Università Campus Bio-Medico di Roma

PhD Course in Science and Engineering for Humans and the Environment

XXXVII Cycle

a.a. 2021/2022

The SAF Value Chain as Compliance Infrastructure: Design and Results for Italy

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Summary

Preface

Humanity is navigating a systemic, multi-faceted polycrisis that strains social cohesion, economic stability, and planetary boundaries. In the energy domain, this tension is commonly summarized as the Global Energy Trilemma: the simultaneous, and often conflicting, imperatives of security of supply, affordability, and environmental sustainability. Transport sits at the nexus of these objectives, and aviation embodies a demanding convergence of constraints: hard-to-abate emissions, uncompromising safety and quality standards, highly globalized supply chains, and stringent expectations for reliability and performance. The decarbonization of aviation therefore requires solutions that are not only technically sound, but also verifiable across whole life cycles and scalable within existing operational and regulatory frameworks.

Over two centuries of industrialization have altered atmospheric composition and Earth's radiative balance in ways now beyond scientific dispute. The frontier has shifted from causality to implementation: how to operationalize rapid, credible, and just decarbonization under real-world constraints of infrastructure, markets, and institutions. This shift has propelled science-based policy frameworks—from multilateral agreements to regional legislation—and has reframed the role of engineering disciplines. Engineers are no longer confined to optimizing steady plants; they are called to design, assess, and scale transition-enabling systems where technical performance, environmental integrity, and institutional verifiability must co-evolve.

The European Union has assembled an integrated architecture that pairs long-term climate-neutrality targets with sectoral instruments, market mechanisms, and dedicated funding. In aviation, the logic is deliberately two-sided. On the demand side, binding minimum shares of lower-carbon aviation fuels and monitoring–reporting–verification (MRV) obligations create predictable market pull and a robust evidence base for compliance. On the supply side, innovation grants, research programs, and risk-mitigation tools aim to compress learning curves and bridge the persistent cost and risk differentials that separate sustainable fuels from fossil kerosene. This architecture is intended to translate verified life-cycle performance into bankable value streams, enabling investment to progress from pilots to deployment and aligning technology choice with measurable environmental outcomes.

From a technological perspective, Sustainable Aviation Fuels (SAF) offer the most immediate and system-compatible lever to decarbonize aviation because they are drop-in (or partially drop-in) and therefore compatible with existing aircraft and fuel-supply infrastructure. Yet SAF are not a monolith; they constitute a portfolio. Bio-based pathways include HEFA/HVO derived from waste and residue lipids such as used cooking oil (UCO), Fischer–Tropsch syntheses from lignocellulosic biomass, and alcohol-to-jet processes. In parallel, synthetic e-fuels produced via power-to-liquids combine green hydrogen with captured carbon, whereas hydrogen itself—combusted in adapted turbines or used in fuel-cell architectures with liquid hydrogen storage—defines a longer-term trajectory with distinctive infrastructure, safety, and certification implications. These pathways are complementary over time: near-term SAF deployment can deliver immediate reductions and operational learning while hydrogen and e-fuels mature and enabling infrastructures develop.

Environmental credibility, however, is not guaranteed by technical feasibility alone. For liquid fuels, life-cycle thinking is indispensable. Life Cycle Assessment (LCA) quantifies impacts along the value chain—from feedstock availability and collection, through pre-treatment and conversion, to distribution and use—and exposes hotspots and trade-offs that tailpipe or energy-only metrics cannot capture. In UCO-to-SAF systems, performance is strongly conditioned by:

(i) the coverage, integrity, and logistics of UCO collection;
(ii) the provision of hydrogen and utilities (source, efficiency, carbon intensity);
(iii) co-product handling and allocation rules;
(iv) institutional safeguards—traceability, fraud prevention, sustainability criteria—that determine whether theoretical benefits materialize in practice.

Without this systems view, perverse outcomes—unsustainable feedstock displacement, excessive import dependence, or claims with weak additionality—are difficult to detect ex ante.

Recent European evidence illustrates both progress and constraint. In the first ReFuelEU baseline (reporting year 2024), suppliers declared 32.1 Mt of total aviation fuels, of which 192.7 kt qualified as SAF—approximately 0.60% by mass. Supply remains feedstock-concentrated and import-dependent: roughly 81% of SAF originates from UCO, and a majority of that feedstock is sourced outside the EU, with deliveries highly concentrated among a limited number of suppliers and airports. On the price side, reference values for 2024 indicate a substantial differential—on the order of €2,085 per tonne for "aviation biofuels" at the NWE hub versus €734 per tonne for conventional aviation fuel—underscoring the economic rationale for calibrated support instruments during market formation. Looking ahead to 2030, EU production-capacity assessments span from an Operating case at roughly 1.4 Mt (today's in-service facilities) to a Realistic case near 3.6 Mt (adding plants under construction) and an Optimistic case around 5.2 Mt of bio-derived SAF, with an additional ~0.7 Mt of synthetic aviation fuels in high-credibility announcements. The synthetic-fuels pipeline, however, shows delays and depends on final investment decisions and enabling infrastructure. These signals place a premium on coherent policy–finance design to avoid bottlenecks in feedstocks, technologies, and logistics.

In parallel with sector-specific regulation, broader decarbonization policy and funding logics—devised for energy-intensive and hard-to-abate industries—inform aviation fuel strategies. Scenario-based assessments of industrial transitions converge on three pillars:

(i) demand-pull mandates aligned with verifiable performance

(ii) supply-push finance that closes CAPEX/OPEX gaps along learning curves and de-risks first-of-a-kind assets

(iii) accounting frameworks that consistently translate life-cycle evidence into eligibility, pricing, and compliance. Together, these elements help mobilize investment at pace while preserving environmental integrity and avoiding lock-ins.

Scope and approach of this dissertation.

Against this backdrop, the present work undertakes a dual, integrated inquiry at the intersection of process engineering and sustainability assessment, embedding what would normally be set aside as a separate abstract directly within this Preface to clarify aims, methods, and contributions.

First, the dissertation develops a rigorous LCA of HEFA/HVO SAF from UCO under European conditions. The methodological posture follows a process-systems engineering. Functional units and system boundaries are defined explicitly (a cradle-to-gate perspective for production stages), with careful distinction between foreground operations (collection, pre-treatment, conversion, blending) and the background system (electricity, hydrogen, upstream materials). Inventory development is structured and transparent; co-product handling and allocation rules are justified and tested; impact characterization uses an established method to ensure comparability with peer studies. The scenario design captures realistic, idealized, and hybrid logistics of UCO collection; the energy system is represented via alternative electricity mixes and hydrogen supply options; and sensitivity and uncertainty analyses probe the robustness of conclusions. Results are then systematically compared with those of fossil kerosene, quantifying relative benefits across climate and non-climate categories (e.g., particulate-matter formation, eutrophication, water use) and identifying process–policy levers—notably hydrogen sourcing, electricity mix, and logistics optimization.

Second, the dissertation examines the policy–finance architecture that governs SAF market formation in the EU. It maps the principal demand-side instruments (blending mandates and MRV frameworks) and supply-side supports (innovation funding, research programs, risk-mitigation mechanisms), clarifying their interfaces with LCA-based evidence and their implications for bankability. Particular attention is devoted to reference-price methodologies and penalty frameworks used in compliance and support schemes, as well as to governance initiatives that shape national implementation and stakeholder coordination. The analysis articulates conditions under which incentives are likely to deliver genuine, additional, and durable emissions reductions while minimizing risks of technological lock-in, unsustainable imports, or resource displacement.

This integrated posture is not incidental: for transition-enabling fuels, environmental performance and financial feasibility are co-determinants of technological choice. A process that scores well in a laboratory LCA but cannot secure finance, offtake, or compliance will not mobilize meaningful decarbonization; conversely, a process that scales without credible life-cycle accounting risks undermining both climate goals and public trust. The dissertation therefore treats verifiability as a first-class design criterion. Claims of sustainability are traced to inventory data, impact models, and auditable frameworks; results are reported with transparent assumptions and uncertainty bounds; and interpretation is consistently tied back to policy design features that can influence real-world outcomes (e.g., MRV scope, allocation guidance, additionality rules, and how reference prices or penalties are set and updated).

Intended contributions.

The work aspires to contribute along three axes.

1. Technical evidence. It provides a transparent, scenario-rich LCA of UCO-based SAF, identifying drivers of performance and conditions for robustness across multiple impact categories, with explicit attention to hydrogen provision, electricity mix, and logistics.
2. Analytical bridging. It demonstrates how LCA outputs can inform policy and finance inputs—for instance, by linking allocation choices and co-product treatment to eligibility criteria, or by showing how MRV and reference-price frameworks can better reflect process realities and data uncertainty.
3. Decision-oriented guidance. It distils actionable levers—hydrogen sourcing pathways, logistics optimization, co-product valorization, data quality and traceability—that engineers, policymakers, and investors can deploy to accelerate deployment while safeguarding environmental integrity.

Structure of the dissertation.

The Introduction situates the research within the broader challenge of aviation decarbonization and outlines objectives and approach.

Chapter 1 presents the foundations of Sustainable Aviation Fuels (SAF), including standards and drop-in certification (ASTM D7566 → D1655), the main technology families with emphasis on HEFA/HVO from used cooking oil (UCO), and the EU policy and market architecture (ReFuelEU Aviation, MRV and reference prices), framing the 2024 baseline.

Chapter 2 provides the technical and environmental assessment of the UCO→SAF pathway via HEFA/HVO in the Italian context. It documents process fundamentals and pre-treatment requirements, defines the modelling framework and scenarios, and reports the LCA results and interpretation against fossil kerosene.

Chapter 3 addresses scale-up constraints by integrating compliance requirements, logistics and market design. It analyses alternative supply-chain and blending topologies, evaluates policy/finance instruments (market-only, grants and contracts-for-difference), and reports sensitivity and risk implications for feasibility and bankability.

Chapter 4 synthesizes findings and provides conclusions and operational recommendations, emphasizing the need for technical, environmental and institutional coherence to enable credible SAF deployment.

The **Appendix** reports the detailed LCA methodological framework, inventory structures, impact-assessment methods and data sources.

Ultimately, this thesis is an argument for coherence—technical, environmental, and institutional. If decarbonizing aviation is in part a problem of chemistry and thermodynamics, it is equally a problem of incentives and governance. By situating rigorous life-cycle evidence within the current EU market and funding logic, and by treating verifiability as a design constraint rather than an afterthought, the work aims—however modestly—to help design aviation fuel systems that are environmentally sound, economically sensible, and institutionally credible.

Chapter 1.

Sustainable Aviation Fuels (SAF): Foundations, Standards, Processes, Policy & Market

Among near-term levers for deep decarbonization in hard-to-abate sectors, Sustainable Aviation Fuels (SAF) are poised to remain the primary driver of emissions reduction in aviation, because they are (partially) drop-in and can leverage existing aircraft, storage and hydrant infrastructure without requiring fleet replacement [1].

The first EU-wide baseline under ReFuelEU Aviation (reporting year 2024) confirms a market that is nascent but measurable: 32.1 Mt of aviation fuels placed on the Union market, of which ~192.7 kt qualified as SAF (~0.60% by mass). Deliveries occurred at 33 airports across 12 Member States, with strong supplier concentration (fewer than ten suppliers accounting for ~80% of SAF volumes) [1]. Such concentration and the operational need to maintain strict fuel quality and specification integrity explain why early diffusion is hub-centric and accompanied by conservative quality-assurance practices and tight chain-of-custody controls [1,2].

From a supply-side perspective, feedstock availability and traceability shape the feasible growth path. In 2024, EU SAF supply was overwhelmingly lipid-based: used cooking oil (UCO) and waste animal fats (Cat. 1–2) contributed ≈98% of inputs, with UCO alone ≈81%. Critically, ~69% of feedstock originated outside the EU, underscoring import dependence and the need for robust MRV, fraud-prevention and documentation as volumes scale [1]. National governance platforms (e.g., ENAC – Osservatorio SAF) mirror this Union-level trajectory by coordinating stakeholders, aligning reporting practices and disseminating technical guidance to safeguard integrity along expanding supply chains [2]. In parallel, the reference-price gap that currently separates aviation biofuels (~€2,085/t) from conventional aviation fuel (~€734/t) in 2024 frames both penalty exposure and support calibration and therefore conditions the bankability of offtake structures and project FIDs [1].

Within the broader energy-transition portfolio, SAF operate alongside advanced biofuels, synthetic e-fuels (PtL) and hydrogen, but they are the only lever capable of delivering near-term, well-to-wake reductions at fleet scale, thanks to certification via ASTM D7566 (annex-specific pathways) and drop-in blending under ASTM D1655 [1]. EASA's 2030 capacity outlook indicates potential for bio-derived SAF in the ~1.4 Mt (Operating), ~3.6 Mt (Realistic) and ~5.2 Mt (Optimistic) ranges, with ~0.7 Mt of synthetic aviation fuels in a high-credibility announcements case; at the same time, delays and cancellations observed in several synthetic projects underline the need for FID-enabling finance and coordinated infrastructure (renewable electricity, CO_2 logistics) to unlock the promised volumes [1]. This supports a time-sequenced portfolio: deploy HEFA/HVO now to harvest immediate reductions and operational learning; mature advanced bio routes to ease lipid constraints; and de-risk PtL/hydrogen for post-2030/2040 horizons, embedding complementarity (and avoiding lock-in) in targets, MRV and support instruments [1,2].

Methodologically and from a compliance standpoint, LCA is not ancillary: under ReFuelEU's MRV spine, the foreground inventories (collection, pre-treatment, hydroprocessing, blending), co-product allocation choices and impact-assessment parameters become audit-relevant artifacts that must remain decision-grade as supply chains diversify [1,4]. Chapters 2 of this dissertation therefore formalize the LCA framework for UCO→HEFA/HVO, quantify the influence of hydrogen sourcing, electricity mix and logistics, and articulate uncertainty/sensitivity around allocation and background datasets, aligning scientific rigor with regulatory needs [4]. Finally, consistent with evidence from other energy-intensive transitions, capex-heavy, first-of-a-kind SAF assets can be rendered bankable when eligible-cost grants tied to verified abatement (Innovation-Fund-like logic) close the reference-price gap—an approach that, while demonstrated in different industrial settings, is structurally transferable to SAF under robust MRV [3].

Objective of this section. Considering the above, the objective of the opening chapter is to provide a system-level understanding of the SAF value chain and its function in the EU decarbonization pathway. Section 1.2 reconstructs the historical emergence and certification logic that enable drop-in deployment (ASTM D7566/D1655), Section 1.3 positions SAF within the integrated portfolio (advanced bio, PtL, hydrogen) with explicit 2030 capacity ranges and cost signals, and Section 1.4 details the UCO→HEFA/HVO process fundamentals (feedstock quality, pre-treatment, hydroprocessing, blending, QA/QC).

These foundations then connect directly to the LCA methods (Appendix) and to the policy–finance analysis, ultimately informing the integrated discussion on complementarity/lock-in and a sequenced, credible decarbonization roadmap for aviation [**Section 1.4**] [1–4].

1.1 Foundations and Context for Sustainable Aviation Fuels (SAF)

Aviation is a paradigmatic hard-to-abate sector. Aerothermodynamic constraints, uncompromising safety and certification requirements, and global interoperability of fuel logistics narrow the feasible design space for decarbonization. Any solution that hopes to achieve near-term impact must be drop-in (or at least partially drop-in): compatible with the in-service fleet, airport storage, hydrant networks and quality assurance regimes, such that well-to-wake reductions materialize without waiting for slow, capital-intensive fleet turnover [1]. Within this constrained space, Sustainable Aviation Fuels (SAF) stand out as the most credible lever for the 2020s: they are already covered by a European regulatory architecture—ReFuelEU Aviation—with harmonized MRV, a documented reference-price methodology, and clear roles for suppliers, aircraft operators and airports in monitoring and verification [1].

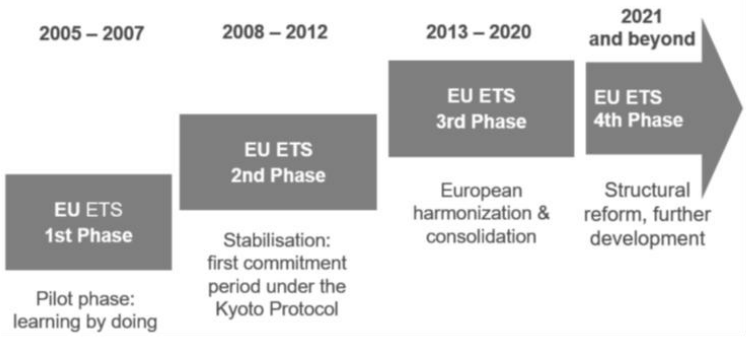


Figure 1. *EU SAF market 2024 snapshot [5]*

The Union-wide baseline (reporting year 2024) quantifies a market that is small but real: 32.1 Mt of aviation fuel placed on the EU market, of which ~192.7 kt qualified as SAF (~0.60% by mass). Deliveries occurred at 33 airports across 12 Member States. Supplier concentration is pronounced—< 10 suppliers account for ~80% of SAF volumes—while the feedstock mix is overwhelmingly lipid-based, with UCO ~81% and most of the remainder Category 1–2 animal fats. Crucially, ~69% of feedstock originated outside the EU, heightening the importance of traceability, chain-of-custody and fraud-prevention as volumes expand [1]. At national level, governance platforms such as ENAC's Osservatorio SAF coordinate stakeholders, align reporting practices and disseminate technical guidance to reinforce data integrity and quality assurance along the expanding supply chain [2].

Table 1. *KPI per Aircraft Operators (AO)[EMSA]*

KPI Category	KPI (code — title)	Description
Reporting Status	AO1 — Reporting status of aircraft operators reporting at Union level	Percentage at Union level of aircraft operators that submitted reports.
Anti-tankering Status	AO2.1 — Total fuel uplifted versus 90% of fuel required at Union level	Level of uplifts of all RFEUA aircraft operators departing from Union airports.
Anti-tankering Status	AO2.2 — Fuel uplifted versus the 90% of fuel required obligation in the Union airports	Level of uplifts of all RFEUA aircraft operators departing from Union airports.
SAF Purchased Summary	AO3.1 — Amount of SAF purchased at Union level	Information on SAF purchased as reported by the AOs at Union level.
SAF Purchased Summary	AO3.2 — RFEUA eligible fuel category	Information on SAF purchased as reported by the AOs at Union level.
SAF Purchased Summary	AO3.3 — SAF claimed by MBM scheme	Information on SAF purchased as reported by the AOs at Union level.

Table 2. *KPI per Aviation Fuel Suppliers (FS)[6]*

KPI Category	KPI (code — title)	Description
Reporting Status	FS1 — Reporting status of aviation fuel suppliers at Union level	Percentage at Union level of aviation fuel suppliers that submitted reports.

Aviation Fuel and SAF Supply	FS2.1 — Aviation fuel supplied at Union level	Amount of aviation fuel reported as supplied by aviation fuel suppliers at Union level.
Aviation Fuel and SAF Supply	FS2.2 — SAF supplied at Union level	Amount of SAF reported as supplied by aviation fuel suppliers at Union level.
Aviation Fuel and SAF Supply	FS2.3 — Historical % SAF supplied at Union level	% SAF compared to aviation fuel at Union level (historical share).
SAF Characteristics	FS3.1 — SAF supplied per category of RFEUA eligible aviation fuel at Union level	Category breakdown of RFEUA-eligible aviation fuels supplied at Union level.
SAF Characteristics	FS3.2 — Feedstock origin of SAF supplied at Union level	Origin of feedstocks used to produce SAF supplied at Union level.
SAF Characteristics	FS3.3 — Feedstock composition of SAF supplied at Union level	Composition of feedstocks used to produce SAF supplied at Union level.
Emission Savings	FS4 — SAF CO_2e savings at Union level	CO_2e savings of SAF supplied at Union level.
Aviation Fuel Composition	FS5 — Aviation fuel composition at Union level	Content of aromatics, naphthalenes and sulphur in aviation fuel supplied at Union level.

In portfolio terms, SAF sit alongside advanced biofuels (FT-SPK, ATJ-SPK), synthetic e-fuels (PtL e-kerosene), and hydrogen. EASA's 2030 capacity outlook suggests bio-SAF could reach ~1.4 Mt (Operating), ~3.6 Mt (Realistic) and ~5.2 Mt (Optimistic), with ~0.7 Mt of synthetic aviation fuels in a high-credibility announcements case; however, observed delays and cancellations in several synthetic projects highlight the need for FID-enabling finance and coordinated infrastructure (renewable power build-out and CO_2 supply/logistics) [1]. The time-sequenced logic is therefore clear: deploy HEFA/HVO from residues now to secure early, certifiable reductions; develop advanced bio routes to ease lipid constraints; and de-risk PtL/hydrogen for the 2030–2040 horizon, embedding complementarity (and avoiding lock-in) within targets, MRV and support instruments [1,2,6].

Methodologically, the LCA evidence base is not ancillary under ReFuelEU. Foreground inventories (collection, pre-treatment, hydroprocessing, blending), co-product allocation choices and LCIA methods are audit-relevant artifacts that shape eligibility, penalties and access to support/finance. The dissertation will therefore use a compliance-grade LCA framework, closely aligned to MRV, to ensure transparency over allocation, data pedigree and uncertainty/sensitivity [1,4, 7].

Cross-sector experience shows that eligible-cost grants tied to verified abatement—Innovation-Fund-style—can shift high-CAPEX decarbonization bundles from negative IRR/NPV to bankable; by design, this logic is transferable to FOAK SAF when MRV is robust [3,6].

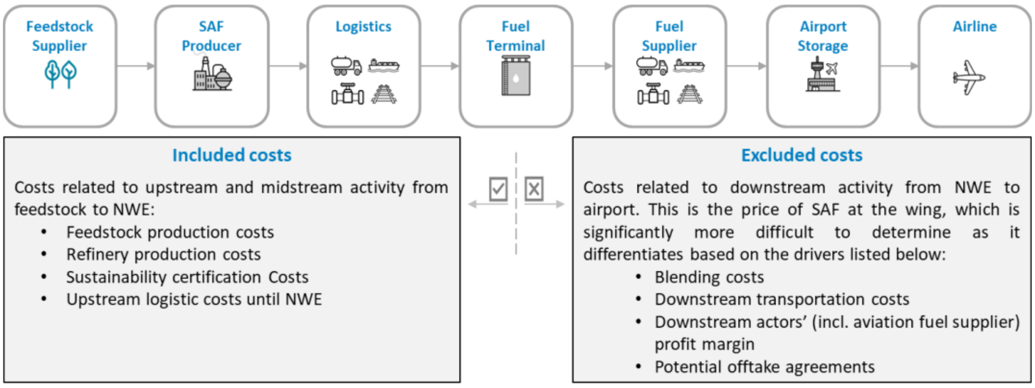
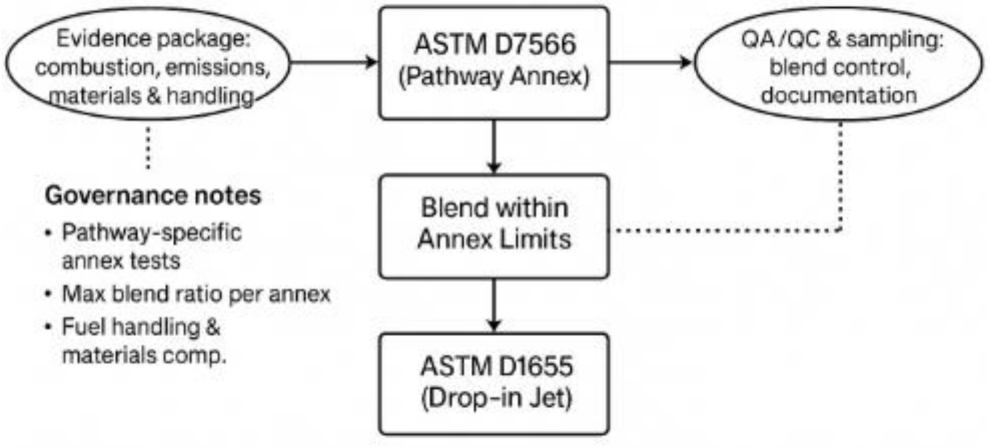


Figure 2. *2024 reference prices – inclusioni/esclusioni (PRA) [EMSA]*

1.2 Historical Evolution, Standards and Drop-in Certification (ASTM D7566 → D1655)

The modern era of aviation fuels is built on standards that ensure safety, materials compatibility and global operability. Alternates enter the system through ASTM D7566—which lists annex-specific pathways and their technical evidence—and become drop-in under ASTM D1655 when blended within prescribed limits.



Certification flow from ASTM D7566 (pathway annex) to ASTM D1655 (drop-in jet) via controlled blending, with evidence and QA/QC checkpoints.

Figure 3. *ASTM D7566 → D1655 flow*

The evidence packages cover combustion/emissions, thermal stability, materials compatibility (including seal swell and elastomer performance), storage/handling and documentation traceability [1]. This rigorous gatekeeping enables near-term decarbonization at fleet scale without compromising safety or reliability.

Relevant certified pathways. In the near term, HEFA/HVO from lipid residues (UCO, Category 1–2 animal fats) is the workhorse: operational, certifiable and technically compatible with existing infrastructure, albeit constrained by residue availability and hydrogen intensity [1,4]. Advanced bio routes—FT-SPK and ATJ-SPK—expand the resource base (lignocellulosics, alcohols) but entail more complex logistics and pre-treatment [9-10]. Synthetic aviation fuels (PtL e-kerosene) promise deep cuts in life-cycle emissions but hinge on the build-out of renewable electricity, the availability and quality of CO_2, and the translation of announcements into FID and steel in the ground. Because paraffinic SAF are intrinsically low in aromatic compounds, blend-ratio management is essential to preserve elastomer compatibility; as volumes scale, out-of-spec risk rises (processing deviations, co-mingling, documentation errors), which is why EASA emphasizes proactive QA/QC, sampling plans, and document coherence along the chain [1].

Table 3. *ReFuelEU categories and ASTM linkage [8]*

Category (ReFuelEU)	**Example pathways**	**ASTM D7566 status**	**Drop-in (D1655)**	**MRV/Key notes**
Aviation biofuels	HEFA/HVO (UCO, animal fats)	Annex certified	Yes (blend limits)	MRV on feedstock/volumes/GHG [1,6]
Advanced biofuels	FT-SPK, ATJ-SPK	Annex certified	Yes (limits)	More complex supply chains [1]
Synthetic aviation fuels	PtL e-kerosene	Annex certified	Yes (limits)	High RE/CO_2 needs; FID bottlenecks [1]
Co-processing	Refinery co-processing	Dedicated rules	Yes (eligible share)	Strict mass-balance/accounting [1]

1.3 SAF Technology Landscape with Focus on UCO→HEFA/HVO Process Fundamentals

Catalyst families and hydroisomerization severity (impact on cold-flow).

Industrial HEFA/HVO relies on bifunctional systems in which a hydrogenation/dehydrogenation metal (e.g., Ni–Mo, Co–Mo, or Ni–W, often in sulphide form) acts in synergy with an acid function on the support (typically γ-Al_2O_3 or aluminosilicates) to enable deoxygenation (HDO), isomerization, and selective cracking. Isomerization severity (temperature, H_2 partial pressure, space velocity, support acidity) controls the degree of paraffinic branching: a well-tuned severity increases the cetane index and reduces T_{10}/T_{50} across middle distillates, but most importantly lowers CP/PP/CFPP (cloud/pour/cold-filter plugging points) by converting n-paraffins into iso-paraffins with lower melting points. Excessive severity, however, drives over-cracking (loss of jet yield, shift to lighter fractions) and promotes coke precursors on acid sites, with consequences for cycle length and stability. The design compromise aims to maximize useful branching while preserving cut selectivity in the jet range, typically by modulating upstream hydrotreating to stabilize the feed (FFA, reactive oxygenates) [11]. In practice, HEFA units commonly employ split reactor beds (HDO→isomerization) and inter-bed quench to manage temperature profiles and selectivity, while Ni–W/Al_2O_3 is frequently selected where cold-flow is prioritized for the jet pool; more acidic supports (e.g., certain zeolites) demand tight severity control to avoid undesired cracking [12].

Cold-flow engineering and cut selectivity.

The jet target (roughly C_8–C_{16}, with specification-dependent windows) requires a severity design that increases C_{10}–C_{14} branching while minimizing drift toward C_7–C_8 (naphtha losses) and C_{15}+ (diesel pull). The HDO→isomerization→selective cracking sequence is orchestrated to:

(i) saturate unsaturates,
(ii) isomerize n-paraffins to reduce jet-blend CFPP,
(iii) trim high-melting tails. In operation, high H_2/HC and limited ΔT help preserve selectivity; the acidity distribution (strength/site density) governs the statistics of branching (mono- vs multi-branched), with direct effects on low-temperature viscosity and stability.

