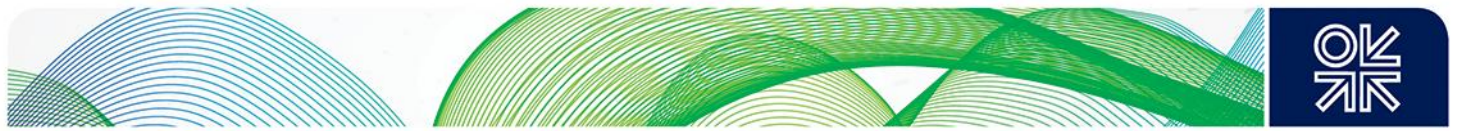
'p5':np.percentile(factory,5),'p95':np.percentile(factory,95)},
        'blended'      : {'mean':np.mean(blended),'std':np.std(blended),

'p5':np.percentile(blended,5),'p95':np.percentile(blended,95)},
        'decomposition': {k: np.mean(v/factory)*100 for k,v in
contrib.items()}},
    }

def run_complete_analysis(self):
    results = {}
    techs   = ['HEFA','RD_HEFA','FT','ATJ','eSAF_FT'] # HEFA and RD_HEFA
adjacent
    locs    = ['EU','US','Brazil']
    h2_range = [2.0,5.0,10.0] # USD/kg [R12-R14]
    dac_range = [100.0,300.0,600.0] # USD/t CO2

    for t in techs:
        results[t] = {}

```



```
        for l in locs:
            results[t][l] = self.run_simulation(t,l,h2_range,dac_range) if
t=='eSAF_FT' else self.run_simulation(t,l)

        self._export_tables(results)
        self._create_plots(results)
        self._run_sensitivity_analysis(results)
        return results

def _export_tables(self, results):
    # Factory-gate
    rows = []
    for t in ['HEFA','RD_HEFA','FT','ATJ','eSAF_FT']:
        for l in ['EU','US','Brazil']:
            r = results[t][l]['factory_gate']

rows.append({'Technology':DISPLAY_TECH[t],'Location':l,'Mean':round(r['mean'],2),'
Std':round(r['std'],2)})
            save_table(pd.DataFrame(rows), f"Table7_FactoryCosts_{self.timestamp}")

    # Decomposition
    rows = []
    for t in ['HEFA','RD_HEFA','FT','ATJ','eSAF_FT']:
        for l in ['EU','US','Brazil']:
            d = results[t][l]['decomposition']
            rows.append({'Technology':DISPLAY_TECH[t],'Location':l,

'CAPEX_%':round(d['capex'],1),'Feedstock_%':round(d['feedstock'],1),

'Energy_%':round(d['energy'],1),'Carbon_%':round(d['carbon'],1),

'Labor_%':round(d['labor'],1),'Maintenance_%':round(d['maintenance'],1),
                        'Utilities_%':round(d['utilities'],1)})
            save_table(pd.DataFrame(rows), f"Table8_Decomposition_{self.timestamp}")

    # Blended
    rows = []
    for t in ['HEFA','RD_HEFA','FT','ATJ','eSAF_FT']:
        for l in ['EU','US','Brazil']:
            r = results[t][l]['blended']

rows.append({'Technology':DISPLAY_TECH[t],'Location':l,'Mean':round(r['mean'],2),'
Std':round(r['std'],2)})
            save_table(pd.DataFrame(rows), f"Table9_BlendedPrices_{self.timestamp}")

def _create_plots(self, results):
    locs = ['EU','US','Brazil']
    fos_ker = [self.locations[l]['kerosene_price'] for l in locs]
```



```
fos_dsl = [self.locations[l]['diesel_price'] for l in locs]

# ----- Figure – Factory-gate costs -----
fig, ax = plt.subplots(figsize=(11.2, 6.8))
x = np.arange(len(locs))
order =
['HEFA', 'RD_HEFA', 'FT', 'ATJ', 'eSAF_FT', 'FOSSIL_JET', 'FOSSIL_DIESEL']
n_series = len(order)
w = 0.9 / n_series

