Review

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Foreword

The oil supply crisis and closure of the Strait of Hormuz due to the US-Iran war, and the summer heatwaves and wildfires are prompting European leaders to accelerate the energy transition, to reduce dependency on fossil crude oil and to accelerate the use of local renewable energy. This *Review* is focused on the potential contribution of our industry to these objectives.

Advanced biofuels can contribute to both European energy security and decarbonisation of transport: several studies, including those undertaken by Concawe and also by the European Commission, have shown the importance of their potential availability in Europe. The first article of this *Review* summarises a study, conducted by Concawe together with Utrecht University and TNO, which investigates Europe's potential biomass-to-advanced-biofuel supply chains under different biomass availability and demand scenarios.

For some time, algae have been considered to be an important potential source of additional biomass to contribute to the decarbonisation of transport, although their development level has remained low. The second article presents the results of a literature review assessing the current state of the algae industry, and examines the challenges and opportunities of various algae-to-liquid biofuel pathways and their economic feasibility and sustainability performance.

The formation of contrails and contrail cirrus from aircraft exhaust vapour emissions have been identified as having an impact on global warming in the same order of magnitude as aircraft CO_2 emissions. The European Union is investigating the potential for tighter controls over the constituents of jet fuel that have been identified as contributors to the formation of contrails, i.e. sulphur, aromatics and naphthalenes. The third article reviews how fuel composition can influence contrail formation and climate, and assesses the impact of a change in fuel specifications on existing refineries and jet fuel availability.

The last article provides a synthesis of an S&P Global Commodity Insights study commissioned by Concawe to assess the potential evolution of Europe's refining and liquid fuel production industry under two scenarios, both of which lead to net-zero greenhouse gas emissions in 2025. The first scenario assumes a rapid and unprecedented electrification across transport modes, and the second relies more on low-carbon and renewable fuels along with a reduced emphasis on electrification.

Jean-Marc Sohier
Concawe Director

Contents

Advanced biofuels are expected to play an important role in decarbonising the EU transport sector, particularly in hard-to-abate segments such as aviation, maritime transport and heavy-duty road transport. However, key questions remain on how Europe can efficiently mobilise biomass feedstocks and develop the infrastructure required for large-scale, cost-effective deployment.

This article summarises a study, conducted together with Utrecht University and TNO, which covers the main lignocellulosic feedstocks listed in Annex IX of the Renewable Energy Directive, and provides a comprehensive, cost-optimised assessment of Europe's potential biomass-to-advanced-biofuel supply chains under different biomass availability and demand scenarios. The study develops and integrates high-granularity data on biomass availability, transport logistics and conversion process technologies, including gasification and Fischer-Tropsch (GFT) and hydrothermal liquefaction (HTL). These technologies serve as representative examples of large-scale, capital-intensive centralised plants and smaller, flexible decentralised systems, respectively.

Using geospatial and optimisation modelling tools, the study identifies which feedstocks and process technologies are best suited for deployment, what supply chain strategies (centralised vs. decentralised) are most efficient, and how integration with existing industrial infrastructure, such as oil refineries, can support a cost-effective scale-up of advanced biofuel production in Europe.

Enquiries: FuelsManufacturing@Concawe.eu

Decarbonising transport is crucial for Europe's greenhouse gas reduction goals, with biofuels expected to play a key role, particularly in the aviation and maritime sectors where electrification is challenging. Among the Annex IX biofeedstocks included in the Renewable Energy Directive, algae initially drew interest due to their rapid growth and carbon dioxide utilisation. However, economic and technical barriers have so far limited their commercial deployment. In Europe, algae production is still largely oriented towards high-value markets such as food, feed and cosmetics, while applications in biofuel production remain at an experimental and pilot scale.

This article presents the results of a literature review assessing the current state of the algae industry, covering both macroalgae and microalgae. It examines the economic feasibility and sustainability performance of various algae-to-liquid biofuel pathways. The analysis discusses key economic barriers and opportunities, as well as sustainability considerations, methodological gaps in current assessments, and research needs that could support future scale-up.