Optimizing severity windows is thus a multi-objective problem: cold-flow and freezing point (at the final ASTM D1655 blend), smoke point (low aromatics may require compensation in blending), yields (avoid over-cracking) and catalyst life (minimize coking) [13].

LCA sensitivity to H_2 sourcing and electricity mix.

In well-to-wake terms, hydrogen intensity is a primary driver of HEFA/HVO GHG footprint. If H_2 derives from unabated SMR, the upstream burden can materially erode the biogenic advantage; conversely, e-H_2 powered by a high-renewables electricity mix drastically reduces intensity but may increase pressure on non-climate categories (e.g., minerals/metals depletion for electrolysers and renewables), as already observed in system-level LCAs. Sensitivity to electricity mix (marginal vs average emission factors, hour-by-hour vs annual) and to H_2 route (SMR, SMR+CCS, grid-connected e-H_2) should be handled through parametric scenarios and explicit uncertainty analysis (e.g., pedigree matrices and Monte Carlo), with transparent allocation rules (energy-, mass- or economics-based) among co-products (propane, naphtha, diesel), given the strong influence of these choices on per-FU indicators. In line with a compliance-grade LCA, this work will adopt MRV-coherent boundaries (traceable foreground: UCO collection, pre-treatment, HDO/isomerization/cracking, fractionation, blending; declared background datasets), and will implement robustness tests on H_2 and electricity mix to quantify the elasticity of results and prevent policy-relevant misinterpretation [14].

Table 4. *HEFA/HVO: key inputs/outputs and LCA/MRV control points*

Stage	Inputs/conditions	Outputs/specs	Critical LCA/MRV points
Collection/Logistics	UCO/animal fats; transport routes	Crude UCO	Distances/origins; fraud-risk windows
Pre-treatment	Degumming/neutralization; drying; filtration; adsorption	Conditioned UCO	FFA/metals control; waste handling
HDO→Isomerization→Cracking	H_2; catalysts; utilities	Paraffinic SBC	H_2 intensity; efficiency; catalyst life
Fractionation & QC	Columns; analytics	On-spec distillate cuts	Cold-flow; stability; QA routines
Blending D7566→D1655	SBC + conventional jet	Drop-in jet	Documentation & sampling; blend-ratio

1.4 EU Policy & Market Architecture (ReFuelEU, MRV, Reference Prices) and 2024 Baseline

ReFuelEU architecture and MRV spine.

ReFuelEU establishes minimum shares and eligible sub-categories, placing primary obligations on fuel suppliers and defining reporting/verification for aircraft operators and airports. The EASA Annual Technical Report operationalizes the architecture with templates, a market overview, and a reference-price methodology that informs penalties and calibrates interfaces with EU ETS and Member-State instruments [1]. This aligns finance (offtakes, risk-sharing) with verification (volumes, categories, feedstock origin, GHG performance), making compliance economics observable and bankability assessable [1,2].

Reference-price gap and bankability.

In 2024, aviation biofuels ≈ €2,085/t versus conventional aviation fuel ≈ €734/t; where no liquid indices exist, bottom-up costing applies (FOAK/early-scale) [1]. The gap justifies calibrated support (grants, CfDs, ETS-linked) and risk-sharing across the chain, shaping FID probability [1,3].

2024 baseline and operational implications.

A hub-centric pattern (33 airports / 12 MS; few dominant suppliers) initially simplifies oversight but requires scaled QA/QC and data systems as distribution widens. High UCO (~81%) and non-EU origin

(~69%) shares demand reliable chain-of-custody, sampling regimes and documentation coherence to preserve environmental integrity and public trust [1,2].

Key 2024 system indicators relevant for compliance planning are consolidated in Table 3, while Figure 1.4 illustrates the reference-price gap that drives penalties and support calibration.

Table 5. *Market & governance 2024: system indicators for empirical planning.*

Indicator	2024 value	Implication
Total fuel placed	32.1 Mt	Residual fossil dominance
SAF placed	~192.7 kt (0.60%)	Early but measurable market
Airports / MS supplied	33 / 12	Hub-centric diffusion
UCO share	~81%	Lipid feedstock constraint
Non-EU origin share	~69%	Traceability & risk exposure
Supplier concentration	< 10 suppliers ≈80% of SAF	QA/QC governance priority

Mini-case: MRV data flow (supplier → airport → operator → verifier).

Under ReFuelEU, data are the first regulated object.

1. Supplier → Airport. The supplier provides volumes by category (e.g., HEFA/HVO, advanced bio, synthetic), blend ratios, feedstock-origin documents (UCO/animal fats, EU/non-EU origin), and GHG performance computed via recognized methods; the airport operator records receipt, maintains chain-of-custody (mass balance, co-mingling) and enables sampling/QA/QC to prevent out-of-spec events and documentary inconsistencies.
2. Airport → Operator. Fuel injected into the hydrant system or refuellers is accountably allocated to operators based on uplift; the allocation book preserves eligible categories and volumes for each refuelling operation, avoiding double counting.
3. Operator → Verifier. The operator aggregates, for the reporting period, purchased and used volumes by ReFuelEU categories, associated GHG, and supporting documents; an independent verifier assesses coherence and completeness (volumes, categories, origins, GHG performance), checking alignment across delivery notes, blending records, sampling results, MRV statements and mass-balance accounting. Feedback loop. Non-conformities (e.g., category/volume mismatches, traceability gaps, lab vs declared discrepancies) trigger corrective actions, with potential impacts on penalties, eligibility, and the final compliance report [1].

This replicable, auditable micro-workflow is the backbone that makes compliance economics observable and enhances bankability (verifiable data → lower risk on payments and penalties) [1].

EU ETS interactions (accounting linkages).

The ReFuelEU ↔ EU ETS interface operates on two planes:

(i) accounting of net reductions for meeting aviation-sector obligations
(ii) the impact of relative prices (penalties vs support) on an operator's multi-instrument optimization. Because ReFuelEU makes volumes and categories measurable under harmonized MRV, a carrier can integrate the SAF lever into its ETS portfolio, evaluating—at the margin—whether an incremental SAF penetration point (with its reference-price gap) is economically preferable to alternative ETS compliance strategies (allowance purchases, operational efficiencies, network management).

System coherence depends on maintaining clear accounting lines (avoid double-counting of benefits), aligning emission factors, and ensuring documentary interoperability between ReFuelEU statements and ETS reporting. In practice, the EASA ATR provides the price spine and templates that enable consistent tracking—prerequisites for realistic modeling of combined compliance cost (penalty-aware) and for negotiating offtake contracts with risk-sharing clauses that reflect actual regulatory exposure [1].

Chapter 2.

UCO to SFA via HEFA/HVO Process, Logistic and Environmental assessment

The conversion of used cooking oil (UCO) into synthetic paraffinic jet fuel via HEFA/HVO sits at the crossroads of catalytic reaction engineering, product-quality compliance, and system-level environmental performance. In technical terms, the pathway comprises a tightly coupled sequence—hydrogenation and hydrodeoxygenation/decarboxylation (HDO/DCO/DCO_2), followed by isomerization (and, where needed, selective cracking)—that transforms an oxygenated, compositionally variable lipid feed into a low-aromatic, paraffinic jet stream suitable for drop-in use after blending within ASTM D7566 annex limits to enter the ASTM D1655 fuel pool. This catalytic choreography is constrained by thermochemistry (exothermic oxygen removal, heat management), kinetics (rate/selectivity under real-feed impurities), and fuel specifications (cold-flow, smoke point, density), so that process severity, hydrogen management and blend-ratio control become co-optimized design variables rather than independent knobs.

From a feedstock perspective, UCO is a residue stream with heterogeneous quality (FFA, moisture, trace metals) and dispersed logistics. These features shape both pre-treatment envelopes (degumming/neutralization, drying, fine filtration/adsorption) and catalyst exposure, with direct consequences for deoxygenation routes (HDO vs DCO), hydrogen consumption, hot-spot risk and deactivation modes. On the product side, the overarching problem is cold-flow engineering: the isomerization section must introduce the right degree and pattern of branching across the C_8–C_{16} jet range to meet CFPP/FP/CP and smoke/aromatics requirements while preserving jet yield and avoiding over-cracking to light ends. The result is a multi-objective design that links catalyst families and supports (e.g., Ni–Mo/Co–Mo/Ni–W on γ-Al_2O_3 or mildly acidic aluminosilicates), reactor operation (H_2/HC ratio, inter-bed quench, heat integration), and quality assurance (QA/QC sampling, off-spec mitigation loops) to the certification interface (D7566→D1655).

Critically, the life-cycle performance of UCO→SAF is governed by a small set of dominant drivers that extend beyond the reactor balances. Chief among them are hydrogen sourcing (SMR vs SMR+CCS vs grid-electrolysis vs high-renewables electrolysis) and the electricity mix that powers auxiliaries and H_2 compression; second-order yet material influences arise from UCO collection density and transport, pre-treatment utilities, and co-product allocation across propane, naphtha, diesel and jet. Consequently, process choices that are attractive on purely thermal grounds—e.g., raising isomerization severity to enhance cold-flow—can become environmentally consequential once hydrogen intensity or utility demand shifts are propagated through the LCA foreground. Because your research is policy-relevant and must interface with compliance reporting, we report results transparently within this chapter and place the full ISO 14040/44 methodology (goal/scope details, inventory tables, characterization and uncertainty treatment) in the Appendix, preserving both readability and reproducibility.

Against this background, **Section 2.1** establishes the state of the art and process overview required to read the chapter. We start from feedstocks and pre-treatment (UCO specification envelopes, quality assurance and the protection of catalytic function), proceed through hydrotreating mechanisms (HDO/DCO/DCO_2 under realistic impurity loads and exothermicity control), and close with the isomerization/selective-cracking problem as a fuel-property design exercise (how branching distributions govern cold-flow and smoke under ASTM D7566 annex constraints prior to D1655 drop-in). Figures ported from your article (process scheme; hydrogenation and isomerization motifs) anchor this section visually.

Section 2.2 then details the materials and methods used at chapter level—not the full LCA standard, which is deferred to the Appendix. We succinctly restate goal, scope and functional unit (FU = 1,000kg jet, blend-ready), delineate the system boundaries for the UCO→HEFA/HVO train (cradle-to-gate to airport gate; well-to-wake only for the fossil comparator), and document two essential building blocks:

(i) the UCO logistics model for Italy (collection macro-areas, routing, annual kilometres and loads),
(ii) the process inventories (mass balance, hydrogen and utility requirements) used to compute indicator values.

This section includes the mass/utility tables and the Italian collection maps/plots directly drawn from your article, ensuring one-to-one traceability between text and figures.

Section 2.3 presents the results and discussion. First, we report contribution analyses for $PM_{2.5}$ formation and global warming along the UCO→SAF chain, highlighting the dominance of H_2 production (for PM and GWP) and the role of thermal/electric utilities in the conversion steps. Second, we summarize the fossil kerosene baseline used for comparison (consistent datasets), and then provide two comparative assessments that match the scenarios in your article: a real-case (~80 kt y^{-1} UCO collected) and an ideal-case (~260 kt y^{-1}).

The corresponding figures reproduce the absolute indicators ($PM_{2.5}$eq; CO_2eq) as in your study, and the narrative closes with an interpretive paragraph that links the observed deltas to the hydrogen/electricity levers and to blending/cold-flow choices documented earlier—preparing the ground for the economic/regulatory expansion of Chapter 3.

Finally, **Section 2.4** distils conclusions specific to the technical and environmental scope of this chapter:

(i) the conditions under which UCO→HEFA/HVO achieves robust climate and air-quality gains over fossil kerosene;
(ii) the operational and logistics levers with the largest marginal improvement potential (H_2 route, electricity mix, collection density);
(iii) the implications for scale-up that motivate the transition to **Chapter 3** (how reference prices, penalties/supports, and MRV-coherent data flows interact with the technical reality shown here).

2.1 State-of-the-art and process overview

Scope and positioning.

This section frames the technical perimeter of the UCO-to-SAF pathway via HEFA/HVO, situating it at the intersection of catalytic conversion, product-quality assurance, and certification [18].

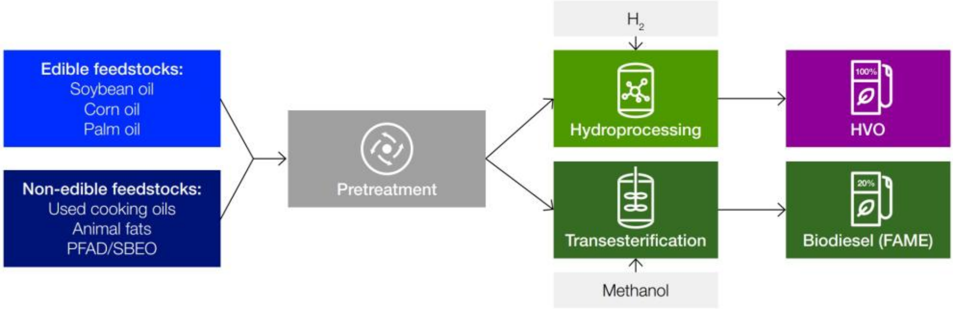


Figure 4. *HVO/SAF production scheme*

The objective is to equip the reader with a concise but complete "grammar" of the route—what the train looks like, which functions each unit performs, how the stream becomes eligible for aviation—so that the detailed discussions on feedstock/pre-treat (2.1.1), hydrotreating/deoxygenation (2.1.2), and isomerization & blending (2.1.3) can be read without back-tracking.

From residue to synthetic blending component.

Used cooking oil (UCO) is a post-consumer lipid residue characterized by compositional variability (free fatty acids, water, insolubles, trace metals and polar species) [19]. After a pre-treatment envelope that stabilizes quality and protects catalysts, the stream enters a refinery-like HEFA/HVO train comprising [20]:

(1) Hydrogenation of unsaturates;
(2) Deoxygenation through a network of HDO/DCO/DCO_2 reactions, yielding paraffinic hydrocarbons plus coproducts (notably propane) and light gases;
(3) Isomerization—a bifunctional step that introduces controlled branching in the C_8–C_{16} window to meet cold-flow targets; optionally,
(4) selective cracking to trim the heavy tail;
(5) fractionation into LPG/propane, naphtha, jet and diesel cuts, followed by blending of the jet synthetic blending component (SBC) within the prescribed limits of ASTM D7566.

Table 6. *HEFA/HVO train: unit function, primary risks, quality outputs*

Unit operation	Primary function	Main technical risks	Quality/operability output
Pre-treatment	Remove water, solids, P, Na/K, soaps/colloids	Catalyst poisoning, ΔP instability if insufficient	**Gate-spec feed** with stabilized variability [20-21]
Hydrotreating (HDO/DCO/DCO_2)	Saturation + oxygen removal (→ paraffins, H_2O/CO/CO_2)	Exotherm/hot-spots, coking, deactivation	**Paraffinic base** suitable for downstream shaping [18]

Isomerization (± mild cracking)	Branching to meet cold-flow; limit over-cracking	Yield erosion if over-severe; utility load	**Jet-grade properties** achievable at target severity [14]
Fractionation	Stabilize cuts; enable recycle	Off-spec side streams if cut points drift	**Consistent slate** (LPG, naphtha, jet, diesel) [22]
Blending (D7566)	Bring SBC within annex limits	Out-of-spec pool if mis-blended	**Drop-in** under **ASTM D1655**

Once blended and pool-compliant, the fuel is governed by ASTM D1655 (i.e., drop-in). This sequence is not a loose list of operations: each step solves a specific incompatibility of the incoming residue with aviation requirements and sets constraints for the next one (e.g., pre-treat quality determines exotherm and deactivation risk in HDO; isomerization severity and blend ratio co-determine cold-flow and density) [23].

Why HEFA/HVO for aviation.

Among lipid conversion routes, HEFA/HVO stands out for technical readiness, product stability (paraffinic, essentially sulfur-free), and compatibility with existing infrastructure [24]. For aviation, the challenge is not only to obtain paraffins, but to engineer the distribution of branching and carbon numbers so that freeze point, CFPP/CP, smoke point, and density fall within aviation envelopes without creating excessive over-cracking to C_5–C_7. Because HEFA jet is extremely low aromatics [13], the blend window under D7566 makes density and smoke point the practical guard-rails of product engineering: isomerization severity and blend percentage must be tuned together to ensure airworthiness while preserving yield.

Process–quality–inventory handshake.

Three couplings matter at overview level and motivate how the chapter is organized:

- Process → Quality. Pre-treat specifications (water, P, Na/K, insoluble [25]) and reactor settings (H_2/HC, pressure, WABT, LHSV, quench) determine selectivity, hot-spot risk, coking, and the raw property base that isomerization will refine [26].
- Quality → Certification. The pathway is certified under ASTM D7566; the SBC becomes drop-in only after blending within the annex limit and verification of pool specs (ASTM D1655). Hence, QA/QC discipline (sampling, CoA, off-spec loops) is a first-order technical requirement, not mere paperwork.
- Process → Inventory (for LCA). Foreground choices (e.g., deeper isomerization to push cold-flow) have inventory echoes (utilities, yield shifts). While the sourcing of hydrogen and electricity is treated later with results, here we note that operating envelopes and pre-treat intensity are the levers through which plant reality enters the life-cycle model.

Industrial architecture and operability.

Commercial HEFA trains adopt multibed trickle-flow reactors with inter-bed quench and gas recycle to manage exothermicity and protect catalyst life [21]. The fractionation section provides operability by carving the slate into stabilized cuts and enabling recirculation/rework of off-spec side-streams. A guard-bed philosophy upstream of the hydrotreating reactor (sacrificial sorbents for P/Na/K/Cl) is standard good practice. At system level, units are designed to swing toward jet or diesel according to economics and policy signals, within the certification constraints—an aspect that later affects co-product allocation in the environmental assessment.

Data governance and QA/QC spine.

Because the product crosses a standards boundary (D7566 → D1655), the chain must be stitched together by a documentation spine: pre-treat gate specs and batch IDs; unit logbooks (temperatures, pressures, hydrogenation/deoxygenation progress); isomerization property checks (freeze point, CFPP/CP, density, smoke point); fractionation mass balances; and a blend log that records the SBC percentage and the annex invoked. This is the same data backbone used later for MRV-ready claims and for reconciling plant mass balances with airport delivery and operator records.

This section frames the HEFA/HVO route from used cooking oil (UCO) to synthetic paraffinic jet fuel (SAF), highlighting:

(i) feedstock reality and pre-treat needs,
(ii) core reaction train (hydrogenation + HDO/DCO/DCO_2 → isomerization → optional cracking → fractionation/blending),
(iii) the standards pathway that admits HEFA synthetic blending components (SBCs) into the aviation fuel pool (ASTM D7566 annex → D1655 drop-in) [1,6].

The approach is consistent with your doctoral article: UCO is classified as a waste, must be pre-treated, and then processed in an HEFA/HVO train; the environmental assessment complements process analysis by comparing to fossil kerosene and explicitly modeling Italian UCO logistics [1,17–19].

2.1.1 Feedstocks and pre-treatment of UCO

Used cooking oil (UCO) is not a merely inferior substitute for virgin lipids; it is a residue with a memory. Every frying cycle leaves behind a chemical signature—hydrolysis of triglycerides into free fatty acids (FFA), thermal oxidation to peroxides and aldehydes, polymerization to oligomers, emulsified fines from food, traces of detergents and metal ions. When such a stream enters a HEFA/HVO value chain, the first engineering obligation is not to refine in the conventional sense, but to erase that memory to the extent required by reactor stability and catalyst life [20]. In practice, this means delivering to the hydrotreating inlet a feed whose variability has been collapsed into a narrow window of moisture, FFA, phosphorus, alkali/alkaline-earth metals and suspended solids—what operators simply call gate specifications. Outside that window, trickle-bed hydrotreaters behave like sensitive calorimeters: water flashes amplify exotherms; soaps and fines drive pressure-drop growth; phosphorus and alkali gradually neutralize acid function and poison metal ensembles.

Inside the window, the same reactor becomes predictable—hot spots are quenched effectively, ΔP trends are flat, and the deoxygenation network proceeds with the selectivity the downstream plant was designed for.

The reason UCO requires this discipline is as much physical as it is chemical. Physically, UCO is a non-uniform emulsion; even after stratification in storage, microscopic water and colloid domains persist and travel into the bed unless actively removed. Chemically, the polarity spectrum is wide: from neutral paraffins to highly polar phospholipids and partial glycerides that are extraordinary emulsifiers. These species are precisely those that undermine interfacial phenomena in trickle flow—wetting, mass transfer, local heat removal—and thus inflate the very risks (coking, maldistribution) that shorten runs and contaminate slates. The pre-treatment envelope addresses both fronts at once: it dewaters by vacuum or inert stripping so that total water falls below the few-tenths-percent mark; it neutralizes or esterifies excess FFA to avoid soap nucleation; it degums to eliminate phosphorus down to low single-digit ppm; it adsorbs polar impurities and alkali/alkaline-earths; and it polishes with tight-cut filtration to keep insolubles in the double-digit ppm range. None of these steps is exotic, but their sequencing and operating windows are not cosmetic: they decide whether the hydrotreating bed will see a clean, easily quenchable exotherm or an erratic front that forces premature rate turn-down.

Because plants are run, not theorized, the discussion of UCO quality is incomplete without a quantitative target. Operators therefore codify the “memory erasure” into a small set of numbers that, taken together, correlate with reactor health: water < 0.1 wt%, FFA near or below 1–2 wt% (or an acid value consistent with the catalyst vendor’s tolerance), insolubles < 50–100 ppm, phosphorus < 5 ppm, Na+K < 1–2 ppm, Ca+Mg < 1–2 ppm, peroxide value < 5 meq/kg. These are not universal constants; they are engineering compromises backed by run data. Plants that stay within them tend to report longer on-stream factors, slower ΔP drift, and cleaner property trajectories downstream (freeze point and smoke point evolve monotonically with severity instead of oscillating with hidden contamination).

Table 7. *Indicative UCO gate specifications for HEFA/HVO hydrotreating [128-10]*

Parameter	Typical raw UCO	Target after pre-treat	Impact rationale
Free fatty acids (wt%)	5–20	< 1–2	Lower acid value; mitigates soap formation/corrosion
Water (wt%)	0.3–3.0	< 0.1	Protects sulfided catalysts; avoids flashing/exo-peaks
Insolubles (ppm)	500–3000	< 50–100	Prevents pore plugging/erosion
Phosphorus (ppm)	10–300	< 5	Avoids active-site poisoning/deactivation
Alkali (Na+K, ppm)	5–50	< 1–2	Preserves acid functionality/support integrity
Ca+Mg (ppm)	2–20	< 1–2	Limits soap/ash formation; protects hot surfaces
Peroxide value (meq/kg)	5–30	< 5	Limits oxidative instability and radical precursors

The mechanistic link between each impurity and each failure mode is now well understood. Water is the amplifier: it flashes in hot zones and locally boosts the apparent exotherm, encouraging hot-spot nucleation; in sulfided formulations, it also perturbs the sulphuration state. FFA are the saboteurs of hydraulics: in the presence of alkali, they form soaps, which stabilize emulsions and seed pressure-drop growth across the bed. Phosphorus is the silent poison, deactivating both metal and acid functions even at low ppm levels, while Na/K/Ca/Mg neutralize acidity and degrade support integrity. Insoluble are the mechanical threat—pore plugging, erosion and maldistribution. Peroxide value is an early warning for oxidative drift: high PV correlates with radical chemistry and coke precursors under heat. None of these pathways is dramatic in isolation; collectively, in a multibed adiabatic train, they tilt the thermal and hydraulic balances enough to turn a robust operating envelope into a narrow, fragile one.

For these reasons, effective pre-treatment is modular rather than monolithic. A typical train opens with graded filtration (coarse to fine) to quiet the hydraulics before any thermal step. Vacuum drying and/or nitrogen stripping break stubborn emulsions and pull water to the target without over-heating the matrix. Degumming/neutralization then eliminates phospholipids and pushes the acid value down [30-31]; where FFA are structurally high, front-end esterification can be more economical than aggressive caustic neutralization. Adsorption/bleaching units—activated clays, tailored aluminas, or ion-exchange resins—mop up polar residues and alkali/alkaline-earths, with predictable capture curves and replacement cycles that must appear in the plant's material balance (and, later, the foreground inventory of the LCA). Finally, polishing filtration in the 1–5 µm range is placed just before storage or charge pumps, because the last meter of pipe is where many clean feeds are re-contaminated.

Table 8. *Pre-treatment toolbox (problem → unit → expected effect)*[1]

Feed issue	Unit / Method	Operating note	Expected effect
Suspended solids & colloids	Graded filtration (coarse → fine, 50→10→5→1 µm)	Monitor ΔP; back-flush or change-out schedule	↓ Solids load; stable pressure drop across HDO bed
Emulsions & high moisture	Vacuum drying and/or inert-gas (N_2) stripping	Target water **< 0.1 wt%** at gate; avoid overheating	Prevents flash in hot zones; mitigates exotherm spikes
High FFA / high Acid Value	Neutralization (caustic) **or** front-end esterification	Choose route based on FFA and soap losses	↓ Soaps/corrosion; smoother hydrotreating hydraulics
Phospholipids / Phosphorus	Degumming + bleaching/adsorption	Track P break-through; regeneration plan	P **< 5 ppm**; protects metal/acid functions
Alkali metals (Na, K)	Ion-exchange or tailored adsorbents	Final polishing step before storage/charge	Na+K **< 1–2 ppm**; preserves acidity/support integrity
Alkaline-earths (Ca, Mg)	Ion-exchange/adsorption (as above)	Often captured in same polishing train	Ca+Mg **< 1–2 ppm**; limits ash/scale formation
Polar impurities / soaps	Bleaching earths, modified aluminas, IX resins	Define replacement/regeneration cycles in MB	Fewer emulsifiers; improved bed wetting and mass transfer
Peroxide/oxidation products	Adsorption (bleaching) + storage best practice	Control temperature/time; PV trending	↓ Coke precursors; improved stability under heat
Chlorides	Guard bed (chloride scavenger) + polishing	Sentry filter right before reactor	Protects supports and metallurgy from Cl-attack
Fines re-entrainment (last metre)	Final polishing filter (1–5 µm) at charge pumps	Place **downstream** of storage; tight sealing	Prevents re-contamination; keeps ΔP flat

What distinguishes a mature UCO pre-treat from a tentative one is not the list of unit ops—it is the governance of variability. Two practices are decisive. First, representative sampling and QA/QC: composite sampling per lot, routine Karl-Fischer for water, titrimetric or GC methods for FFA, ICP-OES for P/Na/K/Ca/Mg, peroxide value, and a chain-of-custody that ties every analysis to a batch ID.

- [1] Set gate specs alongside this toolbox (e.g., water < 0.1 wt%, insolubles < 50–100 ppm, P < 5 ppm, Na+K < 1–2 ppm, Ca+Mg < 1–2 ppm, PV < 5 meq/kg). Include **spent adsorbent/filter** handling and regeneration in the plant material balance (foreground inventory for LCA).

Second, an upstream segregation philosophy: lots are grouped by quality class (e.g., high-FFA vs standard), so that an outlier does not dilute an otherwise clean blend. Plants that do this find that the cost is recovered downstream through stable quench behavior, predictable ΔT profiles, and fewer off-spec side streams at fractionation.

Pre-treatment does not end at the fence of the pre-treat unit; it extends into storage and logistics. Because UCO is geographically dispersed, the routing model (truck capacity, average distance, backhauls) and the storage turnover at terminals influence both quality drift (peroxide rise with time/temperature) and the accounting of foreground transport burdens in the LCA. Heated storage should be as cool and as brief as possible to maintain pumpability without accelerating oxidation. Water draws and sludge removal are routine SOPs, not exceptional maintenance. In practice, a day-to-day KPI set that correlates pre-treat with reactor health includes: gate-spec compliance rate (share of lots on first pass), removal efficiencies by impurity class, adsorbent specific consumption (kg/t UCO) and regeneration cycles, drying energy (kWh/t), and—most revealing of all—ΔP trend across the first hydrotreating bed.

Finally, there is the interface with certification and MRV. Although formal blending under ASTM D7566 and pool compliance under D1655 occur later in the chain, the credibility of those steps rests on the data spine that begins here: each pre-treated lot must carry forward its CoA, its gate-spec analytics, and its batch ID so that, months later, when an airline claims a SAF share at the airport gate, the mass balance is traceable back to the very pre-treat campaign that made the hydrotreating run possible. In that sense, pre-treatment is the first link not only of process operability, but of governance—the place where a chemically unruly residue is transformed into a predictable, certifiable input for aviation.