for i, key in enumerate(order):
    if key == 'FOSSIL_JET':
        m = fos_ker
        e = [JET_STD_USD_PER_KG_20Y] * len(locs)
        # Fossil error bars = yellow (distinct)
        err_kw = {'ecolor': '#c90000', 'elinewidth': 1.8, 'capsize': 4,
'capthick': 1.4}
    elif key == 'FOSSIL_DIESEL':
        m = fos_dsl
        e = [DSL_STD_USD_PER_KG_20Y] * len(locs)
        err_kw = {'ecolor': '#c90000', 'elinewidth': 1.8, 'capsize': 4,
'capthick': 1.4}
    else:
        m = [results[key][l]['factory_gate']['mean'] for l in locs]
        e = [results[key][l]['factory_gate']['std'] for l in locs] #
Monte-Carlo  $\sigma$ 
        # SAF/RD/eSAF error bars = black
        err_kw = {'ecolor': '#000000', 'elinewidth': 1.2, 'capsize': 4,
'capthick': 1.2}

    ax.bar(
        x + i*w, m, w,
        yerr=e, error_kw=err_kw,
        label=SERIES_LABEL[key],
        color=SERIES_COLOR[key],
        edgecolor='white', linewidth=0.7
    )

ax.set_xlabel(f'Location {STYLE["x_loc_unit"]}', labelpad=8)
ax.set_ylabel(f'Factory-gate Cost ({STYLE["y_money_unit"]}', labelpad=8)
ax.yaxis.set_major_formatter(usd_fmt)
ax.set_title('Factory-Gate Costs (2025)', pad=14, fontsize=STYLE["title"])
ax.set_xticks(x + (n_series-1)*w/2); ax.set_xticklabels(locs)
ax.set_ylim(0, 8)
beautify_axes(ax)
ax.legend(ncol=4, loc='upper left', fontsize=STYLE["legend"])

footnote = (
```

```

        "Error bars: SAF/RD/eSAF = Monte-Carlo  $\pm 1\sigma$  (n=10,000), "
        "Fossil Kerosene/Diesel = 2005–2025 monthly spot price  $\pm 1\sigma$  (EIA)
converted to USD/kg."
    )
    fig.text(0.5, 0.02, footnote, ha='center', va='bottom', fontsize=max(10,
STYLE["legend"]))
    fig.subplots_adjust(top=0.90, bottom=0.18, left=0.08, right=0.995)
    save_figure(fig, f"Figure12_FactoryCosts_{self.timestamp}")
    plt.close(fig)

# ----- Figure – Cost decomposition -----
techs = ['HEFA', 'RD_HEFA', 'FT', 'ATJ', 'eSAF_FT']
comps =
['capex', 'feedstock', 'energy', 'carbon', 'labor', 'maintenance', 'utilities']
fig, axes = plt.subplots(1, 5, figsize=(18.8, 5.0), sharey=True)
comp_handles, comp_labels = [], []
for idx, t in enumerate(techs):
    ax = axes[idx]
    xloc = np.arange(len(locs)); width = 0.68
    bottoms = np.zeros(len(locs))

    beautify_axes(ax, y_percent=True) # grid first

    for c in comps:
        v = [results[t][l]['decomposition'][c] for l in locs]
        bars = ax.bar(
            xloc, v, width, bottom=bottoms,
            color=COMP_COLORS[c], edgecolor='white', linewidth=0.5,
            zorder=3, # bars above grid
            label=c.capitalize() if idx==0 else None
        )
        bottoms += np.array(v)
        if idx==0: comp_handles.append(bars[0]);
    comp_labels.append(c.capitalize())
    ax.set_title(DISPLAY_TECH[t], fontsize=12, fontweight='bold',
color=TECH_COLORS[t], pad=8)
    ax.set_xticks(xloc); ax.set_xticklabels(locs)
    ax.set_ylim(0, 100)
    if idx>0: ax.set_ylabel(None)
    fig.suptitle('Cost Decomposition by Technology (2025)', y=1.01,
fontsize=STYLE["title"], fontweight='bold')
    fig.legend(comp_handles, comp_labels, loc='lower center',
bbox_to_anchor=(0.5, 0.02),
ncol=7, title='Components', fontsize=STYLE["legend"])
    fig.text(0.006, 0.5, 'Cost Share (%)', rotation=90, va='center',
fontsize=STYLE["label"])
    fig.subplots_adjust(left=0.06, right=0.995, top=0.90, bottom=0.20,
wspace=0.20)

```



```
save_figure(fig, f"Figure13_CostDecomposition_{self.timestamp}")
plt.close(fig)