Enquiries: FuelsManufacturing@Concawe.eu

Sustainable biofeedstock supply chains for advanced biofuels in Europe towards 2050

This article summarises a study conducted by Concawe in collaboration with Utrecht University and TNO, providing a cost-optimised assessment of Europe's biomass-to-advanced-biofuel supply chains across Annex IX lignocellulosic feedstocks under different biomass availability and demand scenarios. Using high-granularity data and geospatial optimisation modelling, it evaluates advanced biofuel pathways such as gasification and Fischer-Tropsch (GFT) and hydrothermal liquefaction (HTL) under both centralised and decentralised supply chain configurations, and identifies efficient deployment and infrastructure-integration strategies for scaling up advanced biofuel production in Europe.

Author

Themistoklis Neokosmidis (Concawe)

Introduction

Advanced biofuels are expected to play an important role in decarbonising the EU transport sector, particularly in hard-to-electrify segments such as aviation, maritime transport and heavy-duty vehicles, contributing to the EU's target for a climate-neutral economy by 2050. Their successful deployment will rely on ensuring sufficient biomass availability, managing production costs, and developing resilient and efficient supply chains, all of which are key elements for realising Europe's long-term bioenergy potential.

Several studies, including one conducted by Concawe in collaboration with Imperial College London (ICL),[1] have quantified the potential availability of biomass in Europe (based on RED[1] II, Annex IX) at country level. While these studies incorporate technical and sustainability constraints, they exclude the economic and logistical aspects of biomass mobilisation. Yet, the costs of production, transport and conversion will be decisive for the competitiveness of advanced biofuels. Moreover, identifying optimal supply chain strategies, tailored to geography and existing infrastructure, remains critical for determining the most efficient and sustainable deployment pathways across Europe.

In this context, Concawe, together with Utrecht University and TNO, conducted a study to address the following key questions:

1. What are the optimal supply chain configurations (centralised vs decentralised) and main cost drivers for advanced biofuel supply chains in Europe?
2. How do geography and existing infrastructure influence supply chain economics?
3. In what ways do technology selection and economies of scale affect total production costs?

Previous studies have typically focused on regional or national cases with limited treatment of transport infrastructure.[2] By contrast, this study explores these dynamics at a pan-European scale, combining high spatial resolution with detailed modelling of intermodal transport logistics.

Project methodology

Supply chain model overview

To address the above questions, a supply chain optimisation model based on Mixed-Integer Linear Programming (MILP) was developed to determine the economically optimal advanced biofuel supply chains across Europe for 2030 and 2050, under different biomass availability and demand scenarios.

The model covers the EU-27 plus the UK[2] with high regional granularity (NUTS 3).[3] As the MILP framework does not explicitly include geographical coordinates or transport networks, it was coupled with the GIS-based Biomass Intermodal Transport model (BIT-UU), which calculates least-cost transport routes between biomass sources and conversion sites across Europe, integrating all major transport modes

1 Renewable Energy Directive

2 Countries such as Norway and Switzerland were not included in the analysis, as the data and information available in the literature, including that used in the ICL-Concawe study, focus primarily on the 27 European Union member states plus the UK, which was formerly an EU member.