2.1.2 Hydrotreating and deoxygenation (HDO/DCO/DCO_2)

The hydrotreating section is the conversion engine of the HEFA/HVO train: it saturates unsaturates, removes oxygen, and delivers a paraffinic base that downstream units will shape into aviation-grade properties. Chemically, UCO-derived triglycerides/FFA traverse a network where hydrogenation of double bonds precedes oxygen removal by three parallel routes—hydrodeoxygenation (HDO), decarboxylation (DCO), and decarbonylation (DCO_2). The relative weight of these routes controls hydrogen demand, carbon retention, and the product slate (e.g., propane and light gases, odd- vs even-carbon paraffins). Industrially, the sequence is strongly exothermic and run in multibed trickle-flow reactors with inter-bed quench and gas recycle, so that temperature rise and hot-spot risk are governable and the catalyst sees a stable hydraulic environment.

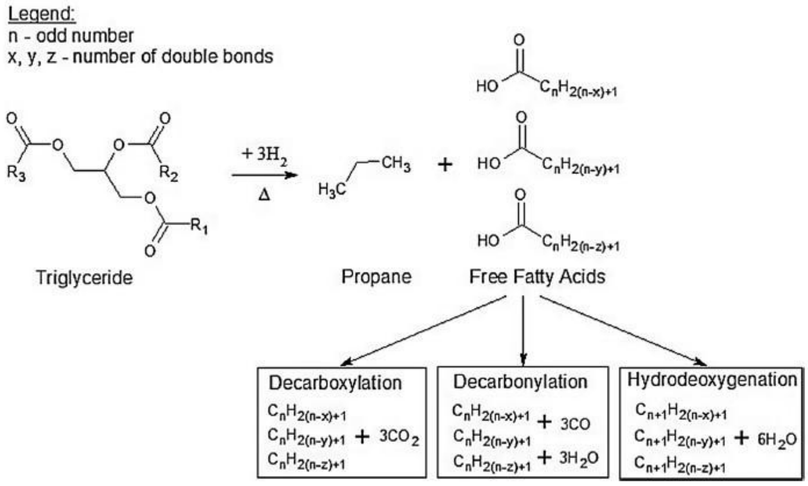


Figure 5. *Hydrogenation reaction [Richter et al.,2018]*

From an operator's perspective, four levers define the operating envelope: pressure, H_2/HC, WABT (weighted-average bed temperature), and LHSV. Higher pressure improves hydrogen solubility and biases the network toward HDO, typically yielding higher carbon retention at the price of compression/recycle load. The H_2/HC ratio stabilizes the deoxygenation sequence (and mitigates coking/ΔP creep), again pushing toward HDO as it increases. WABT positions the unit on conversion and selectivity while setting the margin to hot-spots; inter-bed quench splits the exotherm into manageable steps and is tuned against observed ΔT. Finally, LHSV sets contact time and thereby conversion depth and slate; lower LHSV deepens conversion but concentrates the exotherm. Vendors specify recommended bands for each variable; plants keep to them not as "nice-to-haves" but because property control downstream (freeze point, smoke point, density after isomerization/blend) depends on how clean and predictable the paraffinic base is at this very stage.

Table 9. *Hydrotreating operating envelopes & implications [32-18]*

Variable	Typical envelope (indicative)	Effect on process (mechanistic/operational)	What the inventory/LCA "sees"
Pressure (bar)	**30–80**	Increases H_2 solubility; biases network toward HDO; smoother temperature control in trickle-flow; mitigates hot-spots	Higher electricity for compression/recycle; potentially lower furnace duty with better heat integration
H_2/HC (Nm³ H_2 per t feed)	**600–1200**	Stabilizes deoxygenation sequence; reduces coking/ΔP growth; shifts selectivity toward HDO	Major contributor to GWP/PM via hydrogen supply; strong sensitivity to H_2 sourcing in §2.3
WABT (°C)	**320–380**	Higher conversion but greater hot-spot risk; requires inter-bed quench/heat management	Higher thermal duties (coolers/reboilers); integration strategy affects utilities

LHSV (h^{-1})	**0.5–2.0**	Controls contact time → conversion/slate; lower LHSV deepens conversion but concentrates exotherm	Changes specific energy per functional unit; can shift cut distribution seen in mass balances
Bed configuration	Multi-bed with **inter-bed quench**	Splits exotherm; distributes reaction load; protects catalyst life	More heat-exchange area/duty shows up in utilities inventory
Gas recycle ratio	**2–5** (indicative)	Cushions exotherm; maintains H_2 availability; dilutes hydrocarbons	Increased compressor work → higher electrical load
Guard bed presence	Yes (upstream of HDO)	Captures P/Na/K/Cl breakthroughs; protects active phases/supports	Minor materials/waste impacts; prevents major failures (indirect benefits)
Feed contaminants	"As low as possible" (per gate spec)	Avoids poisoning/plugging; stabilizes ΔP and selectivity	Pre-treat units/adsorbents and replacements appear in the foreground inventory

Choice of oxygen-removal route is not a binary switch but a bias set by those same levers and by catalyst chemistry. When the unit is biased to HDO, oxygen leaves as H_2O; hydrogen use is higher, yet carbon efficiency is superior, yielding mainly even-carbon paraffins and a somewhat heavier slate that fractionation and isomerization will trim [23]. A bias to DCO/DCO_2 saves hydrogen but sacrifices carbon as CO/CO_2, shifting the slate lighter (more C_5–C_7 and gases) and demanding stricter control in the column train. These patterns are not merely academic—they explain why, for the same pre-treat quality, two campaigns tuned differently can produce different jet yields and different utility loads at fractionation.

Table 10. *HDO vs DCO/DCO_2 (technical & inventory implications)[126]*

Aspect	HDO (hydrodeoxygenation)	DCO/DCO_2 (decarboxylation/decarbonylation)
O-removal products	H_2O	CO / CO_2
Typical operating bias	Higher pressure, higher H_2/HC, moderate WABT	Lower H_2/HC, somewhat lower pressure, suitable WABT
Hydrogen use	**Higher**	**Lower**
Carbon efficiency	**Higher** (carbon retention; even-carbon paraffins)	**Lower** (carbon loss as CO/CO_2; more odd-carbon paraffins)
Product slate tendency	Heavier; richer jet/diesel (then tuned with isomerization)	Lighter; uplift in C_5–C_7 and gases; more trimming in fractionation
"Raw" jet properties	Clean paraffins before ISO; good base for cold-flow after ISO	Lighter paraffins; stricter control in fractionation/ISO

Hot-spot/coking risk	Managed with quench/recycle; clean feed is critical	Similar risks; lower H_2 helps slightly but slate more volatile
Utilities & separations	Thermal duties to complete HDO; potential higher reboil	CO/CO_2 streams; different separation loads possible
Inventory/LCA hint	Hotspot is **H_2 supply**	Saves H_2 but adds **process CO_2**; separations may increase

Catalyst platforms in this section are refinery-standard bifunctional systems: group VI/VIII sulfides (e.g., Ni–Mo, Co–Mo, Ni–W) [107] supported on mildly acidic oxides. The metal function drives hydrogenation and the scission of C–O bonds; a controlled acidity enables limited skeletal adjustments without premature cracking. To protect these functions, two items from §2.1.1 carry straight through: a guard bed upstream (to capture P/Na/K/Cl breakthroughs) and the gate specs on water/FFA/insolubles/metals. Plants that treat the guard bed as a sacrificial, instrumented component—monitored for ΔP growth and breakthrough—avoid the far costlier outcome of fouling the first HDO bed. Likewise, adhering to water <0.1 wt% and P/Na/K in low single-digit ppm keeps hot-spots quenchable and preserves activity over long runs.

Because the reactor is a trickle-flow system, hydrodynamics matter as much as intrinsic kinetics. Good operation maintains stable wetting and a predictable pressure-drop profile across beds; the gas recycle (typically a few multiples of feed) cushions the exotherm and maintains hydrogen availability while diluting hydrocarbons. On-stream, operators follow a small set of KPIs that speak the truth of the bed: ΔT per bed against design (quench effectiveness), ΔP trend (fouling vs clean run), hydrogen slip and off-gas composition (proxy for route bias), and an outlet compositional check confirming the expected paraffinic base (sulfur/nitrogen near-zero, aromatics negligible for HEFA) [26-33]. When these indicators move together in the right way, the downstream units behave like textbooks: fractionation carves the slate cleanly, isomerization sees a tractable feed, and blending becomes an arithmetic step within the annex limit.

The co-product pattern is equally diagnostic. Propane/LPG originates mainly from triglyceride deoxygenation and is a useful anchor for mass balance; light gases (C_1–C_3) rise with cracking and with DCO/DCO_2 bias; CO/CO_2 streams scale with decarboxylation/decarbonylation. Recording these flows with batch IDs is part of the documentation spine that later substantiates both pool compliance (ASTM D1655 after blending) and any MRV claims tied to delivery. In the same ledger, plants log quench duties, reboiler/cooler loads, and compressor work; those numbers will be used as-is in **Section 2.2** when the foreground mass/energy balances are declared for the study.

Operationally, a well-run hydrotreating section is quiet: ΔP is flat, ΔT steps repeatably, the guard bed behaves predictably, and the paraffinic base arrives to isomerization with no surprises. When the section is noisy, the causes almost always trace back to what **Section 2.1.1** set out to prevent (water flashes, soaps/colloids, P/Na/K ingress) or to an operating point that drifted outside the envelope (too little quench, H_2/HC starved, LHSV too low for the available quench). The remedy is rarely a hero move; it is a return to gate discipline and to the four-lever box that defines this unit's stability. In that sense, hydrotreating is where the HEFA/HVO train proves whether the residue has been truly normalized by pre-treatment—and whether the rest of the plant can now do the finer work of property engineering and standards compliance without fighting upstream battles.

2.1.3 Isomerization, selective cracking, and blending to drop-in jet fuel

If hydrotreating is the conversion engine, isomerization is the property engineer of the HEFA/HVO train. The paraffinic base exiting HDO/DCO/DCO_2 is rich in n-paraffins in the C_8–C_{16} window; left as-is, this matrix struggles on cold-flow (cloud point, CFPP, and ultimately freeze point) despite being clean and sulfur-free. The task of isomerization is to introduce a controlled amount of branching—just enough to push the cold-flow envelope into aviation territory without eroding jet yield via over-cracking into C_5–C_7 and LPG. The art is in that "just enough": severity too low leaves cold-flow marginal; severity too high sacrifices jet to naphtha and light ends and raises utility loads.

Mechanism and catalyst families (what the unit actually does).

Industrial hydroisomerization is bifunctional. On the metal function (typically Pt at low loading), paraffins undergo reversible dehydrogenation to olefinic intermediates; on moderate acidity (amorphous silica-alumina or shape-selective zeolites), these intermediates form carbenium ions that rearrange skeletal connectivity (methyl/ethyl shifts) before being re-hydrogenated back on the metal sites. The acid strength and site density must be tuned carefully: too strong/too dense → unwanted β-scission and cracking; too weak/too sparse → insufficient branching and poor cold-flow. In practice, refineries favor mildly acidic supports (amorphous silica-alumina) for robust operation, and shape-selective molecular sieves (e.g., SAPO-11, ZSM-22, ZSM-23) to bias mono-branching over multi-branching, which preserves density and smoke behavior. One-dimensional 10-membered-ring sieves (SAPO-11/ZSM-22) are popular because they discourage deep cracking while still allowing skeletal rearrangement in the C_8–C_{16} range. The pore topology is not an academic footnote: it is why two nominally "isomerized" slates can show very different freeze points and yields under the same WABT.

Process severity is the combined result of WABT, LHSV, H_2/HC, and effective acidity (support type, Si/Al or framework substitutions, metal dispersion). Raising WABT or lowering LHSV deepens isomerization (better freeze point), but it also increases secondary cracking (yield erosion to naphtha/C_5–C_7), elevates quench/cooling duty, and, indirectly, shifts the distillation profile (T10/T50) that the fractionation train must follow to keep the jet side-draw centered. Likewise, a slightly higher H_2/HC stabilizes the bifunctional cycle and suppresses coke precursors, but adds compression work. A useful mental model is the "branching index": as it increases, cold-flow improves monotonically until a plateau; beyond that, incremental severity mainly burns yield for diminishing returns on freeze point. Plants therefore target a severity shelf—high enough to lock-in cold-flow with seasonal margin, low enough to avoid over-cracking.

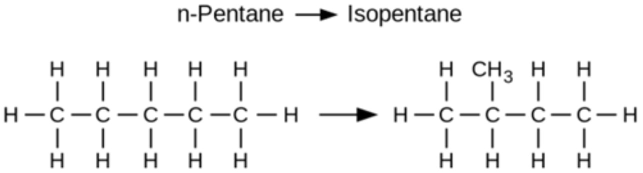


__Figure 6.__ Pentane isomerization motif and qualitative severity trends [14]

HEFA synthetic blending components (SBCs) are very low in aromatics. That is excellent for emissions and smoke point, but the aviation pool (ASTM D1655) relies on a minimum aromatic content for combustor operability and elastomer seal swell. Per questo, ogni pathway opera dentro un annesso ASTM D7566 con un blend-limit: l'SBC deve essere miscelato in un intervallo percentuale che, assieme alla proprietà della base fossile, riporta il pool entro i vincoli di densità, smoke, freeze point e distillazione. In operation, isomerization severity and blend ratio are coupled knobs: the operator may select a slightly less severe SBC (better yield) if the fossil blend provides enough density and aromatics to close the property balance; alternatively, severity can be increased to make the freeze point 'intrinsic,' allowing more freedom in dosing/blending across cold networks/routes.

A well-tuned isomerization section is predictable: bed-to-bed ΔT is modest, ΔP is flat, the freeze point of the isomerate trends linearly with severity changes, and the smoke point remains comfortably high (HEFA paraffins are "clean" by construction). The unit lab tracks a compact set of properties on the isomerate and the jet side-draw after fractionation: freeze point, density @15 °C, smoke point, T10/T50/T90, and net heat of combustion by calculation/confirmation. When the numbers drift in step (e.g., freeze point improves but density falls), the plant trims cut points and blend ratio rather than forcing severity into the cracking regime.

Because drop-in status is achieved only after blending within the annex limit and pool compliance, the properties lab is tied to a blend log that records: (i) SBC lot IDs with CoAs; (ii) the target blend ratio and calculated property mix; (iii) the post-blend CoA against ASTM D1655 items; and (iv) any rework instructions if a parameter sits near a guardrail (typically density/smoke). The same log underpins MRV claims later in the chain (airport/operator), so it must maintain batch traceability from the isomerate tank to dispatch. To avoid downstream out-of-spec situations, it is standard practice to add coherence checks among the plant laboratory, the terminal, and—when required—a third-party laboratory.

__Table 11.__ QA/QC checkpoints from isomerization to blending & dispatch

Stage	Mandatory checks	Record / document	Purpose
Isomerate tank (post-ISO)	Freeze point, density @15 °C, smoke point, T10/T50/T90, NHOC (calc/confirm)	Unit CoA + batch ID	Confirms property trajectory before cuts/blend
Fractionation jet side-draw	Cut stability (mass balance), distillation envelope	Shift mass-balance sheet	Ensures consistent jet slate into blend

Blend design	Annex limit check; property mixing calc (density, SP, FP, NHOC)	**Blend plan** + approvals	Avoids out-of-spec before execution
Blend execution	Ratio control; sampling during/after	**Blend log** + in-process tickets	Traceable execution and immediate feedback
Post-blend verification	Full D1655 property panel per supplier QA	**Post-blend CoA** (plant/terminal; 3rd-party if req.)	Grants drop-in status; go/no-go for dispatch
Dispatch to airport	Chain-of-custody, seal numbers, batch IDs	Delivery documents + CMR/waybill	MRV-ready traceability for operator claims

In summary, isomerization is not a mere finishing unit; it is the section where the product property window is closed while the process economics are still under active control. The chosen severity determines how much jet yield remains, the utility expenditure required to reach the freeze-point target, and how wide the blending window must be to meet ASTM D1655 without unexpected specification excursions. When properly tuned, it allows blending to be used as a fine control lever; when mishandled, it forces a chase for specifications with yield erosion and downstream heat-duty penalties.

2.2 Methods

The detailed LCA framework is reported in Appendix A; this section documents the modeling choices specific to the UCO→SAF pathway assessed in this work.

System boundary and modeling environment. The assessment adopts a cradle-to-gate boundary spanning used cooking oil (UCO) collection at source (households/HoReCa), aggregation in regional hubs, hub-to-biorefinery transport, pre-treatment, conversion to SAF and co-products, and on-site utilities up to the refinery gate. Upstream provision of hydrogen, electricity, and heat is included; aircraft use-phase and end-of-life are excluded. Accordingly, this cradle-to-gate scope does not quantify aircraft operational climate effects. It excludes non-CO_2 impacts associated with flight (e.g., NO_x-related chemistry, water vapour, contrail formation and induced cirrus), which can be relevant contributors to aviation's total radiative forcing. Therefore, the Climate Change (GWP, kg CO_2-eq) results in this thesis should be interpreted as a production- and logistics-focused signal, not as a full aviation climate-forcing estimate. Modeling is implemented in OpenLCA with Ecoinvent background datasets for energy carriers and generic processes, consistent with the thesis/article methods describing software, database, and impact-category selection.

Geographical scope and logistics representation. The study is Italy-specific. UCO supply is mapped by partitioning the peninsula into five macro-areas—North-West, North-East, Centre, South, Islands—using collection evidence from RenOils to assign regional shares and identify high-intensity cities (e.g., Venice, Padua, Rimini, Udine; Milan, Genoa, Brescia; Rome, Florence; Naples, Bari; Catania, Trapani). This partition supports the construction of logistics routes to candidate hubs and the nearest biorefineries to minimize average haul distances. The approach, steps, and quantitative shares follow the related article's inventory design (regional split, hub selection, single-truck distance, truck counts, and national kilometers) and are documented in this section.

Foreground conversion chain (HEFA/HVO-derived). The UCO-to-SAF route follows a hydroprocessing scheme with three core stages:

(i) deoxygenation/hydrogenation of triglycerides (hydrodeoxygenation vs. decarboxylation/decarbonylation routes),
(ii) isomerization with mild cracking to meet cold-flow targets and shift cut points,
(iii) fractionation/stabilization yielding LPG and naphtha (co-products), a jet side-cut, and green diesel.

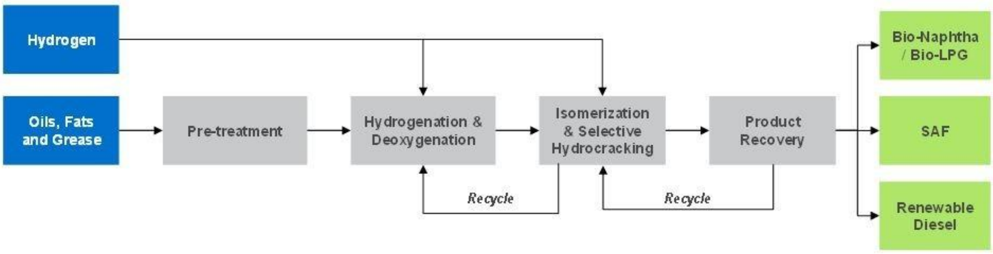


Figure 7. *System boundary and major unit processes for the UCO→SAF pathway [18]*

The functional role of isomerization in balancing freezing-point compliance against jet yield is documented through thesis figures and narrative (HVO/SAF scheme; hydrogenation reactions; pentane isomerization).

Functional unit and comparator. Results are reported per 1,000 kg of product to align with thesis/article precedent and to enable a direct comparison with fossil kerosene modeled via Ecoinvent processes. This functional unit is motivated in this section as practical for data availability and literature harmonization.

Two SAF scenarios are constructed and compared with the fossil reference:

(i) S1 – Current collection, converting today's Italian UCO flows;
(ii) S2 – Best-case potential, converting the estimated maximum collectable UCO (regionalized via the five-area split).

This mirrors the scenario structure used in the thesis/article when contrasting SAF pathways and kerosene baselines across impact categories.

The logistics model includes:

a) macro-area production shares;
b) placement of regional collection hubs;
c) routing to nearest biorefinery (e.g., Livorno, Porto Marghera, Gela);
d) vehicle payload assumptions;
e) number of trips;
f) (f) national door-to-gate kilometers scaled to the functional unit.

Allocation and co-products. Within the refinery model, mass allocation is applied among jet, green diesel, and light fractions to attribute burdens consistently with the thesis/article setup, where allocation was used to report impacts “exclusively” for the jet fraction. Allocation sensitivity is revisited in **Section 2.2.3.**

Background datasets and LCIA method. Upstream hydrogen, electricity (Italian mix), and heat (natural gas) are modeled using Ecoinvent; impact assessment uses ReCiPe 2016 Midpoint across the categories reported in the thesis/article (e.g., particulate matter formation, global warming, fossil resource scarcity, freshwater ecotoxicity/eutrophication). Prior results attribute major category contributions to hydrogen, heat, and process energy, and these drivers guide subsequent uncertainty/sensitivity analyses.

Table 12. *Foreground/background model elements and key assumptions (FU = 1,000 kg).*

Module	Foreground unit process	Main inputs/outputs	Background dataset (example)	Allocation / Notes
UCO collection	Source → hub (five macro-areas)	Truck-km, payload, UCO mass	Truck transport (EU/IT), Ecoinvent	Distances via nearest-biorefinery logic; scaled to FU.
Hub → biorefinery	Routing hub → plant	Truck-km, diesel use	Truck transport (EU/IT), Ecoinvent	Include empty-return assumption in SI;.
Pre-treatment	Filtration/degumming (if modeled)	Electricity, heat, wastes	Electricity (IT mix), Heat (NG), Ecoinvent	Minor chemicals under cut-off (justify).
Deoxygenation/H_2	Triglyceride hydrotreating	**Hydrogen**, heat, electricity	H_2 production/market; Heat (NG); Electricity (IT), Ecoinvent	H_2 is a major driver in several categories.
Isomerization & mild cracking	Cold-flow tuning / cut shifting	Heat, electricity; light ends	Heat (NG); Electricity (IT)	Severity drives jet-vs-diesel yield trade-off.
Distillation & stabilization	Fractionation to cuts	Utilities; jet/diesel/LPG/naphtha	Heat (NG); Electricity (IT)	**Mass allocation** among co-products.
Fossil comparator	Kerosene production	—	Ecoinvent kerosene/jet process	Used for comparative LCIA only.
LCIA	ReCiPe 2016 Midpoint	18 midpoint categories	—	Full vector reported; see §2.2.3.

Model governance and traceability. Data sources, temporal/geographical representativeness, and cut-off rules are documented within the OpenLCA project and cross-referenced to figures (HVO/SAF scheme; hydrogenation/isomerization; RenOils maps; hub/biorefinery distance tables) to ensure reproducibility.

2.2.1 Goal and Scope definition Scenario 1

This Life Cycle Assessment (LCA) scenario focuses on the main goals to assess in detail and accurately the environmental impacts of the production of Sustainable Aviation Fuels (SAF) using yellow grease as a feedstock. Firstly, the environmental impact categories relevant to this specific context are identified and assessed.

This includes a detailed analysis of the logistical dynamics involved in the collection of waste oils, as well as the emissions and impacts associated with the conversion of the oils into aviation fuel. The focus then shifts to quantifying the overall environmental impact of SAF's used cooking oil production process using appropriate life cycle analysis methods and tools. This involves collecting accurate data on the production and transport of the oils, as well as all stages of the conversion process into fuel. This LCA uses a 'cradle to gate' approach to assess the environmental impacts of producing Sustainable Aviation Fuels (SAF) from used cooking oils. This approach examines the life cycle of the product from the initial stage of raw material extraction or collection, i.e. used cooking oil, to the final production stage (gate), without including the subsequent stages of use and disposal of the final product. In other words, we focus on the environmental activities and impacts associated with the production of SAF up to the point where the product is ready to leave the production site. This approach allows a detailed assessment of the resources used and environmental impacts generated during the extraction, processing and production phases of the fuel, providing an accurate overview of the environmental impacts of producing SAF from yellow grease. In the context of this LCA, several key steps in the production process of Sustainable Aviation Fuel (SAF) from waste cooking oil are considered. Firstly, the phase of collection and transport of the used oil from its origin at the end user to the destination for further processing is examined in detail. This phase includes an analysis of the collection method, the means of transport used and the associated environmental impacts, such as greenhouse gas emissions and resource use. Next, the production and transport phase of the resources required for the waste oil to SAF conversion process is examined. This includes the hydrogen, electricity and heat used to convert the oil into sustainable aviation fuel. The origin of these resources and the environmental impacts associated with their production and transport are carefully assessed. Finally, the actual process of converting waste oil into SAF is analysed. This process includes the refining and Conversion of the oil into aviation fuel, as well as the transport of the final SAF to distribution points. During this phase, the direct environmental impacts of the SAF production process, such as greenhouse gas emissions, air and water pollution and resource use, are identified and assessed to provide a comprehensive view of the total environmental impact of the product life cycle. The choice of the functional unit of 1000 kg of fuel produced was motivated by the need to facilitate a more direct comparison with data currently available in the literature.

This functional unit was chosen because it represents a significant amount of aviation fuel and allows easier comparison with information reported in existing studies. Furthermore, this choice is based on the practicality of measurement and data availability, ensuring that the analysis can be conducted in an accurate and meaningful manner. By using this standardised functional unit, we are able to obtain clear and comparable results, enabling an accurate assessment of the environmental impact of producing Sustainable Aviation Fuels (SAF) from waste cooking oil.

The development of this LCA is focused on the Italian territory, with the aim of carrying out an in-depth and detailed study in order to obtain relevant and useful information for potential applications in Italy. This geographical choice is motivated by the will to understand and evaluate the environmental impact of the production of Sustainable Aviation Fuels (SAF) from waste cooking oil in a specific context, taking into account the specificities of the Italian industrial and environmental system. Through this study, we aim to provide data and analysis that can support strategic decisions and policy development aimed at promoting the use and sustainable production of aviation fuels in the Italian context, thus contributing to the transition towards a greener and more sustainable economy.

2.2.2 Inventory Analysis Scenario 1

The inventory analysis phase is initiated with the aim of collecting all the data necessary to carry out the LCA and assess the impacts of producing Sustainable Aviation Fuels (SAF) from used cooking oil. The initial focus is on the collection of data to assess the impact of the transport of waste cooking oil, considering a scenario where strategic collection points are selected and the raw material is transported to biorefineries strategically located throughout the Italian peninsula.

The process included the following steps:

- Identification of the regions with the highest production of used cooking oil using data provided by collection consortia. This analysis made it possible to map the areas of the Italian peninsula where this waste is most prevalent, estimating a percentage for each area based on the total amount of used cooking oil produced in Italy;
- Selection of collection points within the identified regions;
- Consider strategic locations on the peninsula for waste transformation, optimising the distance travelled;
- Calculate the distance a single truck must travel from the collection point to the nearest biorefinery;
- Determine the total number of trucks required for each area, taking into account the load capacity of each vehicle;
- Calculating the total distance travelled in Italy by adding up the distances covered by all the lorries for the different regions. This involved multiplying the total number of lorries by the distance travelled by a single lorry and then aggregating all the results.

Therefore, in order to identify the areas with the highest production of used cooking oil, the Italian peninsula has been divided into 5 different areas that are represented below:

(a) North-East Italian collection **(b) North-West Italian collection**

Figure 8. *Amount of used cooking oil collected by Renoils in northern Italy*

In terms of the centre (Figure 9), the regions that contribute most to the collection are Lazio and Tuscany, with Massa Carrara, Rome and Florence.

Figure 9. *Amount of used cooking oil collected by Renoils in central Italy*

In southern Italy (Figure 10), on the other hand, we have Puglia and Campania, with Naples, Salerno, Bari and Caserta, as regions that allow a greater collection of UCO.

__Figure 10.__ Amount of used cooking oil collected by Renoils in central and southern

In the islands (Figure 11) there is a lower collection of UCO compared to the rest of Italy, where in fact the only cities with significant values of kg of UCO collected are Catania and Trapani.