# ----- Figure - 50% blend prices -----
fig, ax = plt.subplots(figsize=(11.0, 6.3))
for key in ['HEFA', 'RD_HEFA', 'FT', 'ATJ', 'eSAF_FT']:
    m = [results[key][l]['blended']['mean'] for l in locs]
    ax.plot(locs, m, 'o-', lw=2.4, ms=7.5, label=SERIES_LABEL[key],
color=SERIES_COLOR[key])

    ax.plot(locs, fos_ker, 'o-', lw=2.4, ms=7.5,
label=SERIES_LABEL['FOSSIL_JET'], color=SERIES_COLOR['FOSSIL_JET'])
    ax.plot(locs, fos_dsl, 'o-', lw=2.4, ms=7.5,
label=SERIES_LABEL['FOSSIL_DIESEL'], color=SERIES_COLOR['FOSSIL_DIESEL'])

ax.set_xlabel(f'Location {STYLE["x_loc_unit"]}', labelpad=8)
ax.set_ylabel(f'Blended Price ({STYLE["y_money_unit"]}', labelpad=8)
ax.yaxis.set_major_formatter(usd_fmt)
ax.set_title('50% Blend Prices (2025)', pad=14, fontsize=STYLE["title"])
ax.set_ylim(0, 4)
beautify_axes(ax)
ax.legend(loc='upper left', ncol=4, fontsize=STYLE["legend"])
fig.subplots_adjust(top=0.90, bottom=0.16, left=0.08, right=0.995)
save_figure(fig, f"Figure14_BlendedPrices_{self.timestamp}")
plt.close(fig)

def _run_sensitivity_analysis(self, results):
    h2_prices = np.linspace(1, 10, 50)
    c_prices = np.linspace(0, 200, 50)
    eu_cp = self.locations['EU']['carbon_price']
    h2_anchor = self.locations['EU']['h2_price']

    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(18, 8.5))

    # ----- Figure - H2 price sensitivity -----
    for key in ['HEFA', 'RD_HEFA', 'FT', 'ATJ', 'eSAF_FT']:
        base = results[key]['EU']['factory_gate']['mean']
        h2r = self.tech_params[key]['h2_req']
        ax1.plot(h2_prices, base + (h2_prices - h2_anchor) * h2r, '-', lw=2.6,
label=f'{SERIES_LABEL[key]} ({h2r*1000:.0f} gH2/kg)',
color=SERIES_COLOR[key])

        fk_req = self.fossil_h2_req['FOSSIL_JET']
        fd_req = self.fossil_h2_req['FOSSIL_DIESEL']
        ax1.plot(h2_prices, JET_USD_PER_KG + (h2_prices - h2_anchor) * fk_req, '-',
lw=2.6,
label=f'{SERIES_LABEL["FOSSIL_JET"]} ({fk_req*1000:.0f} gH2/kg)',
color=SERIES_COLOR['FOSSIL_JET'])
```



```

ax1.plot(h2_prices, DSL_USD_PER_KG + (h2_prices - h2_anchor) * fd_req, '-
', lw=2.6,
        label=f'{SERIES_LABEL["FOSSIL_DIESEL"]} ({{fd_req*1000:.0f}}
gH2/kg)', color=SERIES_COLOR['FOSSIL_DIESEL'])

ax1.set_xlabel('Hydrogen Price (USD/kg)', labelpad=8,
fontsize=STYLE["sens_label"])
ax1.set_ylabel(f'Factory-gate Cost ({{STYLE["y_money_unit"]}})', labelpad=8,
fontsize=STYLE["sens_label"])
ax1.yaxis.set_major_formatter(usd_fmt)
ax1.set_title('H2 Price Sensitivity (EU, 2025)', pad=12,
fontsize=STYLE["sens_title"])
ax1.set_ylim(0, 10)
beautify_axes(ax1)
ax1.legend(ncol=2, loc='upper left', fontsize=STYLE["sens_legend"])

# ----- Figure - Carbon price sensitivity -----
for key in ['HEFA', 'RD_HEFA', 'FT', 'ATJ']:
    base = results[key]['EU']['factory_gate']['mean']
    ci = self.tech_params[key]['carbon_int'] # kg CO2/kg fuel
    ax2.plot(c_prices, base + (c_prices - eu_cp) * ci / 1000.0, '-',
lw=2.6,
            label=f'{SERIES_LABEL[key]} ({{ci:.2f}} kgCO2/kg)',
color=SERIES_COLOR[key])

    base_esaf = results['eSAF_FT']['EU']['factory_gate']['mean']
    ax2.plot(c_prices, np.full_like(c_prices, base_esaf), '-', lw=2.6,
            label=f'{SERIES_LABEL["eSAF_FT"]} (no CO2 price effect)',
color=SERIES_COLOR['eSAF_FT'])