3 NUTS = Nomenclature of territorial units for statistics — https://ec.europa.eu/eurostat/web/nuts

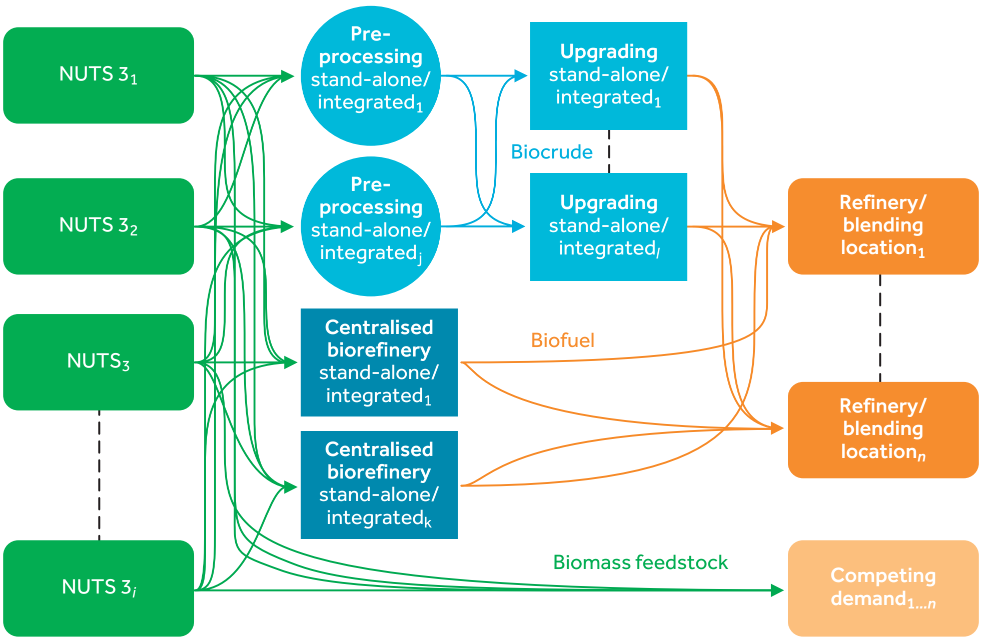
(road, rail, and inland waterways and shipping). In addition to advanced biofuels, the model also calculates the optimal distribution of biomass for other energy uses, such as electricity and heat, ensuring a comprehensive representation of the total bioenergy network.

Figure 1 illustrates the conceptual structure of the simulated supply chains, and the main input categories used in the optimisation are listed below:

- **Biomass availability and production costs:** based on RED II, Annex IX, Part A feedstocks, modelled at high spatial resolution (NUTS).
- **Transport routes, infrastructure and costs:** including solid biomass and liquid products (biocrude or biofuels) moved via different transport modes and distances.
- **Biofuel production costs:** for two thermochemical pathways — gasification and Fischer–Tropsch (GFT) and hydrothermal liquefaction (HTL) — assessed for stand-alone operation and potential integration with existing industrial sites (e.g. biofuel plants or refineries).
- **Advanced biofuel and competing demand:** reflecting demand projections consistent with RED III,[4] FuelEU Maritime[5] and ReFuelEU Aviation,[6] as well as competition from other bioenergy (electricity and heat) and material uses.

Further details on the methodology, model components and input datasets used for the optimisation are presented in the following sections.

Figure 1: Structure of the spatially explicit supply chain optimisation model



Centralised configuration: biomass pre-processing, conversion and biofuel upgrading occur at a single location.

Decentralised configuration: biomass pre-processing (e.g. biocrude production) and biofuel upgrading take place at separate sites.

Stand-alone configuration: facilities operate independently, without integration benefits from co-location with existing industrial sites.

Each biofuel blending location (at oil refineries) and non-transport bioenergy demand point (major cities) is connected to all potential supply locations across the EU-27 + UK (NUTS 3 level).

4 https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng
5 https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en
6 https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en

Biomass availability and production costs

Although biomass availability has been estimated in several previous studies, the spatial resolution of these assessments has generally been limited to the country level. This coarse granularity restricts the accuracy of supply chain simulations. As a result, such studies cannot fully capture the logistical challenges and regional variability affecting biomass mobilisation and transport.

To address this limitation, the present study recalculated biomass availability at a higher spatial resolution, at least at the regional (NUTS 3) level within each country for 2030 and 2050. This enhanced granularity allows for more realistic supply chain modelling, reflecting regional differences in resources, infrastructure and transport networks.

The study focuses on lignocellulosic biofeedstocks, summarised in Table 1 which also presents the methodological approach applied for their calculation. For all feedstocks, three biomass availability scenarios were developed—Low, Medium and High—to account for varying levels of innovation and improvements in agricultural and forestry management practices.