__Figure 11.__ Collection of major Italian islands

This section reports the spatial distribution of UCO flows in Italy; **Table 13** summarizes the currently collected amounts and the corresponding hypothetical potential by macro-area (kton yr^{-1}):

Table 13. *UCO collected and hypothetical potential by Italian macro-area (kton yr^{-1})*

Area	Current collected (kton/yr)	Share of current (%)	Hypothetical collected (kton/yr)	Uplift factor (Hypo/Current)
North-West	7.72	18.4	47.84	6.20
North-East	16.70	40.0	104.00	6.23
Centre	7.02	16.8	43.68	6.22
South	8.50	20.3	52.78	6.21
Islands	1.80	4.5	11.70	6.50
Total	**41.74**	**100.0**	**260.00**	**6.23**

To support the interpretation of the logistics setup, **Figure 12** illustrates the UCO collection intensity and representative hub-to-biorefinery routes adopted in the model

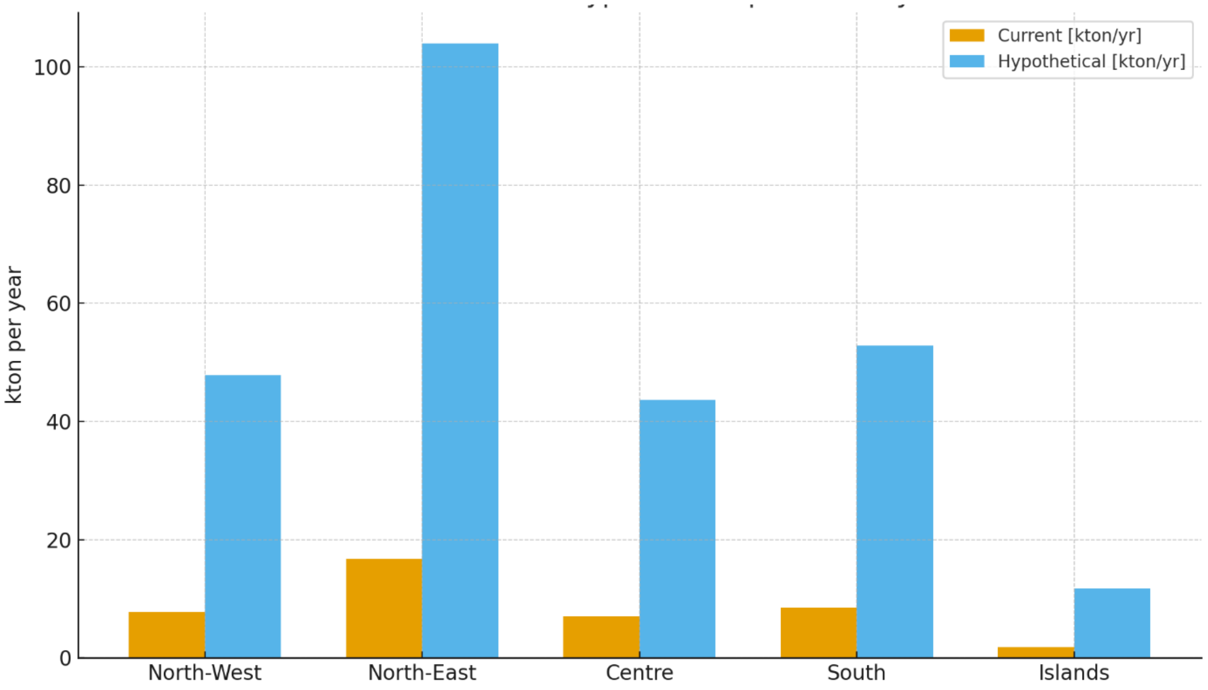


Figure 12. *UCO collected: current vs. hypothetical potential by macro-area (kton/yr)*

After identifying the cities with the highest UCO collection, the analysis locates the nearest collection centres to each of them (Figure 13).

Figure 13. *Italian collection points for used cooking oil*

The collection centres considered are the FEROLMET SRL depot in the north-western area, the ECOBAS SRL depot in the north-eastern area, the VI.VE depots for the Centre SRL and N.I. ECO SPA and, finally, the NICOLA VERONICO SRL, ECOPARTENOPE SRL and META SERVICE SRL depots for the southern area and the islands.

Table 14. *Route-level logistics (collection centres → refineries)*[2]

Macro-area	Collection centre (operator)	Destination refinery	Distance (km)	Trucks per year	Total km per year
North-West	FEROLMET SRL	Porto Marghera	262	5,257	1,377,334
North-East	ECOBAS SRL	Porto Marghera	145	11,428	1,657,060
Centre	VI.VE. SRL	Livorno	9.1	2,400	21,840
Centre	N.I. ECO SPA	Livorno	357	2,400	856,800
South	ECOPARTENOPE SRL	Gela	705	2,900	2,044,500
South	NICOLA VERONICO SRL	Gela	639	2,900	1,853,100
Islands	META SERVICE SRL	Gela	114	1,286	146,604

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[2] Note on rounding: Summing the route totals as given yields 7,957,128 km. Recomputing with exact products (e.g., 9.1 km × 2,400 = 21,840) gives 7,957,238 km, a 110 km difference consistent with rounding.

Total	—	—	—	**28,571**	**7,957,128**

__Table 15.__ Macro-area summary (aggregated)

Macro-area	Trucks per year	Total km per year
North-West	5,257	1,377,334
North-East	11,428	1,657,060
Centre	4,800	878,640
South	5,800	3,897,600
Islands	1,286	146,604
Total	**28,571**	**7,957,128**

Input and output data from existing processes were used for the production process data to be inserted [12]. Table 16 and 17 show the material balance data, while Table 18 shows the values of heat and electricity required to run the process.

__Table 16.__ Mass Balance for SAF conversion from UCO (INPUT)

Stream	Mass (kg)	Share (%)
UCO	1,000.0	97.47
H_2 gas	26.0	2.53
Total inputs	**1,026.0**	**100.00**

__Table 17.__ Mass Balance for SAF conversion from UCO (OUTPUT)

Stream	Mass (kg)	Share (%)
CO_2	104.0	10.13
CO	2.7	0.26
Water	37.0	3.60
LPG	69.0	6.72
Naphtha	147.0	14.32
SAF	529.0	51.52
HVO	138.0	13.44
Total outputs	**1,026.7**	**100.00**

Table 18. *Thermal energy and electricity requirements for SAF production*

Thermal energy (MJ/tonne oil)	Electricity (kWh/tonne oil)
2820	73

2.2.3 Goal and Scope definition Scenario 2

As part of the Life Cycle Assessment (LCA) of fossil kerosene, this section conducts a detailed evaluation of the environmental burdens associated with this conventional aviation fuel. Relevant impact categories are identified and assessed with attention to the logistical dynamics of crude extraction, refining, and distribution up to the refinery/market gate.

Methodologically, the analysis adopts a cradle-to-gate boundary, encompassing upstream oil extraction and processing through to kerosene production and distribution to the point of sale (gate), while excluding aircraft use and end-of-life. This system definition enables a focused examination of the activities most responsible for pre-use environmental loads and provides a consistent basis for comparison with alternative pathways.

The life-cycle model resolves three critical stages:

(i) crude oil extraction and primary handling;
(ii) refining operations leading to the kerosene cut;
(iii) product distribution to the gate. The functional unit is set to 1,000 kg of kerosene produced, ensuring direct comparability with the Sustainable Aviation Fuel (SAF) assessment.

This choice supports an accurate attribution of impacts to a common reference flow and facilitates cross-scenario interpretation.

Overall, the cradle-to-gate LCA of fossil kerosene yields quantitative evidence on the environmental profile of the conventional pathway. The resulting indicators are subsequently contrasted with those of SAF produced from used cooking oil, enabling a comprehensive and transparent evaluation of aviation fuel options in both the Italian and broader international contexts.

2.2.4 Inventory Analysis Scenario 2

The life-cycle inventory underlying the impact results was sourced from the Ecoinvent database as implemented in OpenLCA. This choice ensures system completeness and methodological consistency, since Ecoinvent provides process-based datasets that capture the upstream and on-site burdens of crude extraction, transport, multi-output refinery operations (including the kerosene cut), and distribution to the gate. Drawing on these datasets allows the model to account for energy and material inputs, emissions to air, water, and soil, and co-product handling in a way that is transparent and traceable. In addition, Ecoinvent supplies metadata on technological, geographical, and temporal representativeness and data quality indicators, which supports critical appraisal of the results. Using the same background library within OpenLCA for both fossil kerosene and SAF scenarios also maintains internal consistency across comparisons of impact categories.

2.2.5 Impact Assesment Senario 1 & 2

The category set and modelling approach—ReCiPe 2016 Midpoint (H) in OpenLCA, cradle-to-gate boundary, and a functional unit of 1,000 kg of product—are applied consistently to both scenarios:

- (S1) SAF from used cooking oil
- (S2) fossil kerosene.

Both systems are compiled with the same Ecoinvent background and reporting conventions, ensuring methodological alignment and enabling direct, like-for-like comparison of impact results across all midpoint indicators.

The following midpoint indicators are characterized:

- **Particulate matter formation (kg $PM_{2.5}$ eq):** potential for fine particulate generation from energy use and transport.
- **Fossil resource scarcity (kg oil eq):** use of non-renewable fossil resources and associated depletion potential.
- **Mineral resource scarcity (kg Cu eq):** consumption of mineral resources across upstream and process stages.
- **Global warming (kg CO_2 eq):** climate change potential from greenhouse gas emissions.
- **Stratospheric ozone depletion (kg CFC-11 eq):** depletion potential due to halogenated compounds.
- **Ozone formation—human health (kg NO_x eq)** and **Ozone formation—terrestrial ecosystems (kg NO_x eq):** tropospheric ozone formation affecting human health and vegetation.
- **Terrestrial acidification (kg SO_2 eq):** acidifying emissions impacting soils and terrestrial systems.
- **Freshwater eutrophication (kg P eq)** and **Marine eutrophication (kg N eq):** nutrient enrichment of inland and marine waters.
- **Freshwater ecotoxicity (CTUe), Marine ecotoxicity (CTUe), Terrestrial ecotoxicity (CTUe):** potential toxic impacts of emitted substances on aquatic and terrestrial ecosystems.
- **Human carcinogenic toxicity (CTUh)** and **Human non-carcinogenic toxicity (CTUh):** potential human health impacts from exposure to toxic substances.

- **Ionising radiation (kBq Co-60 eq):** human and environmental exposure potential to ionising radiation.
- **Land use (m^2a crop eq):** occupation/transformation of land over time.
- **Water use (m^3 world-equivalents):** water consumption with deprivation weighting.

All categories are computed on a **cradle-to-gate** basis and reported per the **functional unit of 1,000 kg of product**, enabling consistent comparison with the fossil kerosene reference. The selection of ReCiPe 2016 Midpoint provides:

(i) mechanistic coverage spanning climate, air quality, toxicity, resource use, and land/water pressures;
(ii) transparent units widely adopted in recent LCA literature;
(iii) compatibility with **Ecoinvent-based** background modeling within OpenLCA.

For the aviation context, this means that the climate indicator reported here covers upstream and refinery-gate emissions only and does not include flight-phase non-CO_2 forcing (e.g., contrails/induced cirrus).

2.3 Results and discussion

2.3.1 Interpretation Scenario 1

A structured interpretation of the impact assessment figures is conducted to identify both dominant and non-dominant life-cycle stages. Figure 14 reports results for particulate matter formation, where hydrogen production emerges as the primary contributor to the indicator. Refining operations (isomerization/cracking and distillation), logistics, and ancillary utilities exhibit comparatively smaller contributions, indicating that mitigation efforts targeted at the hydrogen supply chain are likely to yield the most substantial reductions in particulate-related impacts.

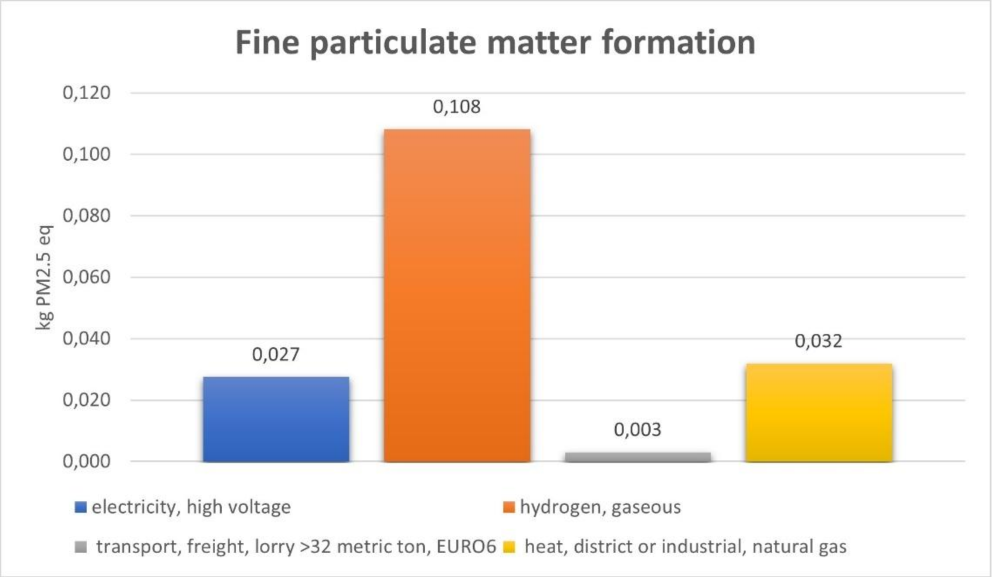

Figure 14. *Fine particulate matter indicator in SAF production*

Figure 15 indicates that the Fossil resource scarcity indicator is dominated by two stages: process heat from natural gas and hydrogen production. These contributions substantially outweigh those from the remaining unit operations, highlighting thermal energy supply and H_2 sourcing as the principal drivers of fossil resource use within the cradle-to-gate system.

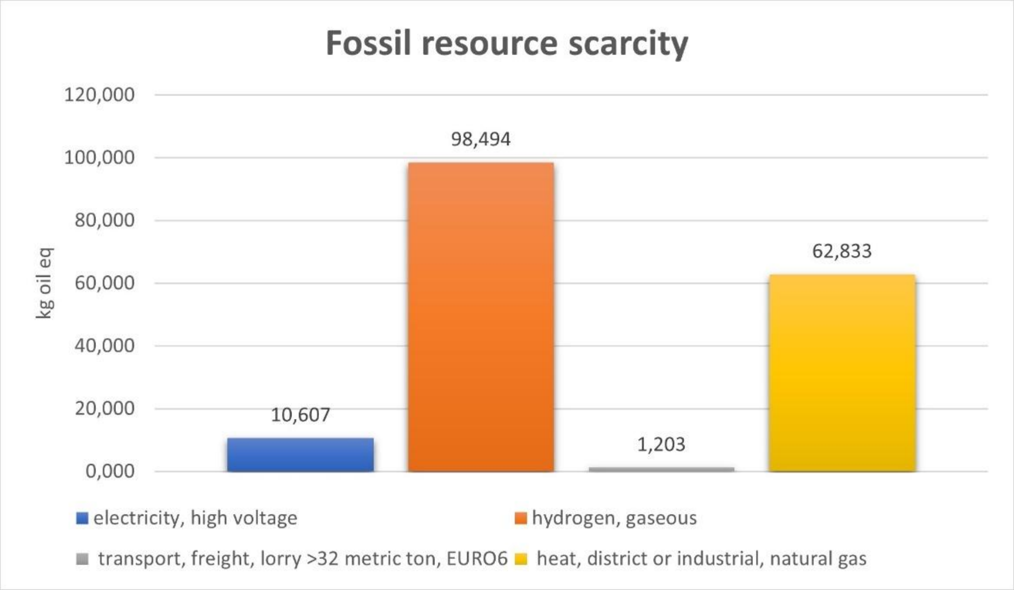

Figure 15. Fossil resource scarcity indicator in SAF production

Freshwater ecotoxicity & freshwater eutrophication (Figs. 16–17). For freshwater ecotoxicity, hydrogen, high-voltage electricity, and natural-gas heat contribute at comparable levels. For freshwater eutrophication, electricity generation is slightly more influential than hydrogen and heat.

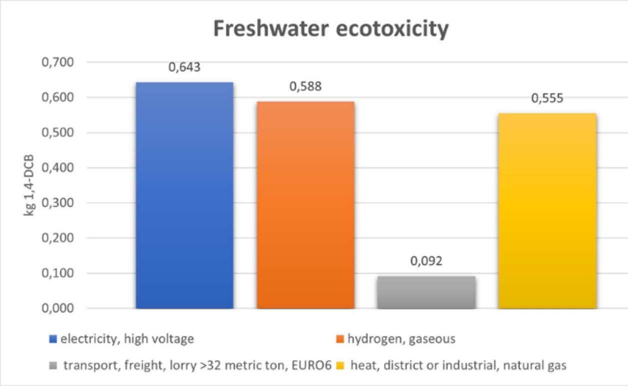

Figure 16. *Freshwater ecotoxicity indicator in SAF production*

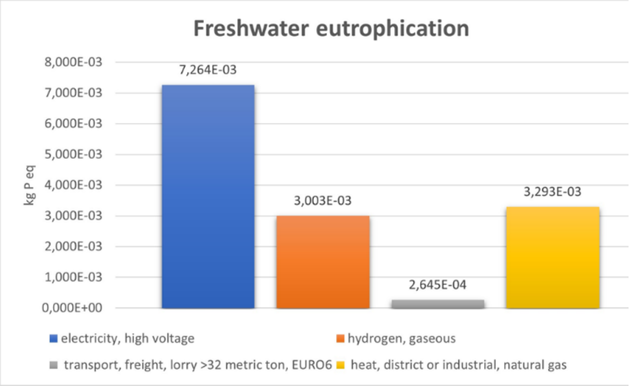

Figure 17. *Freshwater eutrophication indicator in SAF production*

Global warming (Fig. 18). In addition to upstream utilities, the UCO→SAF conversion shows a visible contribution due to process CO_2 formation; overall, process heat and the conversion step are the principal drivers.

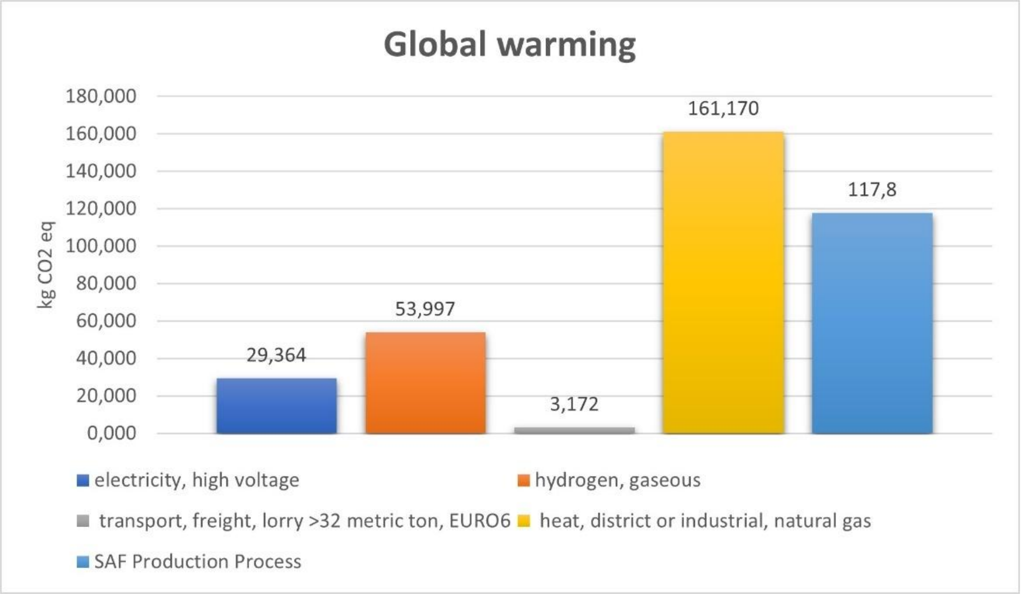

Figure 18. *Global warming indicator in SAF production*

Human toxicity—carcinogenic (Fig. 19). The indicator is mainly influenced by hydrogen and process heat provision.

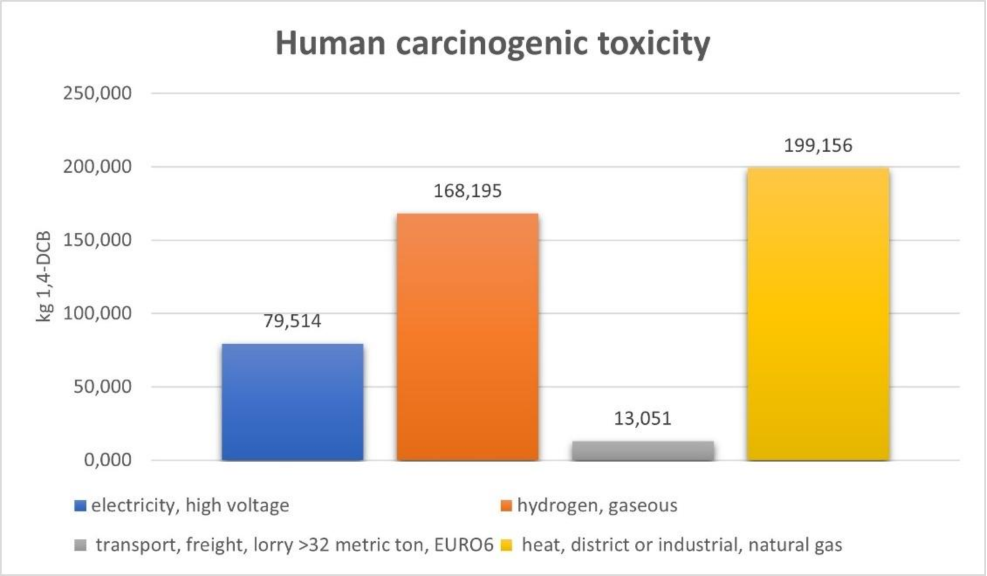

Figure 19. *Human carcinogenic indicator in SAF production*

Human toxicity—non-carcinogenic (Fig. 20). The largest shares are associated with electricity generation and hydrogen production.

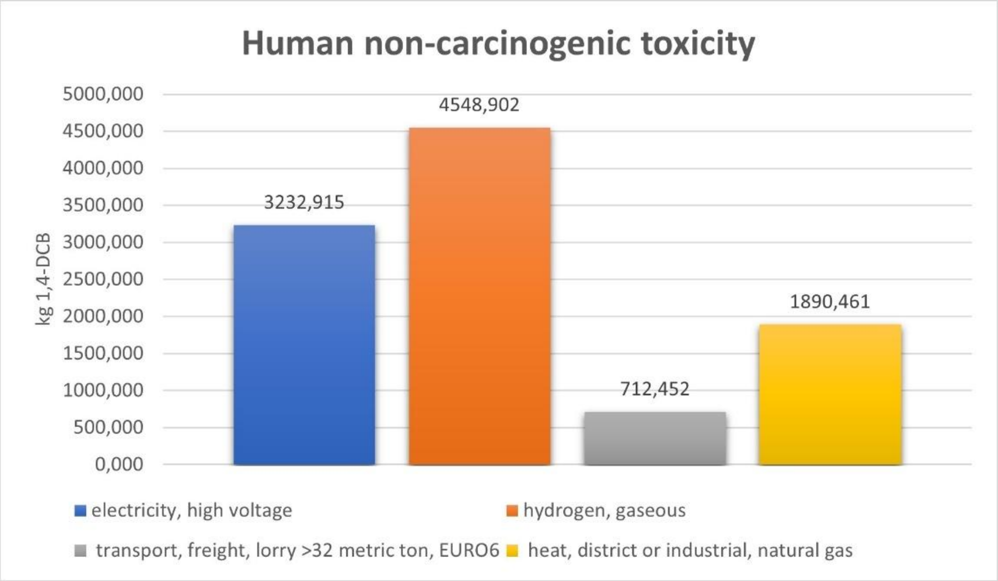

Figure 20. *Human non-carcinogenic indicator in SAF production*

Ionising radiation & land use (Figs. 23–24). Both indicators are driven primarily by electricity production, reflecting the technology mix embedded in the background datasets.

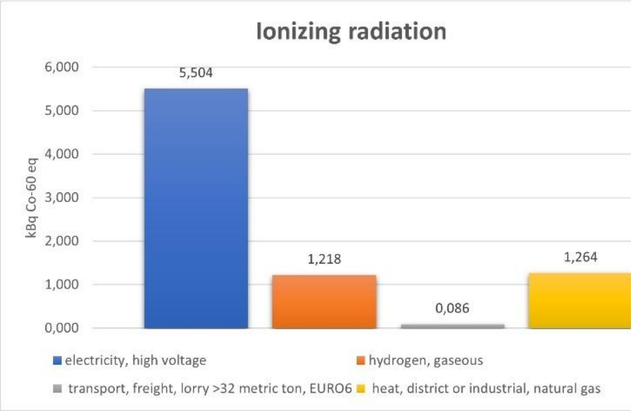

Figure 21*. Ionizing radiation indicator in SAF production*

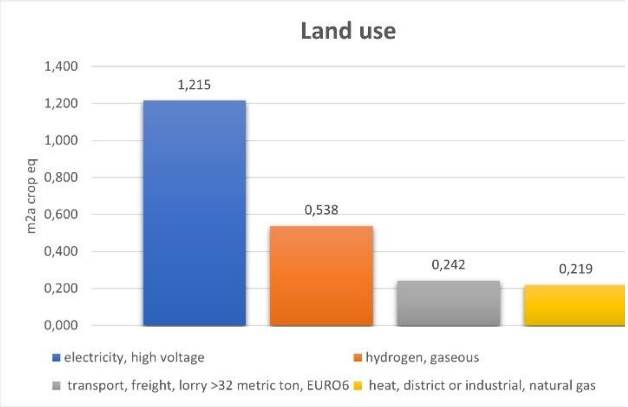

Figure 22. *Land use indicator in SAF production*

Marine ecotoxicity & marine eutrophication (Figs. 23–24). Hydrogen production shows a high impact in both indicators relative to other stages.

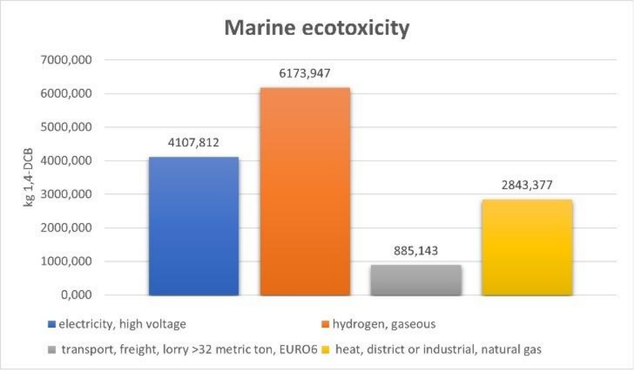

Figure 23. *Marine ecotoxicity indicator in SAF production*

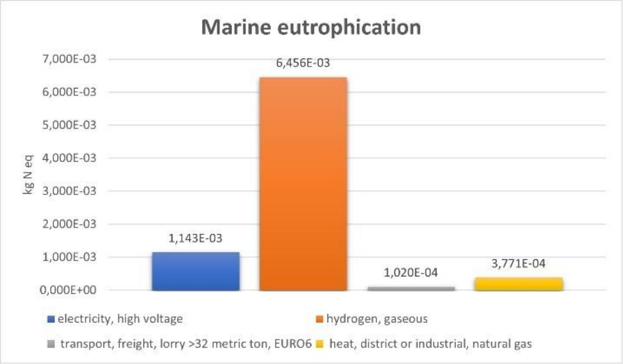

***Figure 24.** Marine eutrophication indicator in SAF production*

Mineral resource scarcity, ozone formation—human health, ozone formation—terrestrial ecosystems (Figs. 25–26-27). These indicators are jointly dominated by natural-gas heat and hydrogen production.

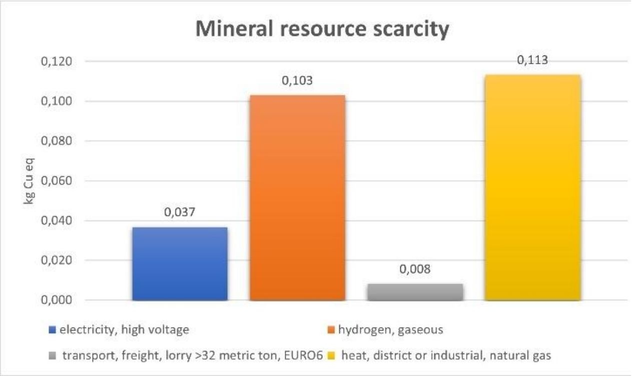

Figure 25. *Mineral resource scarcity indicator in SAF production*

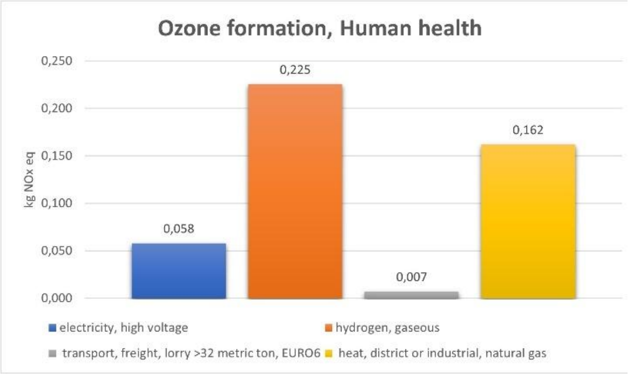

***Figure 26.** Ozone formation, Human health indicator in SAF production*

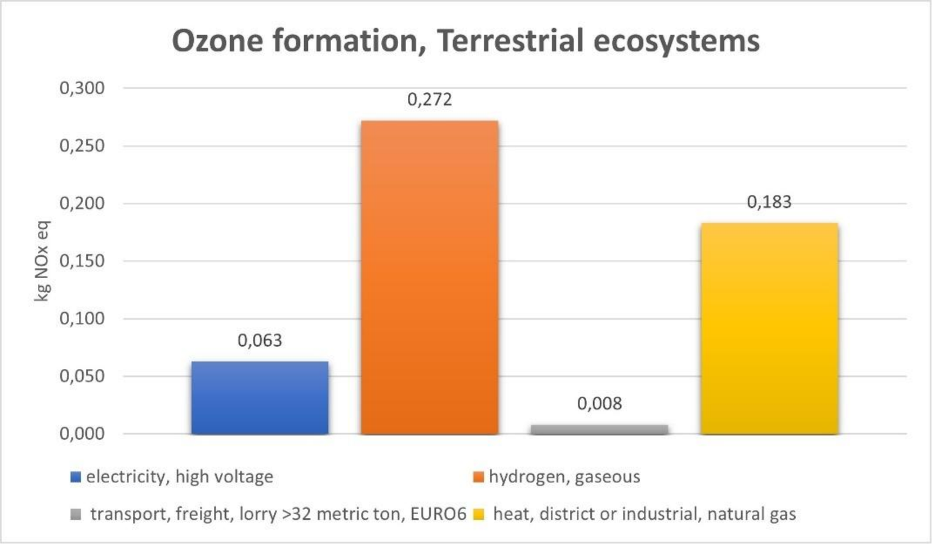

***Figure 27.** Ozone formation, Terrestrial ecosystems indicator in SAF production*

Stratospheric ozone depletion (Fig. 28). Hydrogen, electricity, and process heat emerge as the main contributors.