    fos_jet_line = JET_USD_PER_KG + (c_prices - eu_cp) *
(FOSSIL_JET_EF_KGCO2_PER_KG / 1000.0)
    fos_dsl_line = DSL_USD_PER_KG + (c_prices - eu_cp) *
(FOSSIL_DSL_EF_KGCO2_PER_KG / 1000.0)
    ax2.plot(c_prices, fos_jet_line, '-', lw=2.6,
            label=f'{SERIES_LABEL["FOSSIL_JET"]}
({FOSSIL_JET_EF_KGCO2_PER_KG:.2f} kgCO2/kg)',
            color=SERIES_COLOR['FOSSIL_JET'])
    ax2.plot(c_prices, fos_dsl_line, '-', lw=2.6,
            label=f'{SERIES_LABEL["FOSSIL_DIESEL"]}
({FOSSIL_DSL_EF_KGCO2_PER_KG:.2f} kgCO2/kg)',
            color=SERIES_COLOR['FOSSIL_DIESEL'])

ax2.set_xlabel('Carbon Price (USD/t CO2)', labelpad=8,
fontsize=STYLE["sens_label"])
ax2.set_ylabel(f'Factory-gate Cost ({{STYLE["y_money_unit"]}})', labelpad=8,
fontsize=STYLE["sens_label"])
ax2.yaxis.set_major_formatter(usd_fmt)

```



```
ax2.set_title('Carbon Price Sensitivity (EU, 2025)', pad=12,
fontsize=STYLE["sens_title"])
ax2.set_ylim(0, 10)
beautify_axes(ax2)
ax2.legend(ncol=2, loc='upper left', fontsize=STYLE["sens_legend"])

fig.subplots_adjust(top=0.90, bottom=0.12, left=0.07, right=0.98)
save_figure(fig, f"Figure15_Sensitivity_{self.timestamp}")
plt.close(fig)