Table 1: Overview of the biofeedstocks considered in the study and the methodology applied for each feedstock group to estimate biomass availability at high spatial granularity

Scenario modelling	Low, Medium and High biomass availability scenarios were developed, accounting for different levels of innovations and improvements in agriculture and forestry management practices (in 2030, 2050).
Agricultural biomass	
Feedstocks	Lignocellulosic crops on marginal lands, primary agricultural residues (cereal straw, maize stover, oil crop residues, prunings).
Calculation approach	Crop growth model (AquaCrop developed by the FAO[a]) was used. Climate change, weather, precipitation and soil properties were considered.
Granularity	High resolution (1–10 km^2).
Biomass costs	Production costs were calculated using the calculated biomass yields and accounting for land rent, machinery costs, labour and fertiliser/pesticides input.
Forestry biomass and wood waste	
Feedstocks	Low-grade stemwood, primary and secondary forest residues, post-consumer wood and paper cardboard.
Calculation approach	Country level data from the ICL study were used and scaled to higher granularity (e.g. based on forest density).
Granularity	Regional scale (NUTS 3).
Biomass costs	From the S2Biom project database (all cost factors related to harvesting operations).

[a] Food and Agriculture Organization of the United Nations

It should be noted that not all feedstocks listed in Annex IX of RED II/III were included. Specifically, used oils and fats (Annex IX, Part B) were excluded, as a well-established collection and utilisation infrastructure exists. From Annex IX, Part A, some feedstocks were omitted due to technical, logistical or data-related constraints. These include:

- High-moisture feedstocks such as manure and sewage sludge, which require on-site processing close to their source.
- Municipal biowaste, due to its heterogeneity and need for specialised sorting and pretreatment.[7]
- Secondary agricultural residues, which are difficult to quantify consistently at high spatial resolution.[8]
- Newcomers in Annex IX such as intermediate crops, added to Annex IX after the study's launch, for which reliable modelling tools and datasets are not yet available.

The considered feedstocks cover ~80% of total biomass availability under Annex IX, Part A of RED II calculated in the ICL study.

Biomass and biofuels transport

For the transport modelling, all relevant modes used to supply solid biomass, liquid biocrude and biofuels were considered. These include road transport (trucks), rail, inland waterways and short-sea shipping, as well as intermodal combinations for long-distance supply routes. To optimise the biomass supply chains, the model incorporated the existing European transport infrastructure and network topology (see Figure 2), based on different data sources and tools. For the cost calculations, both fixed and variable transport costs were included and inflated to 2023 EUR.

Figure 2: Transport network topology of the EU showing links (or segments) of road, rail, inland waterways and short sea shipping

[7] Although these feedstocks were not included in the supply chain modelling, their volumes were accounted for by allocating them to bioenergy (electric power and heat generation — E/H) demand to allow flexibility for biofuel supply chains. Their availability volumes (based on the ICL study) were subtracted from the total bioenergy (E/H) demand (see Figure 3, page 10).

[8] Ibid.

Advanced biofuel process technologies and integration strategies

Technology selection and costs

From the available technologies for producing advanced biofuels from lignocellulosic biomass, gasification and Fischer–Tropsch and hydrothermal liquefaction were selected for this study. GFT, currently at a technology readiness level (TRL) of 6–7, is a well-established pathway for producing high-quality drop-in fuels.[3] However, it is capital-intensive and therefore best suited for large-scale, centralised configurations.[4]

In contrast, HTL, with a TRL of 5–6, is an emerging technology being demonstrated at smaller scales.[3] It produces a high-quality biocrude and efficiently processes wet feedstocks. In this study, HTL was assumed to be deployable under both centralised and decentralised configurations.