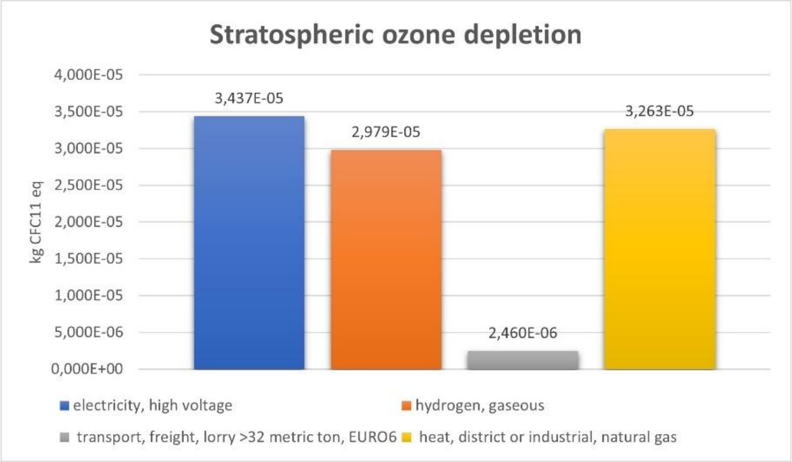

Figure 28. *Stratospheric ozone depletion indicator in SAF production*

Terrestrial acidification & terrestrial ecotoxicity (Figs. 29–30). Both are influenced predominantly by hydrogen production.

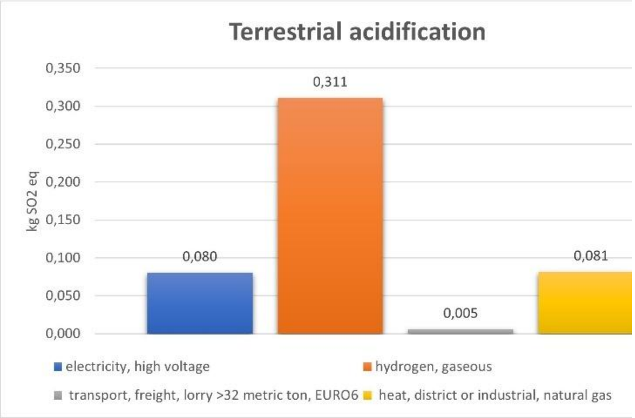

Figure 29*. Terrestrial acidification indicator in SAF production*

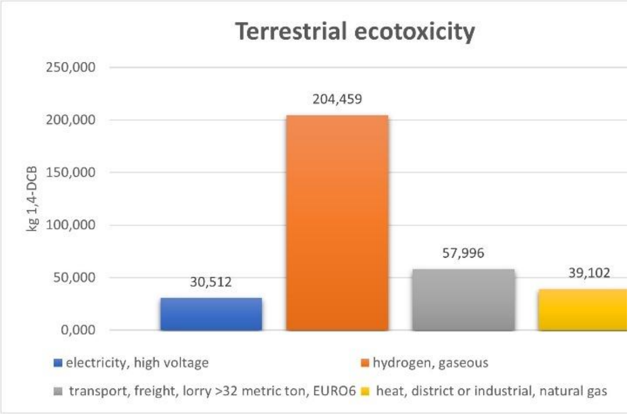

Figure 30. *Terrestrial ecotoxicity indicator in SAF production*

Water use (Fig. 32). The indicator is driven chiefly by electricity generation.

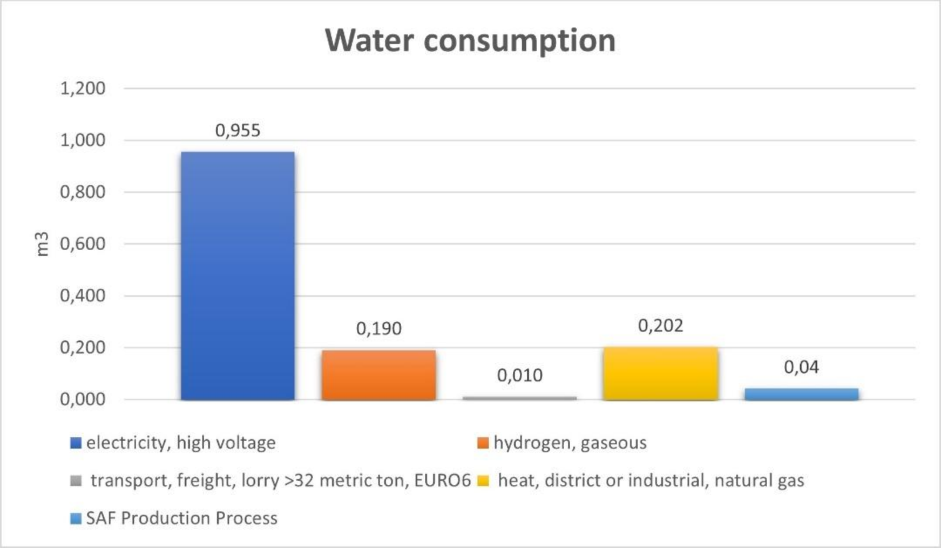

Figure 31. *Water consumption indicator in SAF production*

In summary, interpretation of the cradle-to-gate impact results for the UCO→SAF pathway indicates that hydrogen production is the dominant contributor across multiple midpoint indicators, consistently exceeding the contributions from conversion unit operations, logistics, and ancillary utilities.

2.3.2 Interpretation Scenario 2

A clarification on scope is required to interpret the kerosene results. In this context, the analysis does not resolve impacts by individual kerosene life-cycle stages; instead, it reports the total cradle-to-gate impact of fossil kerosene. This aggregate baseline is presented solely to enable comparison with the UCO→SAF pathway, for which stage-level contributions are analysed in detail. The figures therefore display the total impact results for kerosene, without disaggregation by extraction, refining, or distribution steps.

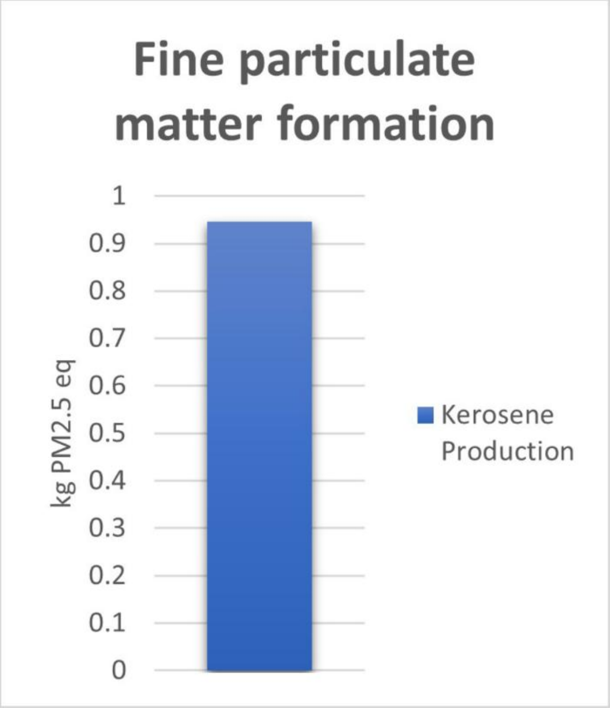

Figure 32_Fine particulate matter indicators for kerosene production_

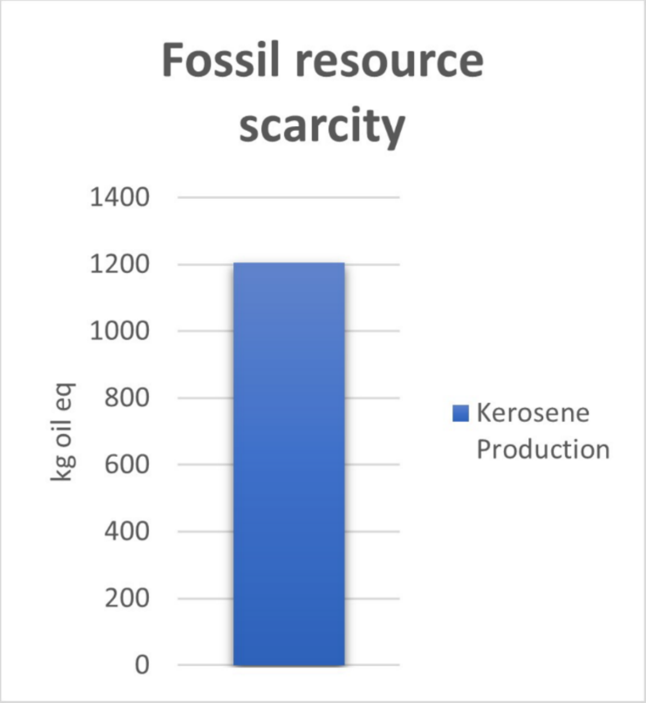

Figure 33. _Fossil resource scarcity indicators for kerosene production_

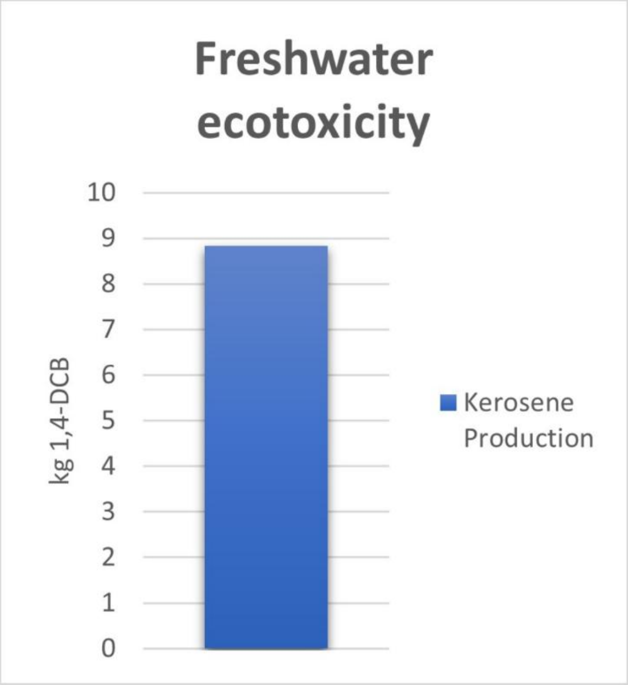

Figure 34. Freshwater ecotoxicity indicator for kerosene production

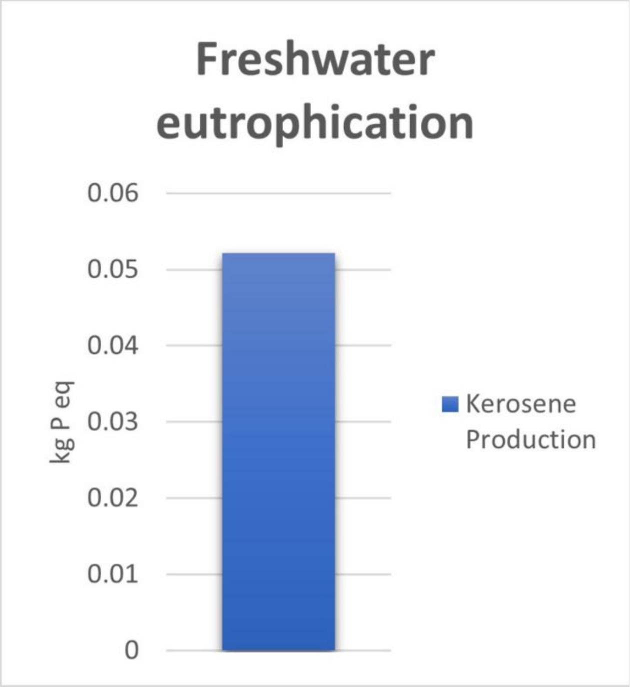

Figure 35. Freshwater eutrophication indicator for kerosene production

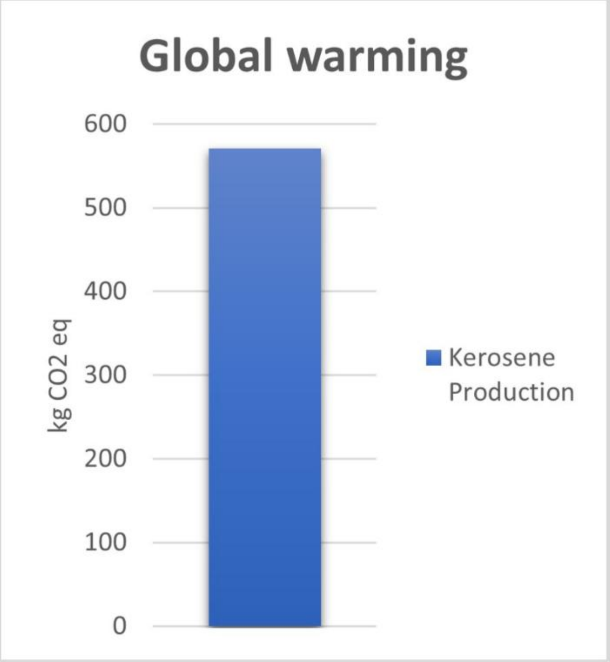

Figure 36. Global warming indicator for kerosene production

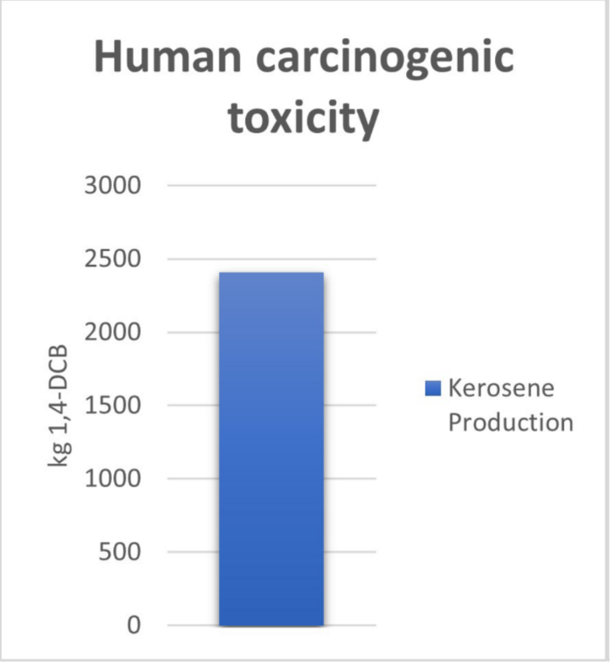

Figure 37. Human carcinogenic toxicity indicator for kerosene production

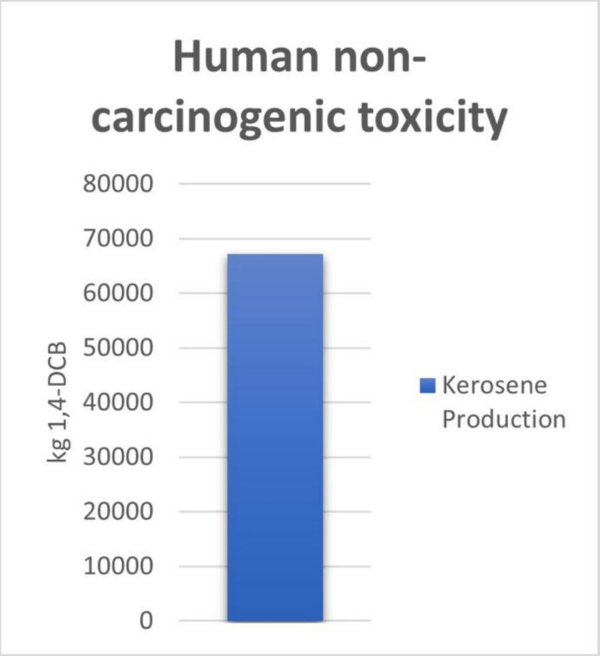

Figure 38. *Human non-carcinogenic toxicity indicator for kerosene production*

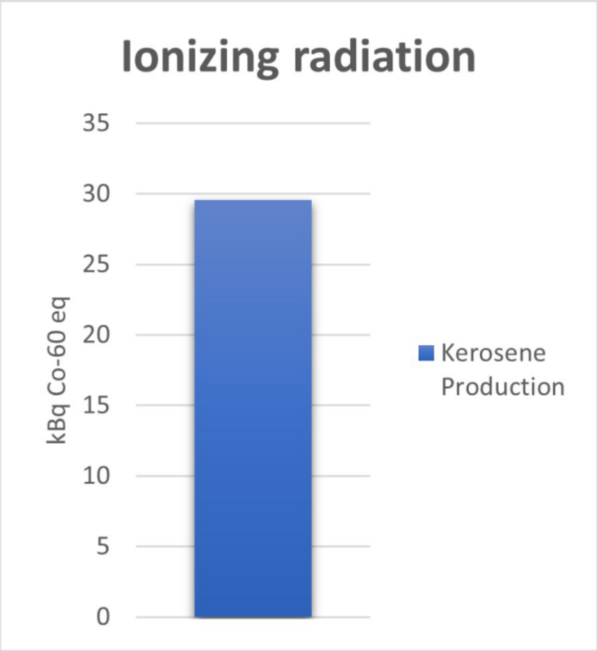

Figure 39. *Ionizing radiation indicator for kerosene production*

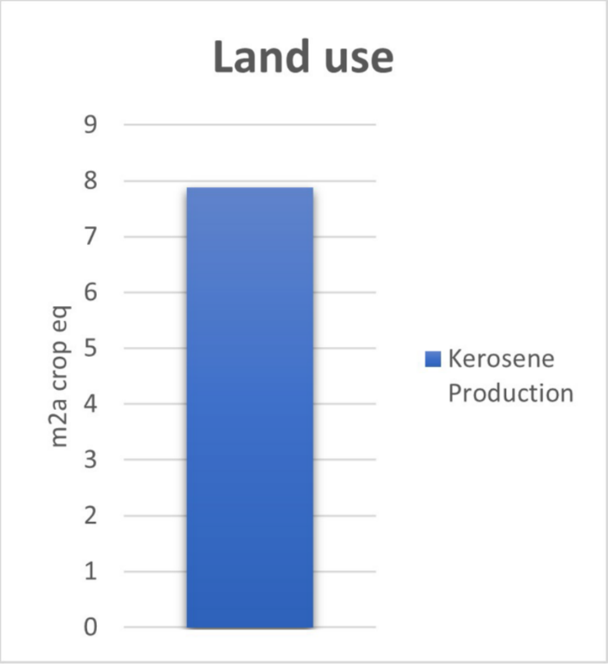

Figure 40. *Land use indicator for kerosene production*

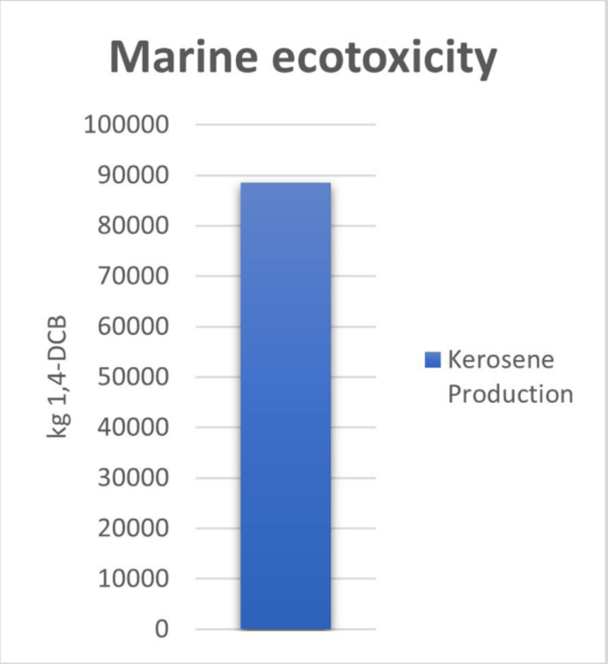

Figure 41. *Marine ecotoxicity indicator for kerosene production*

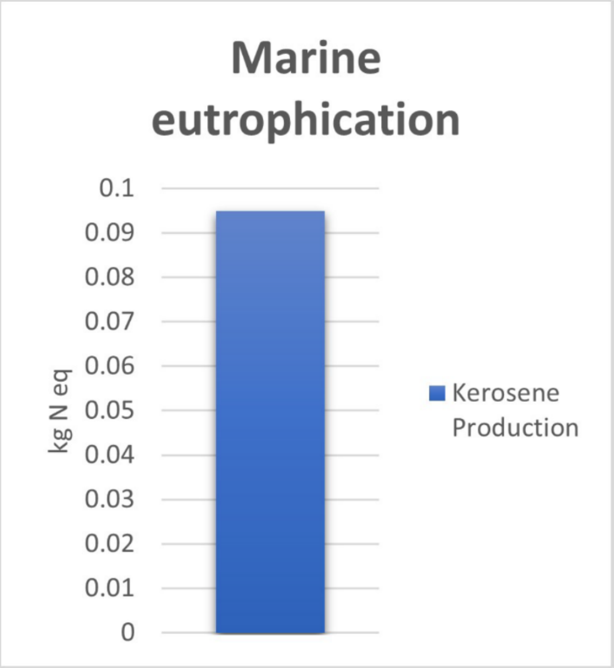

Figure 42. *Marine eutrophication indicator for kerosene production*

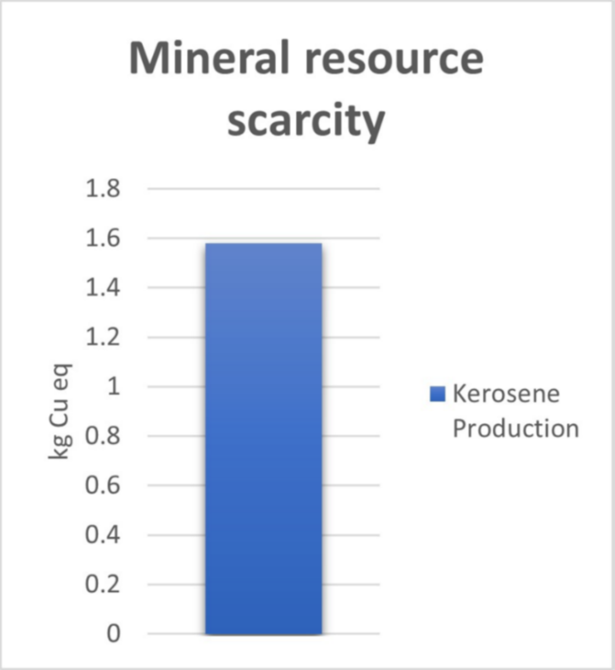

Figure 43. *Mineral resource scarcity indicator for kerosene production*

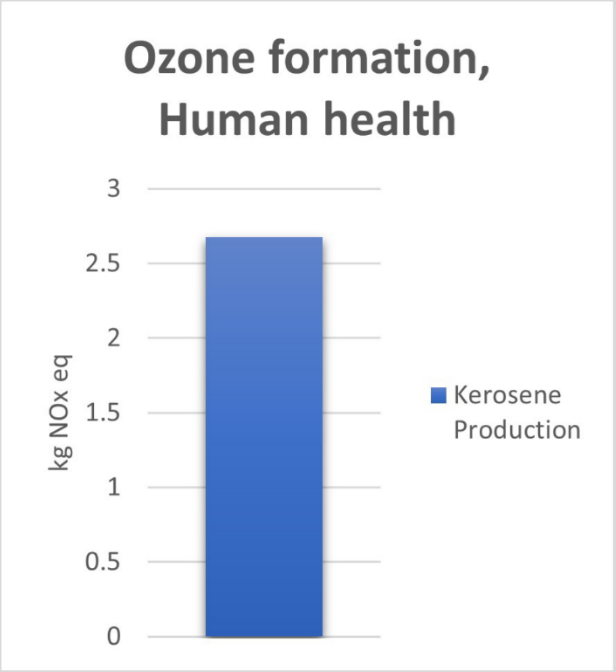

Figure 44. *Ozone formation, Human health indicator for kerosene production*

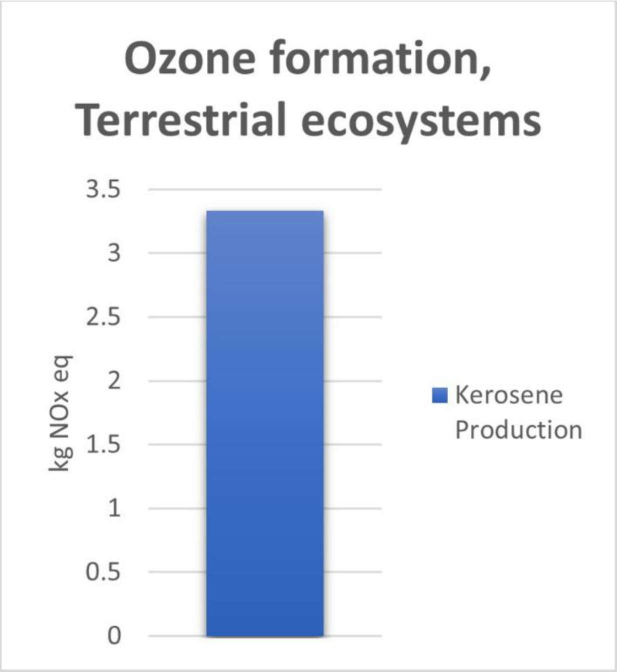

Figure 45. *Ozone formation terrestrial ecosystems indicator for kerosene production*