# --- Main ---
if __name__ == "__main__":
    model = AdvancedSAFCostModel()
    model.run_complete_analysis()

#--- End of code ---
```

## Appendix B: SAF and RD Techno-Economic Model Methodology

This appendix presents the methodology implemented by the provided Python code to compute factory-gate costs, blended prices, cost decompositions, and price sensitivities for multiple SAF pathways.

### 1. Overview

The model evaluates five pathways—HEFA SAF, RD (RD-HEFA), FT SAF (FT), Alcohol-to-Jet SAF (ATJ), and e-SAF via RWGS+FT (eSAF\_FT)—across three locations (EU, US, Brazil). For each (technology, location) pair, it runs 10,000 Monte-Carlo draws with correlated normal shocks on selected cost components, aggregates to factory-gate costs (USD/kg), computes a 50% blended price with the fossil comparator (kerosene for SAF/eSAF, diesel for RD-HEFA), and reports component cost shares (100% stacks). Deterministic one-way sensitivities are produced for hydrogen price and carbon price, anchored at EU baselines.

### 2. Data, Units, and Conversions

Fossil spot prices are constants, converted from USD/gal to USD/kg via densities and 1 gal = 3.785 L. Historical variability ( $1\sigma$ ) is converted the same way and used only as error bars in plotting, not as stochastic inputs.

#### 2.1 Core Constants and Conversions

Symbol	Meaning	Value	Units
$P_{jet,gal}$	Jet fuel spot price (U.S. Gulf Coast)	2.322	USD/gal
$P_{dsl,gal}$	ULSD spot price (New York Harbor)	2.493	USD/gal
<b>GAL to L</b>	Gallon-to-liter factor	3.785	L/gal
$\rho_{jet}$	Jet density	0.80	kg/L
$\rho_{dsl}$	Diesel density	0.84	kg/L
$P_{jet,kg}$	Jet fuel price	0.76684	USD/kg
$P_{dsl,kg}$	Diesel price	0.78411	USD/kg
$\sigma_{jet,gal}$	Jet 20-yr $\sigma$ (monthly spot)	0.83	USD/gal
$\sigma_{dsl,gal}$	Diesel 20-yr $\sigma$ (monthly spot)	0.75	USD/gal
$\sigma_{jet,kg}$	Jet 20-yr $\sigma$ converted	0.27411	USD/kg
$\sigma_{dsl,kg}$	Diesel 20-yr $\sigma$ converted	0.23589	USD/kg
$EF_{jet}$	Jet CO <sub>2</sub> emission factor	3.15	kg CO <sub>2</sub> /kg fuel
$EF_{dsl}$	Diesel CO <sub>2</sub> emission factor	3.21	kg CO <sub>2</sub> /kg fuel

### 3. Technology and Location Parameters

Technology-specific base costs are in USD per kg of finished fuel unless otherwise noted. Hydrogen and electricity requirements multiply local prices to yield USD/kg contributions; carbon uses kg CO<sub>2</sub>/kg times carbon price (USD/tCO<sub>2</sub>)/1000. For eSAF\_FT, hydrogen and DAC costs are treated explicitly via stoichiometry and discrete price ranges.

#### 3.1 eSAF Stoichiometry (n=12 carbon number)

Stoichiometric hydrogen requirement for C<sub>n</sub> alkane (kg H<sub>2</sub> per kg product):

$$H_{2\ req(n)} = \frac{(6n + 2)}{14n + 2} = \frac{74}{170} = 0.43529 \frac{kg_{H_2}}{kg_{fuel}} \quad \forall n = 12$$

Stoichiometric CO<sub>2</sub> requirement for C<sub>n</sub> alkane (kg CO<sub>2</sub> per kg product):

$$CO_{2\ req(n)} = \frac{44n}{14n+2} = \frac{528}{170} = 3.10588 \frac{kg_{CO_2}}{kg_{fuel}} \quad \forall n = 12$$

#### 4. Uncertainty Propagation and Correlation

For each (technology, location), the model draws a 4-vector of correlated normal shocks for capex, feedstock, labor, and maintenance with scale  $\sigma = 0.10$  and a fixed correlation matrix R; utilities receive an independent normal shock with the same  $\sigma$ .

Correlation matrix for shocked components:

$$R = \begin{bmatrix} 1 & 0.7 & 0.6 & 0.6 \\ 0.7 & 1 & 0.5 & 0.5 \\ 0.6 & 0.5 & 1 & 0.4 \\ 0.6 & 0.5 & 0.4 & 1 \end{bmatrix}$$

Shocked component k in Monte-Carlo draw i:

$$x_k^{(i)} = x_{k,0} \cdot (1 + u_k^{(i)}), k \in \{capex, feedstock, labor, maintenance\}$$

#### 5. Deterministic Energy and Carbon Terms

For non-eSAF technologies, hydrogen, electricity, and carbon contributions are deterministic at a given location; for eSAF\_FT, hydrogen price and DAC price are drawn from discrete sets per draw, and carbon cost reflects DAC (no carbon tax).

Non-eSAF energy and carbon contributions (USD/kg):