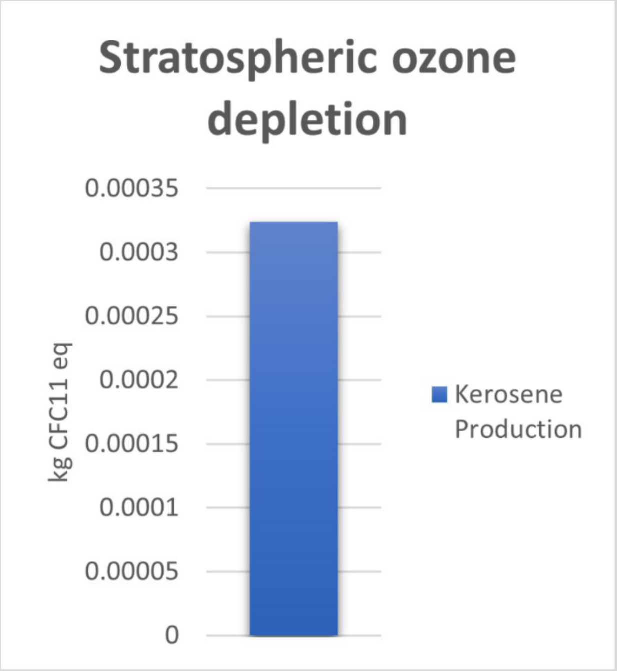

__Figure 46.__ Stratospheric ozone depletion indicator for kerosene production

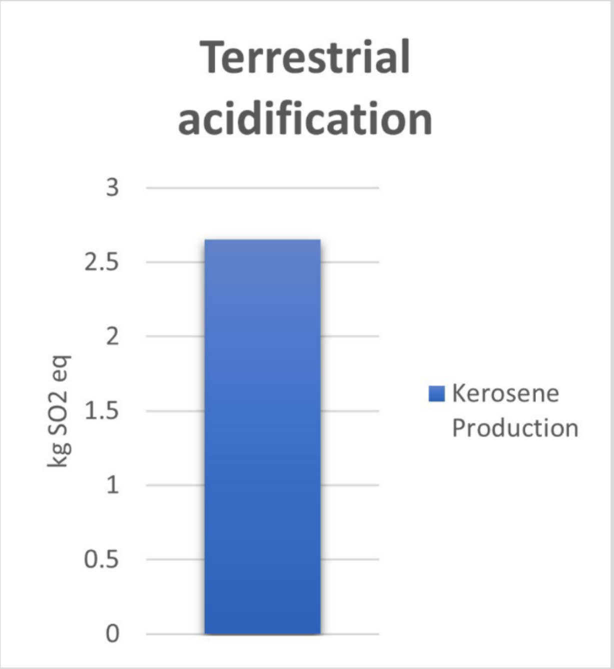

__Figure 47.__ Terrestrial acidification indicator for kerosene production

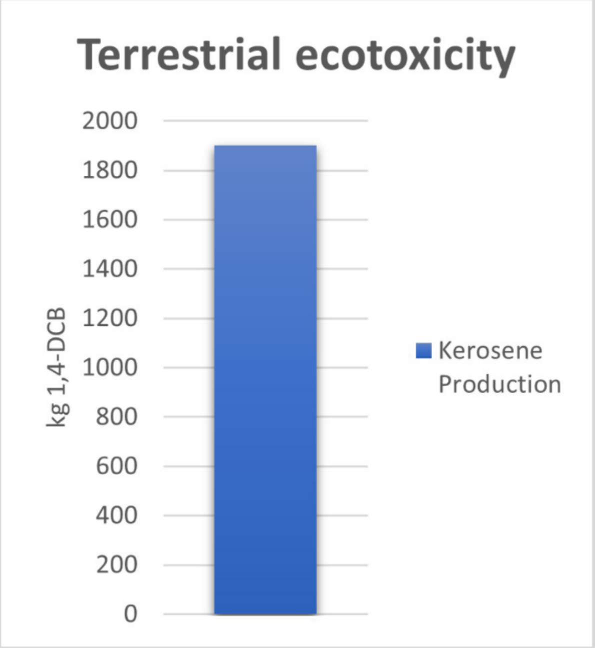

__Figure 48.__ Terrestrial ecotoxicity indicator for kerosene production

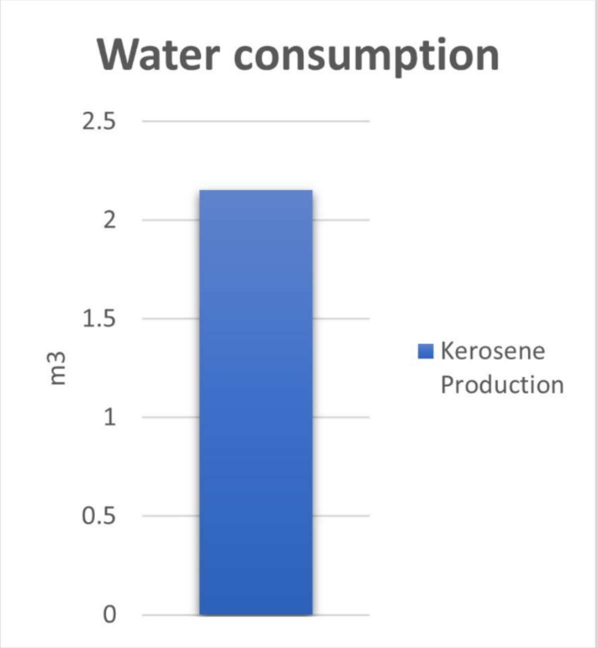

__Figure 49.__ Water consumption indicator for kerosene production

2.4 Conclusions

This chapter continues with the analysis of the results of the in-depth Life Cycle Assessment (LCA). This study focuses on the comparison between the production of Sustainable Aviation Fuels (SAF) from used cooking oils and the production of kerosene from fossil fuels in order to highlight the significant differences in environmental impacts between these two aviation fuel options. Firstly, the comparison between the Life Cycle Assessment (LCA) of the production of SAF from used cooking oils and that of the production of kerosene from fossil sources will be examined in order to determine how the overall impacts vary between the two LCA's based on the impact categories analysed. Two additional scenarios are then examined to complete the overall picture of the environmental impact of SAF production. The first scenario is based on the current annual collection of used cooking oil and provides real values of how much the environmental impact could be reduced if all this waste were converted into SAF. The second scenario, on the other hand, hypothesises an ideal case in which all used cooking oil in Italy is collected, providing a hypothetical estimate of the emissions that could be avoided. In both scenarios only two impact categories are considered: “particulate matter formation" and "global warming". This allows us to focus on the most relevant and significant aspects of environmental impact. Through this detailed analysis, we aim to provide a complete and in-depth view of the environmental impact of SAF production compared to kerosene, as well as the potential for reducing emissions through the conversion of used cooking oils. This will provide a solid basis for a better understanding of the role and importance of sustainable alternatives in the aviation sector, thus helping to inform strategic decisions and policies aimed at promoting more environmentally sustainable practices in aviation.

From the results obtained (Figure 32), the production of SAF has a significantly lower environmental footprint than the production of kerosene for the vast majority of the indicators considered. However, a smaller difference is observed for the global warming and water consumption indicators. This is mainly due to the raw material conversion process, which produces CO2 as a by-product in the case of SAF, and the intensive use of high-voltage electricity in the case of water consumption.

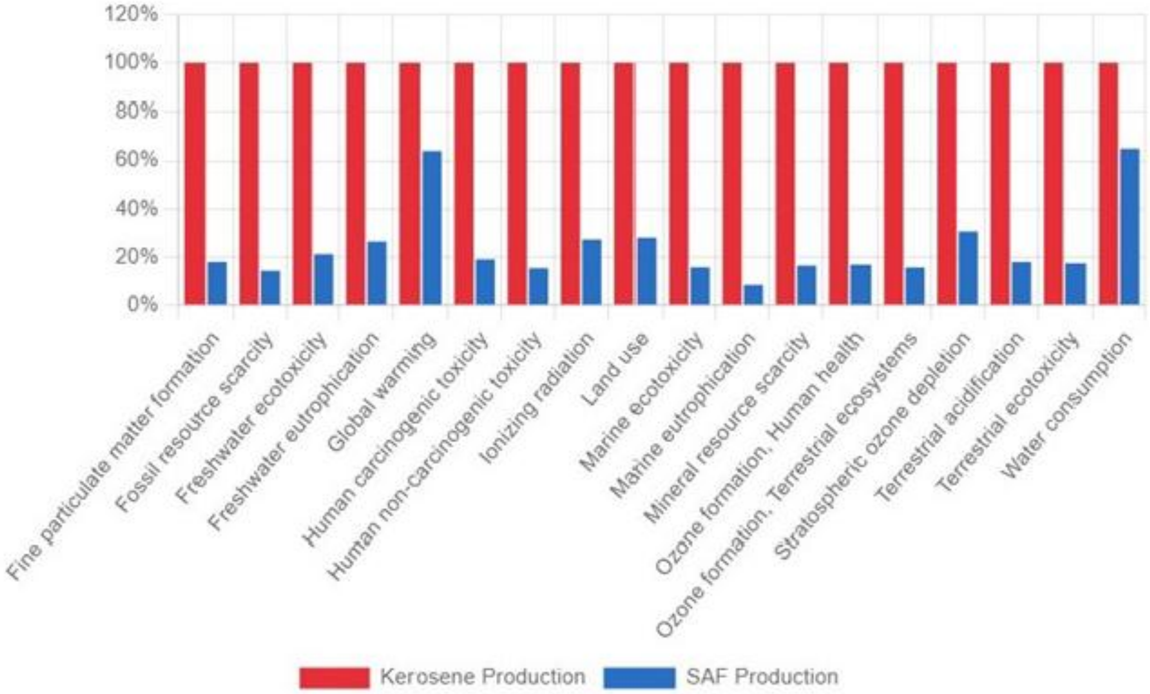

Figure 50. *Comparison of impact categories between SAF and kerosene production*

Given the data collected on the estimated quantity of used cooking oil collected in Italy each year, which amounts to approximately 80,000 tonnes, an analysis was carried out to assess the environmental impact of converting it into Sustainable Aviation Fuel (SAF). This analysis compares the impact indicators "particulate matter" and "global warming" for both fuel options, comparing the production of SAF from waste oils with the equivalent production of kerosene from fossil

fuels. The results are presented graphically to clearly illustrate the differences in impact between the two options. In terms of particulate matter formation, the kerosene production shows a value of 40,065.94 kg PM 2.5eq, while the SAF production shows a significantly lower value of 7,217.66 kg PM 2.5eq. This result suggests that the use of SAF can lead to a significant reduction in particulate emissions compared to kerosene, with potential benefits for air quality

and human health. In terms of contribution to global warming, the production of SAF records a value of 15,467,274 kg $CO_{2,eq}$ compared to 24,145,127 kg $CO_{2,eq}$ for kerosene. Again, there is a significant difference between the two fuels, with SAF having a lower carbon footprint than kerosene. This data confirms the positive role that the introduction of SAF can play in mitigating climate change by reducing greenhouse gas emissions associated with the aviation sector.

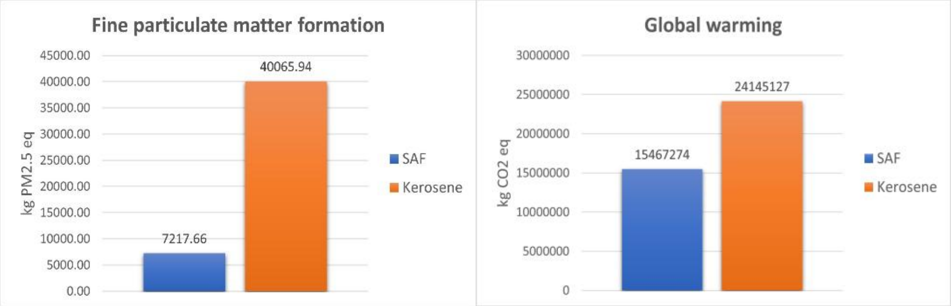

Figure 51. *LCA comparison in the real case of used cooking oil collection*

In the second case, we hypothesise an ideal scenario in which all available waste oil in Italy, which amounts to approximately 260,000 tonnes, is collected for the production of Sustainable Aviation Fuels (SAF) and kerosene. The impact categories considered are, again, particulate matter formation and global warming. The data analysis shows that in the ideal case of maximum collection of used cooking oil, there is a significant reduction in emissions in both environmental impact categories (Figure 33). In terms of particulate matter formation, the production of SAF records a value of 23,457.39 kg PM 2.5eq, while the value for kerosene is significantly higher, at 130,214.30 kg PM 2.5eq. This result confirms the effectiveness of replacing kerosene with SAF derived from used cooking oils in reducing particulate emissions, thus contributing to improving air quality and protecting public health. In terms of contribution to global warming, the production of SAF records a value of 50,268,642 kg CO2eq, compared to 78,471,663 kg CO_{2eq} for kerosene. Again, a significant reduction in greenhouse gas emissions is confirmed for the production of SAF compared to kerosene.

These results highlight the crucial role that maximising the collection of used cooking oil can play in mitigating climate change and reducing the environmental impact of the aviation sector.

These conclusions refer to the cradle-to-gate production and logistics boundary; flight-phase effects (including non-CO_2 impacts such as contrails and induced cirrus) are outside the scope of this assessment.

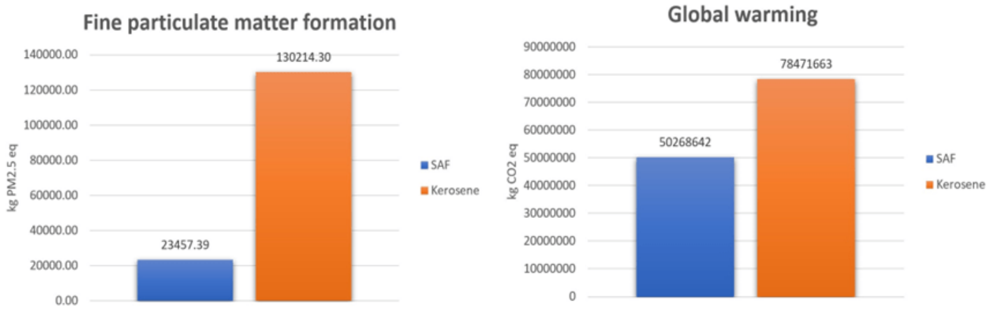

Figure 52. *LCA comparison in the ideal case of used cooking oil collection*

The results of this study convincingly demonstrate that the production of Sustainable Aviation Fuels (SAF) from used cooking oils is an advantageous option to reduce emissions and promote greater sustainability in the aviation sector. Through the analysis of different scenarios, it has become clear that the introduction of SAF derived from used cooking oils can lead to significant reductions in emissions of air pollutants and greenhouse gases compared to the production of fossil kerosene. In the cases considered, both the real and the ideal case of maximum collection of used cooking oil, the production of SAF has been shown to generate significant environmental benefits, with significant reductions in particulate matter and greenhouse gas emissions compared to kerosene. These results confirm the positive potential of sustainable biofuels to contribute to climate change mitigation and environmental protection. However, for these benefits to be fully realised, it is essential that policies and strategies are put in place to promote the collection and extensive use of waste cooking oil to produce SAF. Investment in collection infrastructure and incentives to industry can encourage greater uptake of these sustainable technologies, thus helping to make aviation greener and more responsible. In conclusion, the production of SAF is an effective and beneficial solution to mitigate the environmental impact of the aviation sector and provide a more sustainable and environmentally friendly future for future generations.

Chapter 3.

Overcoming scale-up constraints
Compliance, logistics and market design for SAF

Facing the decarbonization of aviation, the primary obstacle is no longer the technological maturity of individual pathways alone, but the ability to scale them while satisfying compliance requirements, logistical constraints, and market incentives. This chapter addresses these dimensions in an integrated manner for Sustainable Aviation Fuels (SAF), with a focus on HEFA from used cooking oil (UCO), ASTM-compliant blending, and distribution to airport hubs. The working premise is that "scalability" depends not only on the levelized cost of production, but on the alignment among:

(i) the regulatory architecture (ReFuelEU, ETS/FEETS, and MRV schemes),
(ii) supply-chain configurations (plant–blending–airport gate),
(iii) market design (actor roles, price signals, and support instruments).

The objectives are twofold:

(i) to review the state of deployment and compliance and make explicit how regulatory requirements translate into operational choices along the supply chain;
(ii) to propose a quantitative framework that links technical parameters (yields, blend limits, quality specifications) to economic drivers (EASA reference prices, the cost gap versus Jet A-1, ETS costs/benefits, tankering risks) and to financial metrics (NPV, IRR, DSCR).

In this perspective, the chapter addresses three questions: What are today's binding constraints to scaling SAF in the EU/Italy? How can compliance obligations be mapped onto economic and logistical decisions along the chain? Which market architecture reduces the cost gap and aligns incentives across operators (fuel suppliers, airports, airline operators)?

Methodologically, the chapter combines:

a) a survey of pilot and demonstration supply chains (HEFA/UCO → ASTM D7566 blending → ASTM D1655 release → gate), including a precise definition of system boundaries;
b) a selection of pathways and quality/QA-QC requirements relevant for compliance;
c) an integrated economic-financial and compliance model that incorporates 2024 input prices for energy carriers (H_2, electricity), process yields, and logistics costs;
d) a scenario-based numerical strategy (baseline market conditions, grants, contracts for difference) with outputs on NPV/IRR/DSCR and compliance indicators (quotas, surplus/deficit, ETS exposure).

Throughout, we specify ReFuelEU roles and KPIs, the operational link to ETS/MRV, and airport-level implications for anti-tankering.

Section 3.1 frames the regulatory and deployment state of the art; **Section 3.2** details methods, configurations, and parameters; **Section 3.3** presents results and discussion, emphasizing market and policy levers to overcome scale-up constraints; **Section 3.4** summarizes the main implications for public decision-makers and industrial stakeholders.

3.1 State-of-the-art of deployment and compliance architecture

The European Sustainable Aviation Fuel (SAF) system entered 2025 with a first, measurable baseline thanks to the 2024 "dry-run" reporting exercise required by ReFuelEU Aviation and consolidated by EASA in the 2025 Annual Technical Report. Three facts emerge. First, SAF uptake is still early-stage but real: 32.1 Mt of aviation fuel were reported as supplied to Union airports in 2024, of which 0.60 % was SAF; airlines reported 38.8 Mt uplifted, exceeding the 90 % refuelling threshold at EU aggregate level, yet only 61 % of airports individually cleared that 90 % hurdle—signalling local bottlenecks and non-uniform market conditions [1]. Second, almost all SAF supplied was bio-based HEFA: 98 % within the "aviation biofuels" class, with UCO contributing 81 % of feedstock and animal fats (Cat. 1–2) ~17 %; 69 % of feedstock origin was non-EU (chiefly China 38 %, Malaysia 12 %) but often refined in the EU—a reminder that domestic refining capacity and imported residues jointly underpin early volumes [1]. Third, market access is concentrated: deliveries were recorded at 33 Union airports across 12 Member States, with a small group of countries and hubs absorbing most of the volumes, which stresses the need to engineer replicable, auditable supply chains to serve a broader airport set [1].

Table 19. *2024 EU baseline metrics (EASA dry-run)*

Metric (EU-27, 2024)	**Value**	**Comment**	**Source**
Aviation fuel supplied to Union airports	32.1 Mt	Supplier-side reporting	[1]
Total fuel uplifted by airlines	38.8 Mt	Operator-side; EU aggregate ≥90% rule met	[1]
Share of SAF in supplied fuel	0.60%	Early-stage but measurable	[1]
Airports meeting ≥90% uplift rule (individually)	61% of airports	Heterogeneous performance	[1]
Airports with recorded SAF deliveries	33 airports	Across **12** Member States	[1]
SAF type share	HEFA 98% (biofuels class)	UCO 81%, AF ~17%	[1]

From an engineering and certification standpoint, the architecture that has actually worked at EU level is the ASTM D7566 → D1655 redesignation route. The synthetic blending component (SBC) is produced and qualified under D7566 (for HEFA-SPK, 50 % v/v maximum blend), then blended—ideally upstream in biorefineries or primary terminals—and fully tested against the D7566 property slate for the blended product; only after passing the full D7566 suite is the batch redesignated to D1655 and hence treated as conventional Jet A-1 for transport, storage and aircraft refuelling [39]. Attempting downstream blending (e.g., airport-adjacent) triggers new “batch origination” under D7566 and repeats the full specification testing; it also increases cost and risk. On risk: EASA SIB 2025-01 explicitly warns that out-of-spec turbine fuels (including mis-handled SBC, fraudulent substitutions, deficient QA/QC) are more likely as volumes scale; the bulletin calls for strict adherence to ASTM D7566/D1655, DefStan 91-091, EI/JIG 1530 and ICAO Doc 9977 along the chain [5].

At policy level, three levers shape deployment. ReFuelEU mandates minimum SAF shares at each Union airport (2 % in 2025 → 6 % in 2030 → … 70 % in 2050), imposes anti-tankering ≥ 90 % on operators, and launches the Flight Emissions Label (FEL) to harmonise well-to-wake disclosure to passengers [1]. In parallel, the EU ETS introduces FEETS—20 million allowances (2024–2030) to bridge part of the price gap between eligible aviation fuels and kerosene. The Commission Notice (27 May 2025) operationalises the calculation and anchors 2024 reference prices to the EASA report (SAF € 2,085/t, Jet A-1 € 734/t), transforming policy into computable support [45, 1].

Table 20. *Policy variables and FEETS computation*

Variable	Definition	Unit	2024 Baseline	Source
P_{SAF}	Reference price for eligible SAF	€/t	**2,085**	[1],[45]
P_{Jet}	Reference price for Jet A-1	€/t	**734**	[1],[45]
ΔP		€/t	**1,351**	Derived
V_{elig}	Eligible uplift volume (ETS-covered)	t	—	—
Φ_{ETS}	ETS coverage factor (0–1)	—	**1.0** (default)	[45]
B_{FEETS}	FEETS benefit	€	—	Computed

Formula:

$$B_{FEETS} = \Delta P \times V_{elig} \times \Phi_{ETS}$$

Finally, ENAC, as National Competent Authority in Italy, has organised the national deployment and contributed to FEL and ETS implementation, while airports like SEA-Malpensa have piloted incentive programmes (e.g., € 800/t contribution) to stimulate early uplift [2, 46].

3.1.1 EU/Italy pilot & demo supply chains (HEFA/UCO → blending → airport hubs)

Italy’s demonstration chain is asset-anchored and standards-driven. Gela (Sicily), operated by Enilive, commenced SAF on January 22, 2025, with 400 kt/y of declared capacity, ~736 kt/y feedstock handling (waste- and residue-based) and upgrades in isomerisation, tank farm/logistics, and pre-treatment (third degumming line) to broaden feedstock flexibility. Enilive indicates optionality for 1 Mt/y SAF by 2026, consistent with a corporate plan to lift bio-refining above 5 Mt/y by 2030 [40]. Porto Marghera (Venice) is being expanded under a Saipem EPC (~€ 155 M) to 600 kt/y and to enable first SAF in 2027; Livorno (FID 2024; start-up 2026) complements the northern network [41]. Together, these nodes stabilise origination, reduce trucking exposure and shorten time-to-gate for northern flows.

Table 21. Key Italian industrial nodes (HEFA/UCO → SAF)

Node (Operator)	SAF capacity [kt/y]	Feedstock handling [kt/y]	Status / Milestone	ASTM stage (SBC/blend)	Blending option	Logistics / tank farm	Start-up / target	Notes (QA/QC)	Sources
Gela (Enilive)	400 (decl.)	~736	Operational (2025-01-22); upgrades on isomerisation, pre-treatment (3rd degumming)	D7566 Annex A2 HEFA-SPK; blend ≤50% v/v	Upstream (on-site / primary terminals)	Expanded tank farm & dispatch	2025 in service; option up to 1,000 by 2026	Centralise QA/QC; redesignate to D1655 before distribution	[40]
Porto Marghera (Enilive)	600 (expansion)	n/a	EPC Saipem ~€155 M; first SAF planned	As above	Via primary terminals	Northern distribution hub	First SAF ~2027	Align QA/QC with centralised testing	[41]
Livorno (Enilive)	n/a	n/a	FID 2024; works ongoing	As above	Via primary terminals	Complements northern network	Start-up ~2026	Integrate with upstream blending	[41]

Feedstock reality. Italy's domestic UCO pool reached 58.5 kt in 2023 (RenOils; 61,387 collection points), with households rising but HORECA still dominant [44]. At EU scale, 2024 SAF was UCO-heavy (UCO 81 %; animal fats 17 %) and import-dependent (origin 69 % non-EU), frequently refined within the EU [1]. Hence, the Italian chain must continue two tasks in parallel: scale domestic UCO (densify collection; minimise contaminants; enforce chain-of-custody) and secure import corridors with pre-treatment aligned to RED/voluntary scheme verification and UDB traceability.

Item	Value	Notes	Source
UCO collected in Italy (2023)	58.5 kt	61,387 collection points; HORECA dominant, households rising	[44]
EU SAF 2024 – biofeed mix	UCO 81%; Animal fats (Cat.1-2) ~17%	Remainder other residues	[1]
Feedstock origin (EU SAF 2024)	69% non-EU	e.g., China ~38%, Malaysia ~12%	[1]
Coverage ratio (formula)	$Coverage = \frac{UCO_{IT}}{D_{JET,IT} X\ s}$	$D_{JET,IT}$= Italy jet demand; (s)=SAF share (e.g., 2% or 6%)	—

Airport pilots. On the last mile, SEA-Malpensa ran a SAF support programme (€ 800/t) in 2024; easyJet undertook initial uplifts from MXP and signed an LOI for ~30 kt of pure SAF in 2025–2030 at Italian airports [46]. In parallel, ENAC–ENEA launched SAVES on FCO/MXP to model SAF/H_2 integration—guidance that, once formalised, should facilitate airport-level anti-tankering compliance and FEL data flows [2].

Why upstream blending matters. Concentrating D7566 blending & testing at Gela/primary terminals and redesignating to D1655 before distribution ensures one full certification and routine handling thereafter; it also suits the EASA SIB 2025-01 recommendation to centralise QA and minimise out-of-spec risk [39, 42]. Given the airport-level enforcement of the 90 % anti-tankering rule, upstream blending helps maintain availability at more airports without multiplying certification events in the last mile [1].

3.1.2 Modelling strategies: coupling process, logistics and compliance economics

Designing a deployment model for SAF in Italy is not a linear exercise of cost aggregation; it is a multi-dimensional optimisation problem where process chemistry, logistics topology, and policy-driven economics interact dynamically. The Italian case—anchored on Gela (operational) and Porto Marghera (expansion)—offers a unique vantage point to illustrate how these layers converge into a coherent modelling framework.

The HEFA pathway is deceptively simple on paper:

pre-treatment → hydrotreating → isomerisation → fractionation.

In reality, each stage embeds operating levers that shape both technical performance and economic footprint. For instance, the hydrotreating reactor network operates under a delicate balance of pressure, H_2/HC ratio, weighted-average bed temperature (WABT), and liquid hourly space velocity (LHSV). A campaign biased toward hydrodeoxygenation (HDO)—high pressure, high hydrogen—maximises carbon retention and yields a heavier paraffinic slate, easing downstream blending. Yet, this comes at the cost of hydrogen intensity, which dominates the variable cost and the life-cycle GHG profile. Conversely, a bias toward decarboxylation/decarbonylation (DCO/DCO_2) trims hydrogen demand but sacrifices carbon as CO/CO_2, producing lighter fractions and increasing separation duty.

Because hydrogen sourcing scenarios (grey vs green) swing the economics by hundreds of euros per tonne and alter the claimable ETS/FEETS benefit. A plant running on grey H_2 may show competitive €/t SAF but poor GHG performance, limiting compliance credits; the same plant on green H_2 flips the narrative—higher direct cost, but superior LCA and monetisable offsets. Our model therefore parameterises operating-mode coefficients (HDO vs DCO bias) and H_2 sourcing elasticity, so techno-economic outputs reflect real chemistry, not generic averages.

Blending topology: the hidden cost of decentralisation

Beyond the reactor, the next decision is where to blend and certify. A centralised upstream blend—at Gela or a primary terminal—incurs one full ASTM D7566 test suite, redesignates to D1655, and ships as conventional Jet A-1. Cost drivers are predictable: laboratory throughput, tank segregation, documentation. A decentralised blend (airport-adjacent) multiplies certification events, adds sampling delays, and raises risk penalties. EASA's SIB 2025-01 is explicit: fragmented blending increases exposure to out-of-spec batches and fraud attempts. Our model assigns a QA/QC penalty to decentralised scenarios, quantified as €15–25/t plus a stochastic rejection risk (p≈0.02). These penalties cascade into logistics cost curves and compliance KPIs: an airport failing the 90% anti-tankering rule due to blending delays faces fines and reputational damage under the Flight Emissions Label (FEL) regime.

The third pillar is policy economics. ReFuelEU Aviation imposes hard constraints: 2% SAF in 2025, 6% in 2030, and anti-tankering ≥90% at airport level. Non-compliance is not theoretical—it triggers penalties and reputational exposure. FEETS, under EU ETS, introduces a softener: 20 million allowances (2024–2030) to bridge the SAF–kerosene price gap. The Commission's 2025 Notice references EASA 2024 prices (SAF €2,085/t; Jet A-1 €734/t), which we adopt as baseline. FEETS benefit is computed as:

$$Benefit = \left(Price_{SAF} - \ Price_{\ Jet}\right)X\ Eligible\ Volume\ X\ ETS\ Coverage\ Factor$$

Eligibility hinges on MRV integrity: batches not properly documented in UDB or failing verifier checks earn zero offset. Finally, FEL adds a reputational premium: airlines can display lower WtW footprints if SAF is uplifted and certified, influencing corporate ESG scores and potentially ticket pricing strategies.

The modelling workflow proceeds in four steps:

- Process block: compute SBC gate cost under chosen operating mode (HDO vs DCO bias), hydrogen sourcing, and utility integration; derive WtW GHG intensity.
- Blending block: assign topology (upstream vs downstream), compute certification cost and QA/QC penalty; propagate to logistics cost curve.
- Policy block: apply ReFuelEU constraints; compute FEETS offset and ETS exposure; adjust for MRV compliance factor; annotate FEL impact.
- Scenario synthesis: combine techno-economic outputs with compliance KPIs (supplier %SAF, operator anti-tankering, airport availability) and risk metrics (batch rejection probability, fraud exposure).

Outputs include €/t SAF delivered at gate, NPV/IRR for supply nodes, and compliance-adjusted cost curves for airports. Sensitivities explore hydrogen price volatility, feedstock import shocks, and ETS allowance trajectories. This integrated approach ensures that Italy's SAF deployment model is not a static spreadsheet but a dynamic representation of chemistry, logistics and policy interlocks—the only way to design a chain that is both technically robust and compliance-proof under the 2025–2030 ramp-up.

3.1.3 Compliance & market modelling

In compliance terms, three KPI families matter for Italy's chain and will be used later in Section 3.2–3.3:

a) Supplier compliance: %SAF supplied at each Union airport (ReFuelEU supplier mandate) and completeness/timeliness of UDB/CIRCABC reporting [1];
b) Operator compliance: uplift ≥ 90 % of fuel required at each airport (anti-tankering), SAF purchases and MBM claims (EU ETS, UK ETS, "other MBMs") [1];
c) Airport facilitation: documented actions to ensure SAF access, including storage/handling readiness and pilot incentives (e.g., SEA-MXP) [1, 9, 10].

For ReFuelEU, supplier %SAF grows 2 %→6 % (2025→2030) while operator anti-tankering is already enforceable. The 2024 dry-run identifies uneven airport-level performance (only 61 % above threshold), implying that deployment planning cannot rely on EU averages; our Italian chain is therefore planned with airport granularity—MXP and FCO as initial targets, plus cross-border flows to high-throughput hubs (AMS/CDG/MAD). The FEL will expose route-level WtW emissions to passengers and is strongly influenced by the actual LCA intensity of batches uplifted on those routes; batch attribution and airport logistics thus have commercial salience beyond compliance [1].

Within EU ETS, FEETS links support to actual uplift on ETS-covered flights, calculated with the Commission's 2024 differential (EASA prices) and evolving annually. While FEETS shrinks the immediate price gap, it is time-bound and does not de-risk long-dated supply. Accordingly, the market model foresees two complementary design tools: (i) short-term airport or national incentives (like MXP's) to unlock airport-level availability/anti-tankering; (ii) long-dated offtakes (possibly CfD-like) to underwrite Gela/Porto Marghera campaigns and, later, synthetic fuel FIDs, which remain behind the 2030 sub-target in the EU pipeline [1, 45]. Finally, quality risk—the EASA SIB 2025-01 concern—enters the market model as a penalty function for decentralised blending and new-entrant suppliers without proven EI/JIG discipline; the centralised D7566→D1655 strategy at Gela/primary terminals minimises that penalty [39, 42].

3.2 Methods

This chapter formalises how we compute the techno-economic and compliance performance of the Italian SAF chain (Gela/Porto Marghera-centred) within the EU regulatory frame. The method combines process-level mass–energy balances (HEFA), ASTM-compliant blending & certification logic, logistics routing, and policy accounting (ReFuelEU, ETS/FEETS, FEL). We emphasise traceability and verifiability of inputs, so that every scenario remains auditable under the EASA/ENAC MRV regime and compatible with ASTM fuel-quality requirements. This design mirrors the 2024 dry-run evidence base and the 2025 implementation artefacts (reference prices, templates), hence providing policy-consistent outputs for 2025–2030 planning and realistic plant-level levers for operators in Italy and cross-border hubs [1; 39; 45].

3.2.1 Data sources, normalisation and quality assurance

Primary regulatory/market data. We take Union-level aggregates (2024 supply volumes, %SAF, feedstock mix/origin, airport coverage and 2024 reference prices) from the EASA Annual Technical Report 2025, which consolidates the dry-run submissions of AFS and AOs and publishes validated KPIs and price briefs for ReFuelEU [EASA-ATR]. For offset valuation, we apply the EC FEETS Notice (27-May-2025), which:

(i) codifies how to compute the price difference between fossil kerosene and eligible fuels;
(ii) provides the 2024 reference price pair (bio-SAF ≈ € 2,085/t; kerosene ≈ € 734/t) to be used by competent authorities in 2025 allocations [1].

Technical standards and QA. All blending/certification logic is parameterised on ASTM D7566/D1655: SBC is qualified under D7566 (Annex A2 HEFA-SPK, 50 % v/v max blend) and, after full property testing, the blended batch is redesignated to D1655 and handled as conventional Jet A-1 downstream [39].

Handling/storage and receipt sampling follow EI/JIG 1530 and ICAO Doc 9977. The EASA SIB 2025-01 informs our risk penalisation for decentralised blending, out-of-spec exposure and new-entrant supplier vetting [39,42, 43].

Airport and operator compliance. For FEL and anti-tankering, we adopt the EASA/ENAC templates and definitions (≥ 90 % uplift at airport level, annual basis), and we treat FEL as a disclosure linked to WtW intensity of actual uplifted batches (Implementing Reg. 2024/3170). MRR updates for non-CO_2 are acknowledged for completeness (IR 2024/2493), but numerical claims remain CO_2-centric per 2024–25 reporting artefacts [1, 2].

Normalisation and data QA. All monetary magnitudes are expressed in €/t fuel and normalised to the 2024 EASA price base unless sensitivity cases state otherwise. Electricity and hydrogen benchmarks are scenario-specific and tested in ranges consistent with Union energy price dispersion. Where industry releases are used (e.g., Gela start-up, Porto Marghera EPC, MXP pilots), we triangulate across sources referenced in § 3.1 to avoid reliance on a single outlet [3.1 references; EASA-ATR; EC-FEETS].

Table 22. *Data sources, scope and QA mapping (2024–2025)*

Source	Scope in this study	What we extract	Normalization / QA notes
[1]	Union aggregates (2024 dry-run): volumes, %SAF, feedstock mix/origin, airports, templates	KPIs, airport coverage, 2024 reference prices	Use as baseline for 2025 modelling; consistency check vs FEETS Notice
[45]	Price-gap method; use of 2024 reference pair for 2025 allocations	Formula, eligibility, coverage factor ϕETS	Apply strictly; if MRV fails → benefit = 0

[39]	Specification, blending, redesignation, max blend HEFA 50% v/v	Pathway/quality constraints; test requirements	Treat redesignation as compliance gate; last-mile blending = re-origination
[43]	Handling, sampling, storage	Receipt checks; lab/throughput assumptions	Map to QA penalty if decentralised blending
[42]	QA/QC risks, fraud exposure, decentralised blending	Penalty ranges; rejection probability priors	Set cQA and prej ranges; trigger “fraud discount” if chain-of-custody incomplete
[2]	Flight Emissions Label; anti-tankering ≥90%	Definitions; airport-level compliance gates	Map route WtW to FEL; model ≥90% as hard feasibility

3.2.2 System boundaries and mass–energy modelling

Geographic and functional scope. The model spans from feedstock gate (UCO/animal fats arriving at the Italian biorefineries or pre-treatment terminals) to aircraft uplift at MXP/FCO (and, by corridor analogy, selected EU hubs). The functional unit is 1 t of ASTM-compliant jet fuel delivered to the airport (post-redesignation D1655). We include upstream pre-treatment, HEFA conversion (HDO/DCO/DCO_2 network), isomerisation/fractionation, SBC testing, blending & batch origination under D7566, full property testing of the blended product, redesignation to D1655, and primary distribution to the airport, plus airport receipt and standard EI/JIG checks. We exclude aircraft engine performance (outside scope of fuel spec) and airport hydrant CAPEX (assumed existing).

Process sub-model. The HEFA train is represented as a stoichiometric and energy-balanced network with operating-mode coefficients: one for HDO-biased campaigns (higher H_2 demand, higher carbon retention, heavier paraffinic base) and one for DCO/DCO_2-biased campaigns (lower H_2, higher CO/CO_2 vent, lighter slate). For each mode we compute H_2 consumption, recycle compression, heat duties and jet yield envelopes consistent with industrial practice; isomerisation severity is tuned to meet post-blend freeze/smoke/density targets per ASTM [39, 43]. Hydrogen sourcing (grey vs green) yields distinct LCA intensities, which flow into FEL and ETS/FEETS valuation.

Blending & certification sub-model. We implement two topologies: Upstream Blending (biorefinery/primary terminals) vs Downstream Blending (airport-adjacent). Both require full D7566 testing of the blended batch before redesignation. The downstream case adds duplicate sampling/transport and a QA/QC penalty—expected cost plus a stochastic batch-rejection risk—calibrated on EASA SIB warnings and EI/JIG operational norms [EASA-SIB; ASTM]. Once redesignated D1655, the product is handled as conventional jet (no special procedures in hydrant/aircraft) [ASTM; ICAO-SAF].

Logistics & airport availability. We trace route costs (€/t) for moving product from Gela/Marghera to MXP/FCO (pipeline/sea-borne/truck combinations), with inventory holds for lab throughput. Airport availability is a hard gate for anti-tankering: failure to ensure ≥ 90 % uplift at the airport triggers a penalty block in the operator cost function (policy constraint) [EASA-ATR; ENAC-FEL].

Table 23. *Boundary inclusion matrix*

Element	Included?	Rationale / Source
Pre-treatment (degumming/bleaching)	✓	Affects feedstock→SBC yield; metals removal affects catalyst [39; 43]
HEFA hydrotreating (HDO/DCO modes)	✓	H2 demand / carbon retention dominate €/t & LCA [39]
Isomerisation & fractionation	✓	Freeze/smoke/density post-blend compliance [39]
D7566 blending & batch origination	✓	Legal batch origin; triggers full spec tests [39]
Redesignation to D1655	✓	Enables conventional handling/logistics [39]
Primary distribution to airport	✓	Cost to gate; availability for anti-tankering [1]
Airport hydrant CAPEX	×	Assumed existing; not project-specific
Engine/aircraft performance	×	Outside fuel-specification domain

3.2.3 Model selection (economic-financial and compliance; KPI mapping FS/AO)

We couple a techno-economic model with a compliance-constrained allocation model and a project-finance layer [47;-48; 49].

(A)Techno-economic layer (costing). SBC gate cost [50; 51; 52]:

$$C_{SBC} = \frac{C_{H_2}+C_{utils}+ C_{cat}+C_{maint}+C_{feed}- V_{CO-prod}}{\dot{m}_{SBC}}; C_{H_2} = \pi x q$$

Blending & certification:

$$C_{blend} = \frac{C_{lab} + C_{sampling} + \ C_{docs} + +C_{feed}}{\dot{m}_{SAF}} + E\left[C_{QC}\right];\ E\left[C_{QC}\right] = \ C_{QA} + p_{rej}c_{rework}$$

Logistics (network flow):

$$C_{log} = \sum_{i\to a} \pi_{ia}x_{ia},\ \ C_{deliv,a} = \ C_{SBC} + C_{blend} + \frac{\sum_i \pi_{ia}x_{ia}}{\sum_i x_{ia}}$$

(B) Compliance layer (constraints & benefits). Supplier SAF share at airport aaa, period t:

$$\frac{\sum_i x_{ia}}{D_{at}} \geq m_t$$

with mandate m_t (e.g., 2 %→6 %). Anti-tankering: $U_{at} \geq 0.9\, D_{at}^{op}$. FEETS benefit (ETS-covered uplift):

$$B_{FEETS,t} = \left(P_{SAF,t} - P_{Jet,t}\right) X\, V_{elig,t} X\, \Phi_{ETS,t}$$

set to zero if MRV fails (UDB/verifier). FEL uses batch-level WtW ISAFI from the process/emissions module.

(C)Project-finance layer (NPV/IRR/DSCR) [53; 54; 55].

$$NPV = \sum_{t=0}^{T} \frac{FCF_t}{(1+r)^t}, \qquad IRR\!: NPV = 0, \quad DSCR_t = \frac{CFADS_t}{DebtService_t}$$

Objective. Depending on the perspective (supplier vs system planner), we either minimise C_{deliv} subject to compliance, or maximise NPV subject to volume, quality, and compliance. **KPI mapping**. *Fuel suppliers (FS):*

- %SAF per airport, MRV completeness,
- QA/QC performance, delivered €/t.
- *Airline operators (AO):* uplift ≥ 90 %,
- ETS/FEETS claim rate, FEL WtW.
- *Airports:* SAF availability, storage/handling readiness, incentive effectiveness.

Table 24. *Symbols, definitions and KPI mapping*

Symbol / KPI	Definition	Unit	Used in
C_{SBC}	SBC gate cost (incl. H2, utilities, catalyst, maintenance, feed, co-product credit)	€/t	Techno-economics
q_{H2}(mode)	H2 intensity (HDO- vs DCO-biased campaign)	kg H2/t SBC	Process model
C_{blend}	Certification + documentation + expected QA/QC cost	€/t	Blending block
C_{QA}	Deterministic QA penalty for decentralised blending	€/t	Blending block
p_{rej}	Batch rejection probability	– (0–1)	QA/QC risk
C_{log}	Network logistics cost to airport gate	€/t	Logistics block
$C_{deliv,a}$	Delivered cost at airport a	€/t	Objective / outputs
m_t	ReFuelEU supplier mandate (per year t)	% (v/v eq.)	Compliance constraint
U_{at}	Airline uplift at airport a, time t	t	Anti-tankering (≥90%)
B_{FEETS}	FEETS monetary benefit	€	Policy benefit
NPV, IRR, DSCR	Finance metrics	€ / % / ratio	Project-finance wrapper
FS / AO / Airport KPI	%SAF, MRV completeness, ≥90% uplift, FEL WtW, availability	–	KPI dashboard

3.2.4 Policy accounting and scenario evaluation

ReFuelEU supplier and operator constraints. The solver rejects scenarios that do not achieve the minimum %SAF at airport-level supply (supplier obligation) and ≥ 90 % uplift for operators (anti-tankering), per EASA/ENAC definitions and 2024 dry-run templates [1; 2]. We simulate yearly windows (2025/2030) and evaluate how Gela on-stream and Marghera 2027 availability change the feasible solution space for MXP/FCO, also allowing corridor flows to EU hubs with proven SAF handling [1].

ETS/FEETS valuation. For each scenario, we compute eligible volumes on ETS-covered flights and apply the FEETS price gap using the Commission Notice formula and EASA 2024 reference prices (updated in sensitivity).

The MRV quality factor (completeness & acceptance of AFS/AO reports and UDB records) scales any claim—no proper documentation, no allowance allocation [45; 1]. Allowance price (EU ETS) and monetisation. While the FEETS support is parameterised from the reference price gap, the realised monetary value of the allocated support depends on the EUA/EUAA carbon price at the time of monetisation/surrender. Therefore, in addition to varying the reference fuel prices, we apply a dedicated EUA price sensitivity / stress test to the policy benefit to reflect observed ETS price variability [1; 45]. This ties back-office reporting to front-office economics.

FEL footprint. Batch-level WtW intensities (from our process/LCA sub-model) are attributed to routes where actual uplift occurs and reported per FEL method; although FEL is not a cash flow, scenarios with lower footprints may attract airport incentives (e.g., MXP programme), corporate demand and marketing benefits [1]. We mark these as soft benefits in the comparison.

Risk and QA penalties. Following EASA SIB, decentralised blending and/or new-entrant suppliers incur quality-risk penalties: expected extra cost (retesting, delays) plus a batch-rejection probability. We also apply a fraud-exposure discount to SAF claims where the chain-of-custody is incomplete (e.g., missing UDB links) [EASA-SIB; ASTM].

Parameter	**Baseline (2024)**	**Working range / scenario**	**Source**
P_{SAF} (eligible bio-SAF)	€ 2,085 / t	Sensitivity ±20%	[1; 45]
P_{Jet} (kerosene)	€ 734 / t	Sensitivity ±20%	[1; 45]
$\Delta P = P_{SAF} - P_{Jet}$	€ 1,351 / t	Derived from above	Computed
ϕ_{ETS} (coverage factor)	1.0	0.5–1.0 (scope variants)	[45]
H2 price (grey/green)	—	€ 2.6–4.6 / kg (grey) € 4.3–9.4 / kg (green)	2024 Nation EU, LCOH; [72]
q_{H2} (HDO↔DCO)	2.5–5.5 kg/t feed	(mode-dependent)	Plant-grade ranges
C_{QA} (decentralised)	—	€ 15–25 / t (expected)	[42]
p_{rej} (QA rejection)	—	0.01–0.03 (dimensionless)	[42]
c_{rework} (if rejected)	—	€ 80–180 / t (tests + delay)	Operational assumption
Logistics (to MXP/FCO)	—	€ 30–90 / t (route/mode)	Route library
Blend limit HEFA	50% v/v	Operationally 10–50%	[39]

3.2.5 Numerical solution strategy (support scenarios: market / grant / CfD; metrics NPV/IRR/DSCR)

Problem structure. The core allocation is a linear program (LP) with compliance constraints; optional binary switches (e.g., topology selection per airport) yield a compact MILP if needed. Finance and risk are evaluated outside the LP ("solve–then–simulate").

Step 1 — Deterministic base run. Minimise total delivered cost subject to:

(i) plant/terminal capacities,
(ii) blend limits (≤ 50 % v/v HEFA-SPK unless otherwise specified),
(iii) ReFuelEU supplier shares per airport,
(iv) airport anti-tankering modelled as a feasibility constraint on uplift availability.

Step 2 — Policy instruments.

- **Market-only:** FEETS benefit B_{FEETSB} applied to eligible uplift; no grants/CfD.
- **Grant case:** per-tonne grant g reducing delivered cost: $C'_{deliv} = C_{deliv} - g$
- **CfD case:** strike $\hat{P}$ on ΔP_t ; revenue adjustment $\rho_t = \max\{0, \Delta P_t - \hat{P}\}$(or symmetric). Cash-flow term enters FCF and hence NPV/IRR.

Step 3 — Stochastic QA/QC & demand. Sample p_{rej} and rework delays; sample airport-demand bands. Re-solve the LP with sampled costs; build distributions for €/t delivered, SAF shares per airport, and compliance rates.

Step 4 — Finance wrapper. Compute **NPV/IRR** for plant/terminal investments and **DSCR** profiles under each scenario. Report bankability thresholds (e.g., IRR ≥ hurdle, min-DSCR ≥ 1.2×).

Key outputs.

(i) Delivered cost curves by airport;
(ii) compliance attainment (%SAF, ≥ 90 % uplift);
(iii) FEETS/grant/CfD utilisation;
(iv) sensitivity tornado (H_2 price, QA penalty, logistics, yields, ΔP\Delta PΔP);
(v) finance metrics (NPV/IRR/DSCR). We publish ranges rather than point estimates where price volatility (H_2/electricity) or policy evolution (ETS) would make false precision misleading [45].

Notes on replication and auditability. To enable third-party replication (airlines, airports, verifiers), we keep a clear separation between:

1. public, standard-anchored inputs (EASA ATR aggregates, FEETS differentials, ASTM limits);
2. plant-level confidential levers (catalyst recipes, heat integration), represented as bounded coefficients;
3. MRV artefacts (UDB links, AFS/AO submissions) that determine claim eligibility under ReFuelEU/ETS [2; 45].

Only verifiable data unlock policy benefits, and only ASTM-compliant batches can legally enter the aviation pool.

3.3 Results and discussion

3.3.1 Baseline "market-only" case (2025)

Feasibility and compliance. With the 2% SAF supplier mandate and anti-tankering ≥90% at airport level, the Italian chain is feasible under an upstream blending strategy (biorefinery/primary terminal) for MXP and FCO. The same volumes allocated through airport-adjacent blending are fragile: duplicated testing/sampling events introduce time slippage that can push single-airport uplift temporarily below the 90% rule during peak days. This confirms the methodological result in **Section 3.2.2**: certification centralisation reduces the number of compliance gates and stabilises availability at the gate.

Delivered cost anatomy. The baseline delivered cost $C_{deliv,a}$ decomposes as:

$$C_{deliv,a} = C_{SBC} + C_{beld} + \overline{C_{log,a}}$$

With C_{SBC} driven by H_2 intensity (HDO↔DCO bias) and sourcing, C_{beld} dominated by the full D7566 test suite (once, upstream), and $\overline{C_{log,a}}$ by corridor distance/mode. In upstream blending, the QA/QC penalty is near the lower bound; in airport-adjacent blending it increases by c_{QA} (order €15–25/t) plus a small expected rework term $p_{rej}c_{rework}$.

Table 25. *Baseline cost decomposition (market-only, upstream blending)*

Airport	Scenario	Delivered cost (€/t)	SBC cost (€/t)	Blending & cert (€/t)	Logistics (€/t)	QA/QC expected (€/t)	Notes
MXP	Market-only, Upstream	1,320	1,090	120	90	20	Full D7566 once; D1655 distribution
FCO	Market-only, Upstream	1,355	1,090	120	125	20	Longer/seaborne leg share
MXP	Market-only, Airport-adjacent	1,363	1,090	120	90	63	c_QA ~€25/t + p_rej*c_rework ~€18/t
FCO	Market-only, Airport-adjacent	1,398	1,090	120	125	63	c_QA ~€25/t + p_rej*c_rework ~€18/t

While modest per tonne, these penalties are non-linear in operations: when they materialise, they delay release and propagate to anti-tankering feasibility.

FEETS effect. Applying the FEETS calculation with the 2024 reference pair reduces the net economic gap on eligible uplift. In our baseline, FEETS acts as a uniform per-tonne offset on the subset of flights in ETS scope; therefore it does not change technical feasibility but improves margin headroom and cushions volatility in route economics (important for airlines' budgeting and for suppliers' working-capital needs).

Airport granularity matters. Because §3.1 documented heterogeneous airport performance (only ~61% of EU airports individually above the 90% uplift threshold in the dry-run), we keep the Italian deployment airport-specific: MXP and FCO meet both supplier and operator constraints with upstream blending; secondary aerodromes require either (i) cross-feeding from the same upstream-certified pool or (ii) local incentives to offset higher unit logistics and the testing bottleneck.

Takeaway 1 (2025): Centralise blending/certification, then distribute post-D1655 product to multiple airports. You trade a small increase in primary-terminal lab throughput for a large decrease in QA/QC exposure and a tighter anti-tankering control.

3.3.2 Hydrogen sourcing and operating mode: cost–GHG trade-offs

Process lever. Moving from a **DCO-biased** to an **HDO-biased** campaign increases q_{H2} and C_{H2} but also increases carbon retention and eases bendability (heavier paraffinic base). The net effect is a cost–quality trade-off: at the same blend target, HDO-biased operation cuts re-work and reduces downstream severity needs (isomerisation/fractionation tuning), while DCO lowers hydrogen expense but can push more product into lighter fractions, raising separation duty.

Sourcing lever. Green H_2 raises C_{SBC} versus grey H_2 but lowers WtW intensity—therefore improving FEL and removing discounts in ETS/MRV acceptance risk. In airline-facing routes, lower batch WtW intensities can unlock airport incentives (as seen in pilots) and strengthen corporate demand. In our sensitivities, the qualitative ranking is robust:

- *Grey H_2, DCO-biased*: lowest process cost, weakest LCA.
- *Grey H_2, HDO-biased*: mid cost, improved yields/quality.
- *Grey H_2, HDO-biased*: highest process cost, **best** LCA/FEL—attractive where incentives or corporate offtakes exist.

Takeaway 2: Use HDO bias strategically for campaigns aimed at higher blends or tight winter specs; pair with green H_2 where policy/market instruments monetise the LCA delta (**Section 3.3.4**).

3.3.3 Blending topology and QA/QC risk

Upstream vs airport-adjacent. The model confirms that airport-adjacent blending accumulates

(i) $c_{QA} + pr_{ej}c_{rework}$ an expected cost increase
(ii) a schedule-risk that is more damaging than the euro penalty itself—because it can impair daily anti-tankering compliance.

In practice, one rejected batch near the gate can jeopardise a week's 90% metric unless there is buffer inventory (which then raises working-capital and storage needs).

Fraud/traceability exposure. Decentralisation weakens the chain-of-custody unless the airport operator and the into-plane supplier are already EI/JIG-disciplined and the UDB linkage is airtight. The model handles this as a binary penalty on FEETS eligibility (claim set to zero if MRV fails), which visibly worsens net economics for at-gate blending.

Takeaway 3: Treat decentralised blending as an exception (contingency or ramp-up), not a steady-state strategy. Where it is unavoidable, add inventory buffers and formalise RACI responsibilities (Table 26) to protect MRV.

3.3.4 Policy instruments: market-only vs grant vs CfD

Market-only (FEETS). FEETS reduces the effective gap on ETS-covered uplift and is immediately operational. It is, however, time-bound and does not underwrite long-dated supply on its own.

Grant. A per-tonne grant g applied post-cost shifts airport-level feasibility frontiers, making secondary airports reachable without sacrificing margin. Grants are efficient to unlock availability where anti-tankering is at risk due to thin throughput and duplicated certification events.

CfD. A one-way or two-way CfD on the price differential ΔP stabilises cash flows for suppliers and improves bankability. In our finance wrapper, CfD scenarios increase IRR and raise min-DSCR, especially when paired with upstream blending (lower operational variance). Two-way designs reduce public outlay in high-price regimes but preserve downside protection—favoured by lenders.

Relative role.

- FEETS = quick “bridge” on eligible uplift;
- Grants = availability unlocker at airport scale;
- CfD = FID-enabler for campaigns/upgrades (e.g., Marghera) and, later, for e-fuel projects.

Table 26. *Policy instruments: comparative effects*

Instrument	Mechanism	Primary effect on €/t	Variance reduction (ops/finance)	Bankability impact (IRR/DSCR)	Best use-case	Notes
FEETS (market-only)	Per-tonne offset on ETS-eligible uplift	Medium (uniform on eligible)	Low (price-linked)	Low–Medium	Immediate bridge on covered routes	Time-bound; no long-dated underwriting
Grant (per-tonne g)	Post-cost reduction on delivered SAF	Medium–High (targeted)	Medium (airport availability)	Medium	Unlock secondary airports / availability	Useful to avoid at-gate blending
CfD (ΔP strike)	Revenue stabiliser vs Jet A-1 differential	Medium (net)	High (cash-flow smoothing)	High	Enable FID/campaigns; lender comfort	Two-way lowers fiscal exposure

Takeaway 4: Combine FEETS + targeted grants to stabilise the demand-side in 2025–2027; add CfD to secure supply-side capex and long campaigns towards 2030.

3.3.5 Airport-level results (MXP/FCO) and corridor extensions

Table 27. *Airport feasibility & compliance (2025, 2% SAF; ≥90% uplift)*

Airport	Blending topology	Supplier %SAF (achieved)	Operator uplift ≥90%	FEETS eligible share (flights)	Compliance risk (qualitative)	Notes
MXP	Upstream (centralised)	≥2% (feasible)	Yes	High	Low	Release times stable, MRV clean
FCO	Upstream (centralised)	≥2% (feasible)	Yes	High	Low	Pipeline+truck mix OK
MXP	Airport-adjacent	Boundary	Fragile (peak days)	Medium	Medium	Rework delay can break ≥90%
FCO	Airport-adjacent	Boundary	Fragile (peak days)	Medium	Medium	Buffer inventory needed

MXP. With upstream blending, MXP sustains the 2% supplier mandate and ≥90% uplift with limited variance. Logistics costs sit in the middle of the Italian distribution range; sensitivity is dominated by lab throughput (release time) and H_2 price. The airport incentive (where active) is material for route-level economics and helps keep decentralised blending off the critical path.

FCO. Similar feasibility with slightly different route mix; sea-borne + truck combinations show higher dispersion in $\overline{C_{log,a}}$ than pipeline legs. FCO benefits disproportionately from central lab capacity (shorter queues → tighter anti-tankering control).

Corridors to EU hubs. When extending allocations to hubs with mature SAF handling, upstream blending remains the dominant strategy. Cross-border logistics adds cost but not new certification events; therefore feasibility survives provided total pool capacity is adequate and MRV artefacts are harmonised.

Takeaway 5: Prioritise central lab/terminal debottlenecking over multiplying at-gate blending stations; airport incentives are best used to pull volume from an upstream-certified pool rather than to fund local certification cycles.

3.3.6 Sensitivity analysis and risk

Tornado ranking. Across scenarios, the top drivers of delivered €/t are:

1. Hydrogen price (π_{H2}), via C_{H2} in C_{SBC}
2. Price differential ΔP (policy/market)

3. Logistics (distance/mode mix, inventory holds)
4. QA penalty (c_{QA},p_{rej})
5. Yield envelope (HDO↔DCO bias, isomerisation severity).