$$H_2 = h \cdot p_{H_2}, \quad Elec = e \cdot p_{elec}, \quad Carbon = c \cdot \frac{p_c}{1000}$$

eSAF DAC cost per draw (USD/kg fuel):

$$DAC^{(i)} = (p_{DAC}^{(i)} \cdot 0.001) \cdot CO_{2\ req}$$

Note: With  $CO_{2\ req} = 3.10588$  kg/kg and  $P_{DAC}$  chosen from [100, 300, 600] USD/tCO<sub>2</sub>.

#### 6. Factory-Gate Cost (per draw) and Summary

Factory-gate cost in draw i (USD/kg):

$$F^{(i)} = \underbrace{x_{capex}^{(i)} + x_{feed}^{(i)} + x_{labor}^{(i)} + x_{maint}^{(i)} + x_{util}^{(i)}}_{shocked} + \underbrace{H_2^{(i)} + Elec + Carbon^{(i)}}_{energy + carbon}$$

$$\bar{F}, s_F, F_5, F_{95} \text{ computed over } i = 1, \dots, 10,000$$

#### 7. Blended (50%) Price

50% blend of factory-gate with fossil comparator (USD/kg):

$$B^{(i)} = \beta F^{(i)} + (1 - \beta) p_{fos}, \quad \beta = 0.5$$

#### 8. Cost Decomposition

Scalarized energy and carbon terms for shares:

$$\bar{E} = \overline{H_2^{(i)}} + Elec, \quad \bar{C} = \overline{Carbon^{(i)}}$$

Component share definition (% , sums  $\approx 100$ ):

$$s_k = 100 \cdot E_i \left[ \frac{X_k^{(i)}}{F^{(i)}} \right], X_k^{(i)} \in \{X_{capex}^{(i)}, X_{feedstock}^{(i)}, X_{labor}^{(i)}, X_{maintenance}^{(i)}, X_{utilities}^{(i)}, \bar{E}, \bar{C}\}$$

## 9. Sensitivity Analyses

Hydrogen price sensitivity (USD/kg):

$$C_{H_2}(p) = \underbrace{\bar{F}_{EU}}_{\text{factory mean at anchor}} + (p - p_{H_2,EU}^*) \cdot h$$

Note: For fossils,  $h = 0.006$  kg H<sub>2</sub>/kg fuel; for each pathway,  $h$  is its hydrogen intensity.

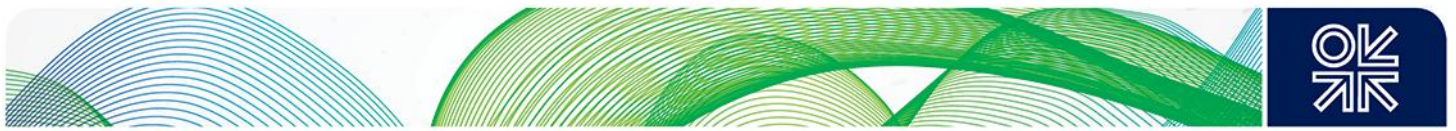
Carbon price sensitivity (USD/kg):

$$C_{CO_2}(p) = \bar{F}_{EU} + \left( \frac{p - p_{C,EU}^*}{1000} \right) \cdot c$$

Note: eSAF\_FT curve is flat (no tax effect) as carbon is represented via DAC within factory-gate.

## 10. Symbols and Variables

Symbol	Meaning	Units	Typical/Default
$F^i$	Factory-gate cost in draw i	USD/kg	—
$B^i$	Blended price (50%) in draw i	USD/kg	—
$\beta$	Blend ratio	—	0.5
$x_{capex}^i$	CAPEX component (shocked) in draw i	USD/kg	—
$x_{feed}^i$	Feedstock component (shocked) in draw i	USD/kg	—
$x_{labor}^i$	Labor component (shocked) in draw i	USD/kg	—
$x_{maint}^i$	Maintenance component (shocked) in draw i	USD/kg	—
$x_{util}^i$	Utilities component (shocked) in draw i	USD/kg	—
<b>H<sub>2</sub>, Elec, Carbon</b>	Energy and carbon contributions	USD/kg	—
$h$	Hydrogen intensity	kg H <sub>2</sub> /kg fuel	HEFA 0.03; RD 0.025; FT 0.005; ATJ 0.02; eSAF 0.435
$e$	Electricity intensity	kWh/kg fuel	HEFA 0.20; RD 0.18; FT 0.50; ATJ 0.30; eSAF 0.60
$c$	Carbon intensity	kg CO <sub>2</sub> /kg fuel	HEFA 0.50; RD 0.45; FT 0.30; ATJ 0.40; eSAF 0.00
$p_{H_2}$	Hydrogen price (location)	USD/kg	EU 5.6; US 5.0; BR 3.5
$p_{elec}$	Electricity price (location)	USD/kWh	EU 0.150; US 0.081; BR 0.122
$p_C$	Carbon price (location)	USD/t CO <sub>2</sub>	EU 85; US 0; BR 0
$p_{fos}$	Fossil comparator price	USD/kg	Jet 0.76684; Diesel 0.78411
$u_k^i$	Normal shock for component k	—	$\sigma=0.10$ , corr=R
$R$	Correlation matrix of shocks	—	see part 4 in this appendix
$\sigma$	Std. dev. of shocks	—	0.10
$EF_{jet}, EF_{dsl}$	Fossil emission factors	kg CO <sub>2</sub> /kg	Jet 3.15; Diesel 3.21
$CO_{2req}$	Stoichiometric CO <sub>2</sub> for eSAF	kg/kg	3.10588



## 11. Assumptions and Limitations

1. Factory-gate scope only (no delivery logistics, no policy credits).
2. Only selected components are stochastic; hydrogen/electricity/carbon are deterministic except for eSAF hydrogen and DAC (discrete choices).
3. Fixed correlation matrix; not estimated from data.
4. Energy and carbon shares are scalarized to their Monte-Carlo means to avoid ratio-of-randoms artifacts.
5. Fossil baselines are single spot levels converted to USD/kg; historical  $\sigma$  used only for display.
6. Carbon tax does not apply to eSAF\_FT; DAC internalizes CO<sub>2</sub> procurement.
7. Blend is linear on USD/kg basis at 50%.
8. Random seed fixed at 42 for Monte-Carlo reproducibility.