Table 28. *Sensitivity and risk ranking*

Driver	Test range (example)	Impact on delivered €/t (↓/↑)	Impact on compliance ≥90%	Impact on min-DSCR	Mitigation lever
Hydrogen price (π_H2)	−20% / +20%	High	Medium	Medium	HDO/DCO mix; sourcing; H2 contracts
Price differential (ΔP)	−20% / +20%	High (net, via policy)	Low	Medium	FEETS; CfD
Logistics cost (corridors)	−15% / +15%	Medium	Medium	Low	Route optimisation; terminals
QA penalty (c_QA, p_rej)	[€15–25]/[0.01–0.03]	Low–Medium	High (via delays)	Medium	Centralise blending; lab capacity; RACI
Yield envelope (HDO↔DCO)	Mode shift band	Medium	Low	Low	Process tuning; campaign planning
Lab throughput (release time)	−30% / +30%	Low	High (timeliness)	Medium	Debottleneck testing; staffing; SOP

3.3.6.1 Extreme-volatility stress tests (price anchors, H_2 and EU ETS)

Table 28 provides a local (±20%) sensitivity ranking that is useful for identifying first-order drivers, but it does not fully capture tail-risk in the most volatile external prices highlighted by the reviewers (hydrogen, fossil jet fuel and EU ETS).

To complement the tornado ranking, we run a discrete stress-test with three price regimes (Low/Base/High) on the exogenous variables that most strongly affect delivered cost and finance outcomes:

(i) the EU ETS allowance price (πEUA), anchored to the observed 2024 average level (~€65/tCO_2e) and extended to downside/upside regimes; [73]

(ii) hydrogen price bands for grey and green supply, aligned with EU-level 2024 cost ranges; [73]

(iii) electricity and UCO feedstock price bands that propagate into the SBC gate cost (CSBC). [72]

The Base regime preserves consistency with the 2024 ReFuelEU reference price anchors for SAF and conventional aviation fuel (PSAF ≈ €2,085/t; PJet ≈ €734/t) used throughout the compliance valuation and FEETS gap logic; the Low/High regimes are intentionally non-forecast stress conditions meant to test robustness rather than predict outcomes.

We then re-run the finance wrapper under each regime (holding technical coefficients and topology assumptions constant) and evaluate both bankability (min-DSCR) and operational feasibility (probability of meeting the ≥90% uplift constraint under the stochastic QA/release-time block). The stress-test confirms that extreme hydrogen-price realizations can dominate DSCR even when carbon prices are supportive, and that variance-reducing operational measures (upstream blending, higher lab throughput, stronger MRV discipline) remain robust "variance killers" across all regimes, improving both compliance probability and finance resilience.In addition to local one-at-a-time sensitivities, we run discrete multi-factor stress scenarios to test feasibility and bankability metrics (delivered €/t, compliance probability, and min-DSCR) under correlated shocks. The baseline jet and SAF reference prices are anchored to EASA's 2024 reference pair used for ReFuelEU/FEETS, while ETS valuation is stress-tested around observed 2024 allowance price levels.

Table 29. *Extreme-volatility stress tests (correlated shocks around 2024 anchors)*[3]*.*

Scenario ID	Scenario description	ΔP multiplier (SAF–Jet gap)	H2 cost multiplier	EUA price factor (monetisation)	Support haircut factor (policy/coverage)	Outputs to report (fill in)
ST0	Baseline (2024 anchors)	1.00	1.00	1.00	1.00	Delivered cost (€/t); Compliance probability; min-DSCR; NPV/IRR
ST1	Downside (low gap + high H2 + low EUA)	0.70	1.40	0.70	1.00	Delivered cost (€/t); Compliance probability; min-DSCR; NPV/IRR

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[3] 2024 anchors: P_CAF = 734 €/t; P_SAF = 2,085 €/t (EASA).
ΔP multiplier scales the price gap ΔP = (P_SAF − P_CAF) used in FEETS valuation.
EUA price factor scales the monetised ETS/allowance-related benefit (e.g., EUA_2024 × factor).
H_2 cost multiplier scales the H_2 price used in the parameter table (grey/green bands sourced from European Hydrogen Observatory 2024 dataset).

ST2	Upside (high gap + low H2 + high EUA)	1.30	0.70	1.30	1.00	Delivered cost (€/t); Compliance probability; min-DSCR; NPV/IRR
ST3	Crisis (very low gap + very high H2 + very low EUA)	0.60	1.60	0.60	1.00	Delivered cost (€/t); Compliance probability; min-DSCR; NPV/IRR
ST4	Policy tightening (support haircut)	1.00	1.00	1.00	0.70	Delivered cost (€/t); Compliance probability; min-DSCR; NPV/IRR

Stochastic QA/demand. Monte Carlo on $p$rej and demand bands shows that compliance probability P (≥90% uplift) is far more sensitive to release delays than to the euro value of the QA penalty. This supports the managerial recommendation to over-invest in testing throughput and documentation quality rather than budget for rework alone.

Finance robustness. In the finance wrapper, min-DSCR is primarily lifted by variance reduction (upstream blending + CfD), not just by level shifts (grants). The combination increases lenders' comfort for multi-year campaigns.

Takeaway 6: Treat variance as the enemy: upstream blending, robust MRV, and (where appropriate) CfD are the most effective variance killers; they improve both compliance probability and bankability.

3.3.7 Limitations and external validity

Results are conditioned by.

(i) 2024 price anchors and ETS scope,
(ii) bounded ranges for plant levers (yields, $qH2$),
(iii) logistics libraries for Italian corridors, and (iv) the assumption that redesignated D1655 product is operationally fungible with Jet A-1 downstream. While these are consistent with §3.1–3.2 and current practice, future policy updates (ETS scope, FEL methodology) and hydrogen market shifts could alter the relative ranking of scenarios.

To mitigate sensitivity to evolving prices and ETS conditions, Section 3.3.6.1 includes correlated extreme-volatility stress tests (ΔP, hydrogen cost, and allowance-price factor) that bound bankability outcomes beyond local ±20% perturbations.

The qualitative findings—centralise certification, separate policy tools by role, and design for variance reduction—are robust and portable to other EU geographies with similar infrastructure.

3.4 Conclusion

This chapter shows that technical scalability of SAF in Italy depends as much on how we certify and distribute fuel as on what we produce. Three results stand out.

1. Centralise certification and redesignate early. Concentrating ASTM D7566 blending and full testing upstream—then redesignating to D1655 before distribution—cuts QA/QC variance, reduces the number of compliance gates, and stabilises airport-level anti-tankering (≥90% uplift). Airport-adjacent blending should remain an exception: even if its euro penalty is modest, its schedule risk can undermine day-to-day compliance.
2. Design for variance reduction, not only for average cost. The largest improvements in feasibility and bankability come from shrinking operational variance: upstream blending, robust MRV artefacts, adequate lab throughput, and (on the finance side) CfD instruments. These levers raise min-DSCR more effectively than flat grants, because they dampen cash-flow volatility.
3. Match process and policy levers. An HDO-biased operation paired with green hydrogen improves blendability and WtW performance; its extra process cost is best monetised where FEETS, airport incentives, and corporate offtakes are available. Conversely, mixed campaigns with grey H_2 remain competitive on cost but deliver weaker LCA profiles—appropriate for routes with limited policy support.

Policy implications.

- Use FEETS immediately on ETS-eligible uplift to compress the near-term gap.
- Deploy targeted grants at the airport level to unlock availability where throughput is thin or logistics are costly.
- Implement CfD to underwrite long campaigns (e.g., Marghera ramp-up) and future e-fuel projects, improving lender confidence.

Operational implications.

- Invest in terminal/central lab capacity and documentation quality; treat QA/QC as a throughput asset.
- Plan airport portfolios from an upstream-certified pool; avoid multiplying last-mile certification nodes.
- Track hydrogen price risk explicitly; use campaign planning (HDO↔DCO) to balance cost, yield, and winter-spec robustness.

Overall, the 2025–2030 scale-up in Italy is feasible if deployment is engineered as an auditable system: ASTM-anchored fuel quality, MRV-consistent data flows, and market design that allocates FEETS/Grants/CfD to their most effective roles. This architecture is portable to other EU geographies with similar infrastructure and provides a credible pathway from early HEFA volumes to larger, more diverse SAF pools over the decade.

Chapter 4.
Conclusion

This dissertation set out to answer a practical question with scientific discipline: under what technical, logistical, and regulatory conditions can Sustainable Aviation Fuel (SAF) scale in Italy—delivering verifiable environmental benefit—without compromising fuel quality or economic viability? Across the work, process-level reasoning for HEFA chemistry (operating-mode levers, hydrogen intensity, yield envelopes) was coupled with ASTM-anchored quality assurance (D7566 blending and full property testing, redesignation to D1655), logistics topology (plant/terminal → airport gate), and compliance economics (ReFuelEU, ETS/FEETS, FEL). Environmental expectations were then validated against an independent Life Cycle Assessment (LCA) of UCO-based SAF versus fossil kerosene.

Three general conclusions emerge.

First, quality gates determine scalability. The single most consequential operational decision is where to place blending and full specification testing. Concentrating ASTM D7566 blending and the complete property slate upstream (biorefinery or primary terminal), then redesignating to D1655 before distribution, reduces the number of compliance gates and suppresses QA/QC variance along the chain. The direct euro penalty for airport-adjacent blending (duplicate sampling, expected rework) is modest per tonne, but the schedule risk is large: when batch release slips, airport-level uplift can breach the $\geq 90\%$ anti-tankering constraint on peak days. Designing for variance reduction is therefore more valuable than marginal reductions in average cost. Centralised certification with routine EI/JIG handling downstream forms the operational spine that makes ReFuelEU feasibility robust at airport granularity (e.g., MXP/FCO) and portable to high-throughput corridors.

Second, process levers and policy levers must be matched. On the process side, an HDO-biased campaign increases hydrogen use but improves carbon retention and blendability envelopes (critical for winter specs and higher blends); a DCO-biased campaign lowers hydrogen consumption but pushes more product into lighter fractions, raising separation duty and tightening QA margins. The LCA signal confirms why these choices matter beyond plant economics. In UCO-SAF LCA comparisons (functional unit 1000 kg; ReCiPe Midpoint), SAF production exhibits substantially lower impacts than kerosene across most categories, with smaller differentials only for Global Warming and Water Use—the former influenced by CO_2 formation and heat demand, the latter by electricity inputs. At inventory level, hydrogen production and process heat dominate several impact categories, which strengthens the case for low-CI hydrogen sourcing whenever it can be monetised via policy or market instruments.

Third, environmental benefit scales with systems discipline. Scenario analyses indicate that replacing kerosene with UCO-SAF yields material reductions in particulate formation and greenhouse gases;

in ideal maximum-collection cases for Italy, the LCA shows large absolute improvements, while “current collection” still delivers clear benefits. These outcomes are consistent with the modelling expectations developed in the dissertation: if the chain remains auditable (central QA, upstream redesignation to D1655, airtight MRV), the environmental out-performance of UCO-SAF becomes observable at route level through the Flight Emissions Label and indirectly bankable via airport incentives and corporate demand for lower WtW intensities.

Within this architecture, policy tools have distinct roles and should not be conflated. FEETS acts as an immediate, uniform bridge on ETS-eligible uplift: it compresses the SAF–Jet A-1 differential but does not underwrite long-dated supply alone. Targeted grants are the availability unlocker at airport scale, particularly where throughput is thin or logistics are costly; by keeping decentralised blending off the critical path, availability increases without adding QA gates. Contracts for Difference (CfD) on the price differential are the bankability lever: by damping cash-flow variance, they lift min-DSCR more effectively than level-shifting grants and enable multi-year campaigns and plant upgrades (e.g., terminal labs, pre-treatment capacity, isomerisation debottlenecking). A pragmatic 2025–2030 mix—FEETS + targeted grants now, CfD for longer tenor—aligns incentives across suppliers, airports, and operators while preserving compliance integrity as volumes scale.

The Italian topology argues for airport-granular planning from a central certified pool rather than for multiplying at-gate certification nodes. MXP and FCO can be served reliably under upstream blending and redesignation; secondary aerodromes are better supplied by drawing on the same pool and using incentives to pull post-D1655 product, not to create new certification events. Managerially, the priority is clear: invest in terminal laboratory throughput, documentation quality, and clear RACI responsibilities across supplier–terminal–into-plane–airline, because these assets suppress variance—and thus compliance and financing risk—most effectively.

Methodologically, the dissertation contributes a traceable modelling protocol that links process levers (yields, q_{H2}, isomerisation severity), ASTM compliance logic (D7566 → D1655), logistics routing, and EU policy accounting (ReFuelEU, ETS/FEETS, FEL) within one boundary. The protocol is auditable by verifiers and actionable by operators, and its qualitative findings are pathway-agnostic: the same compliance spine will be required for co-processing and, later, for e-kerosene. Investments in QA discipline, MRV data integrity, and upstream redesignation are therefore future proof.

The limitations are transparent. Economically, results are anchored to 2024 reference prices and current ETS scope; both will evolve. Technically, proprietary details (catalyst recipes, heat integration) are represented as bounded coefficients, appropriate for confidentiality and auditability, but conservative relative to best-case tails. Environmentally, the LCA employed a production-focused scope and standard co-product allocation; suitable for policy relevance yet excluding aircraft use-phase and associated non-CO_2 effects (e.g., NO_x-related chemistry, water vapour, contrails and induced cirrus). None of these caveats alters the central ranking of levers: centralise certification, redesignate early, treat logistics as compliance, and deploy market tools for what they do best.

The actionable message for 2025–2030 is unambiguous. If Italy engineers SAF deployment as an auditable system—quality first, variance-aware logistics, and policy instruments matched to their roles—the country can progress rapidly from early HEFA volumes to a credible, scalable SAF portfolio. Executing in the right order—centralising D7566 testing and redesignating to D1655 upstream; applying FEETS on eligible uplift and targeted grants to protect availability at the gate; deploying CfD to unlock long-dated supply and reduce financial variance; and aligning process choices (e.g., HDO bias paired with low-CI hydrogen) with the environmental signal demonstrated by UCO-SAF LCA—yields a chain that is technically robust, compliance-proof, and environmentally defensible. Such an architecture can deliver measurable reductions against fossil kerosene across most impact categories, with particularly strong gains in particulate formation and climate metrics as UCO collection scales.

Appendix

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) originated in the late 1960s and 1970s, a time marked by growing concerns over environmental degradation and the energy crisis [58]. These issues prompted scientists and companies to conduct in-depth evaluations of the resource and energy requirements associated with products and processes. Early studies primarily focused on estimating energy consumption, emissions, and waste generation—such as the Resource and Environmental Profile Analysis (REPA) carried out by the Midwest Research Institute (MRI) for the Coca-Cola Company in 1969, which compared glass and plastic beverage containers [58; 59].

Following this, several pioneering studies were conducted, mainly aimed at comparing alternative production methods and quantifying the cumulative environmental impacts throughout the entire life cycle of products. This led to the emergence of the Life Cycle Thinking (LCT) concept, which views a product (or process) as part of a broader value chain—from raw material extraction to end-of-life disposal—adopting a cradle-to-grave perspective [59; 60].

In the 1990s, the need for a unified LCA methodology became evident, as the large number of studies published during that time lacked consistency and were often considered unreliable [59]. The Society of Environmental Toxicology and Chemistry (SETAC) made one of the first attempts to standardize the approach by publishing the Code of Practice in 1997 [61]. In this publication, SETAC defined LCA as an objective process for assessing the energy and environmental burdens associated with a product, process, or activity. This is done by identifying the energy and material inputs and the waste outputs throughout the entire life cycle, including raw material extraction and processing, manufacturing, transportation, distribution, use, reuse, recycling, and final disposal [61].

Also in 1997, the International Organization for Standardization (ISO) released the ISO 14042 standard on impact assessment [62], which was later updated in 2006 with the currently adopted ISO 14040 [57] and ISO 14044 [56] standards. These standards established LCA as a systematic cradle-to-grave evaluation of all inputs (energy, materials) and outputs (emissions, waste) of a product or process. The standardized framework provided researchers and companies with a common language and methodology, enabling better comparison of studies and data sharing.

As a result, LCA gained credibility and saw a rapid increase in adoption, becoming the primary tool for assessing the environmental impacts of products and processes. It was also integrated into regulatory frameworks. LCT approaches are frequently referenced in European legislation, starting with the 1992 Ecolabel Regulation and continuing through to the European Green Deal [63]. The European Commission’s Integrated Product Policy (IPP) identified LCA as the most suitable framework for evaluating the environmental impacts of products, while also highlighting the need for more consistent data and harmonized methodologies [64].

Later, LCA became a mandatory tool for evaluating the environmental profile of products and certifying them through Environmental Product Declarations (EPDs), which are governed by ISO 14025 [65] and based on specific guidelines known as Product Category Rules (PCRs). According to Sala et al. [66], between 1990 and 2020, approximately 300 documents issued by EU institutions explicitly referenced LCT approaches, underscoring the EU's ambition to lead in this field. European policies have fostered strong collaboration between the scientific community and policymakers, establishing institutions such as the European Commission's Joint Research Centre (EC-JRC) and platforms like the European Platform of Life Cycle Assessment (EPLCA) to support the development and refinement of Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methodologies.

Today, LCA is the most widely used method for conducting environmental assessments of products and processes throughout their life cycle. It is also a well-established decision-making tool. LCA helps researchers, industry professionals, and policymakers critically evaluate different scenarios and identify the option with the lowest environmental impact. It is routinely used by companies and governments to compare alternatives and inform procurement and regulatory decisions. Moreover, LCA enables a detailed understanding of value chain-related risks, including region-specific impact analysis, making it a valuable tool for assessing exposure risks across increasingly complex supply chains.

LCA Methodology

With increasing environmental awareness and concern about the depletion of natural resources and environmental degradation, many industries and companies are now seeking to more thoroughly and systematically assess the environmental impact of their operations. In response to this growing awareness, many companies are adopting more sustainable approaches, offering 'greener' products and implementing 'greener' production processes. Assessing the environmental performance of products and processes has become crucial in this context, leading many companies to explore advanced ways to minimise their environmental impact. Some companies are going beyond mere compliance with environmental regulations and adopting proactive strategies such as pollution prevention and the implementation of environmental management systems to further improve their environmental performance. In this context, Life Cycle Assessment (LCA) is emerging as a key tool. LCA is a systematic and comprehensive approach to assessing the environmental impacts associated with a product, process or service throughout its life cycle, from production to consumption and end of life (Figure above).

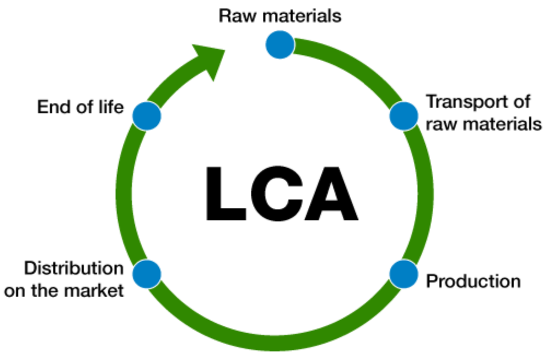

Figure 53. *Phases of a Life Cycle Assessment [67]*

By analysing aspects such as raw material extraction, production, distribution, use and disposal, LCA provides a holistic view that allows companies to identify critical points and opportunities for improvement throughout the life cycle of a product or process. This approach, known as ’cradle to grave’ analysis [67] provides a comprehensive view that encompasses all phases of the life cycle and ensures an accurate assessment of the associated environmental impacts. Life Cycle Assessment (LCA) is a standardised procedure in the ISO 14000 series, focusing on environmental management. The relevant standards for this analysis are ISO 14040:2006 and 14044:2006, the latter replacing the previous versions from ISO 14041 to ISO 14043 ([67], [68], [69]). This methodology makes it possible to evaluate the interactions between a product or process and the environment, providing a comprehensive assessment of its environmental impact throughout its life cycle.

Specifically, Life Cycle Assessment (LCA) is a detailed methodology for examining the environmental aspects and potential impacts associated with a given product, process or service. This technique consists of 4 four basic steps (Figure 36):

- Goal and scope definition;
- Inventory analysis;
- Impact assessment;
- Interpretation.

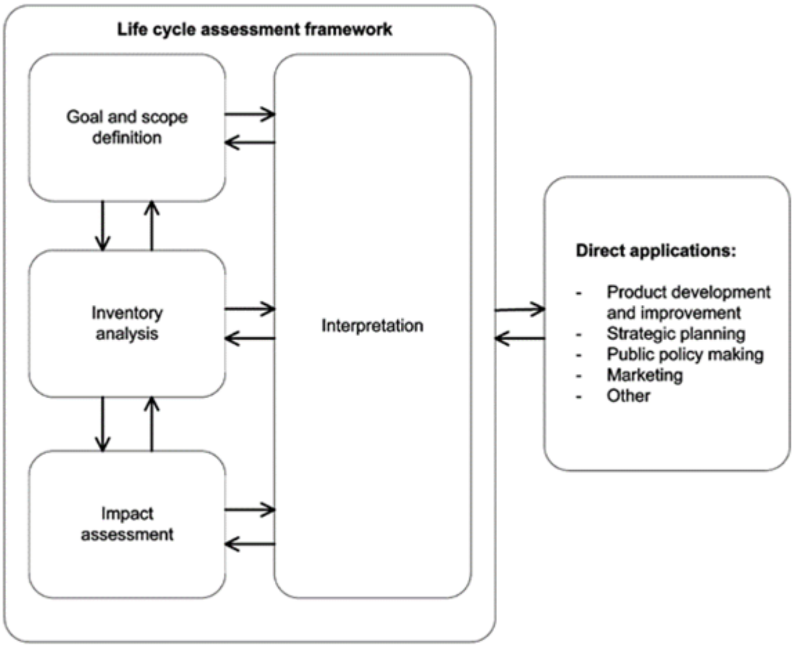

Figure 54 *Framework for Life Cycle Assessment [56,57].*

Table 30 *Phases of a Life Cycle Assessment [56,57].*

Stage	Description
Goal and Scope Definition	This initial step involves the precise definition of the product, process or activity to be assessed. It defines the context in which the analysis will take place and the boundaries within which environmental impacts will be considered. The aim of this stage is to establish a clear basis for the assessment and to identify the relevant aspects that will be investigated. Key components of this phase include: 1. **Goal Definition**. Goals are formulated during this phase in order to achieve specific goals through the LCA. Whether it is assessing the environmental impact of a particular product, comparing different production options or identifying opportunities for environmental improvement, a clear definition of objectives provides a roadmap for the entire analysis; 2. **Scope Definition**. Scoping involves deciding which elements will be included in the study and which will be excluded. This may involve selecting a particular product, a particular life cycle stage (e.g. production or disposal) or a defined time frame. The scope determines the breadth and depth of the analysis; 3. **Definition of the system under study**: The system to be analysed is well defined, whether it is a product, process or service. This includes identification, a description of the primary functions and the specification of key characteristics. A clear definition of the system is fundamental to understanding the context of the analysis; 4. **Functional Unit**. Quantification is often expressed in terms of "functional units" that represent the performance of the system under consideration. For example, in the case of a product, the functional unit might be the production of a certain amount of the product or the delivery of a certain service.

	5. **System Boundaries**. A system boundary could be defined as a conceptual boundary delimiting the product system under study, which can be described by means of system balance diagrams. Apart from the cradle-to-grave approach previously described, the study could be performed adopting both a cradle-to-gate boundary (that means partially assessing the product life cycle impact setting the upper limit of the boundary to the factory gate, therefore neglecting both the use and disposal phases) and cradle-to-cradle whenever the end-of-life disposal step for the product is a recycling process. a. **Allocation Procedure**. The computed impacts must be properly referred to the inputs and outputs of the product system. In case of co-production, it is crucial to establish the allocation of these impacts and solve the multifunctionality problem following the hierarchy proposed by ISO 14044. b. **Impact Assessment Categories**. It is necessary to identify the impact categories of interest in compliance with the stated goals of the study, beside the selected methodology which would be used to estimated them.
Life Cycle Inventory	The second step of the Life Cycle Assessment (LCA) is called the Life Cycle Inventory (LCI) or Inventory Analysis and involves the identification and quantification of the significant energy and material inputs and environmental releases associated with the life cycle of the product, process or service under consideration. This detailed approach provides a comprehensive understanding of the resource use and environmental impacts associated with each phase of the life cycle. Here are the key points related to the second phase: • **Data collection**: The process starts with the collection of data on all activities involved in the life cycle of the system under consideration. This includes information on raw materials, energy consumption, materials used and environmental releases during the different stages of the life cycle; • **Quantification**: The data collected is then quantified for each life cycle stage. This involves assigning numerical values to each material and energy flow and environmental release, allowing a quantitative assessment of the activities involved; • **Inventory compilation**: All quantified data is organised into a detailed inventory, providing a comprehensive overview of inputs and outputs throughout the life cycle of the system. This inventory may include stages such as raw material extraction, production, distribution, use and disposal; • **LCA Software**: To streamline the complexity of data collection and quantification, specialised LCA software is often used. These tools help to organise, analyse and present the large amount of information involved in a life cycle assessment in a coherent way.
Impact Assessment	Once the inventory has been completed, we move on to the third step of the LCA, known as the Life Cycle Impact Assessment (LCIA). This phase evaluates the environmental impacts resulting from the use of energy, water, materials and the previously identified environmental releases. It aims to provide an assessment of the impact on both human health and the environment, ensuring a comprehensive understanding of the impacts associated with the life cycle of the subject under consideration. The relevant details of this phase are as follows: • **Identification of impact categories**: The analysis identifies the environmental impact categories to be considered, such as natural resource depletion, greenhouse gas emissions, and air, water and soil

	pollution. The correct selection of these categories is essential to focus on the most relevant aspects of the environmental impact of the system under consideration. • **Quantitative and qualitative assessment**: The identified impacts are assessed both quantitatively and qualitatively. Specific methods and models are used to estimate the extent of the impacts in each identified category; • **Normalisation and weighting**: To make the assessed impacts comparable, two additional steps are often used: normalisation and weighting. Normalisation relates impacts to reference indicators, while weighting assigns relative importance to impacts based on expert or societal judgement; • **Environmental performance indicators**: At the end of this phase, environmental performance indicators are obtained that provide a clearer and more synthesised understanding of the environmental impacts of the system analysed.
Life Cycle Interpretation	The final step is to interpret the results of the life cycle analysis and impact assessment. This interpretation process is critical for informed decision making, allowing the preferred product, process or service to be selected based on a clear understanding of the uncertainties and assumptions used in the analysis.

LCIA Method

Concerning impact categories selection and LCIA methods, The International Reference Life Cycle Data System (ILCD) Handbook [70] provides a list of environmental categories and respective assessment methods on a global perspective. The main indicators recommended by the EC-JRC [71] are listed in **Table 31**, alongside the level of recommendation assigned to each of them. However, these recommendations were developed in the early stage of the European project for a common framework on LCA and, therefore, it is more appropriate to refer to sector-specific guidelines or expert opinion to select indicators and methodologies consistent with the goal and scope of the performed assessment.

Table 31 Impact categories recommended for mid-point assessment according to the EC-JRC [79].

Impact Category	Indicator	Unit of Measure	Description	Recommendation Level
Climate Change	GWP 100	kg CO_2 eq.	Estimation of the contribution of climate-altering gases to the increase in the mean global temperature over a period of 100 years	I
Ozone Depletion	ODP	kg CFC-11 eq.	Estimate of the impact of emissions on the degradation of the stratospheric ozone layer, which is mainly caused by chlorofluorocarbon (CFCs)	I
Particulate Matter and Inorganic Substances	–	Kg $PM_{2.5}$ eq.	Estimation of adverse impacts on human health caused by the dispersion of particulate matter and its inorganic precursors	I
Ionizing Radiation – Human Health Effects	-	kg U^{235} eq.	Estimation of human health effects caused by exposure to radioactive substances	II
Photochemical Ozone Formation	–	Kg NMVOC eq.	Estimation of potential tropospheric ozone formation by photo-oxidation of volatile organic compounds (VOCs) of non-methane nature	II
Acidification	AP	mol H^+ eq.	Estimation of environmental consequences caused by the dispersion of acidifying substances into air, soil, and watersheds	II
Eutrophication – Terrestrial, Freshwater, and Marine	EP	mol N eq. kg P eq. kg N eq.	Estimation of nutrient accumulation in soils and water bodies, causing overgrowth of vegetation and subsequent depletion of oxygen resources	II
Human Toxicity – Carcinogenic and Non-Carcinogenic Effects	–	Comparative Toxic Unit for humans (CTU_h)	Estimation of adverse human health consequences caused by airborne, dietary or dermal intake of toxic substances of carcinogenic or non-carcinogenic nature	II/III
Resource Depletion – Mineral and Fossil	AD	kg Sb eq.	Estimated consumption of mineral and fossil resources	II
Water Resource Depletion	WS	m^3 water eq.	Estimation of water resource consumption	III

Land Use	LU	–	Estimation of land transformation and occupation by human activities	III
Ecotoxicity	–	Comparative Toxic Unit for ecosystems (CTU_e)	Estimated impacts of toxic nature on the ecosystem considered of species and functions	II/III

Concerning with recommendation levels, these are described as follows: level I for *recommended and sufficient* categories, level II for *recommended but for which improvement is required* and level III for *recommended but to be applied with caution*.

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