Although other thermochemical routes with higher TRL than HTL, such as fast pyrolysis, are also available, HTL was prioritised due to the better availability of cost data in the literature. Overall, the analysis was limited to two processes (GFT and HTL) to account for modelling constraints, particularly those related to computational feasibility. These technologies also serve as representative examples of large-scale, capital-intensive centralised plants and smaller, flexible decentralised systems requiring further upgrading later on, respectively.

The cost data for both technologies were derived from scientific publications after a comprehensive review of available information. For each, capital (CAPEX) and operational (OPEX) expenditures were estimated (inflated to 2023 EUR), including potential credits from co-products such as surplus electricity generation. For 2030, the current cost basis was applied, reflecting the expected delayed large-scale deployment of these technologies, while for 2050, a cost reduction factor was assumed to account for technological learning and capacity growth, consistent with International Energy Agency (IEA) projections.[4]

Up to the maximum demonstrated capacity per configuration (see Table 2 on page 9), the economies of scale for process equipment were estimated from literature data.[5,6] As the CAPEX-capacity relationship is inherently non-linear, it was linearised through curve segmentation for integration into the optimisation model.

Table 2: Technology selection (GFT, HTL), and corresponding product yields [4,5,7] and maximum plant scale,[5,6] applied under different supply chain configurations (centralised, decentralised)

	Centralised				Decentralised			
Technology	**Yield** ($GJ_{biofuel}/GJ_{biomass}$)		**Maximum scale** (ktoe/year biofuel)		**Yield** ($GJ_{biocrude}/GJ_{biomass}$) or ($GJ_{biofuel}/GJ_{biocrude}$)		**Maximum scale** (ktoe/year biocrude or biofuel)	
	2030	2050	2030	2050	2030	2050	2030	2050
GFT	0.38	0.45	338	398	-	-	-	-
HTL	0.47	0.66	414	578	0.44	0.62	254	345
Upgrading biocrude— stand-alone	-	-	-	-	1.06	1.06	1,549	1,608

Biorefineries location and integration strategies

Access to transport infrastructure and opportunities for integration with existing industrial sites are key factors influencing the location and economics of new biorefineries. Integration with existing industrial plants can offer significant capital synergies, as well as access to utilities and hydrogen streams required for advanced biofuel production and upgrading (see Table 3).

Accordingly, this study assumed that centralised facilities (GFT and HTL) could be located within intermodal terminals (e.g. ports) or industrial sites such as biofuel plants, pulp mills or refineries, where integration benefits can be realised through shared infrastructure and reduced investment costs. In contrast, decentralised HTL facilities could be built near biomass production areas or adjacent to pulp mills or biofuel plants, which are often close to feedstock sources. The cost reduction factors associated with these integration levels were derived from de Jong *et al.* (2015).[8]

Table 3: Possible host locations of advanced biofuel production and their integration benefits

Location/host side	Integration strategy	Integration benefits
Oil refineries	Retrofitting or repurposing	Access to utilities (natural gas, electricity) and fossil fuel infrastructure
Kraft pulp and paper mills	Co-location	Access to utilities (natural gas, electricity) and solid fuel infrastructure
Existing biofuel plants	Co-location	Access to utilities (natural gas, electricity) and infrastructure
Intermodal terminals	Greenfield	Access to intermodal transport infrastructure
NUTS 3 regions	Greenfield	Access to local biomass

Integration with existing refineries offers the greatest technical and economic synergies, given the similarity of equipment and operational experience in thermochemical processing and hydroprocessing. Therefore, the model considered centralised GFT and HTL plants located at retrofitted refinery sites as a potential configuration. An extra case was also examined to assess the feasibility of repurposing existing refinery hydroprocessing units, further enhancing integration and cost efficiency.

Biomass demand across sectors

The final input for the supply chain modelling involved defining the total biomass demand at both EU and country levels. First, the biomass demand for material and biochemical uses, as estimated in the ICL study,[1] was incorporated to account for competing non-energy applications, with these quantities subtracted from the total availability estimated earlier in the study.

For energy-related demand, publicly available data consistent with the latest EU legislative frameworks (RED III and the Fit for 55 package[9]) were applied. Two main data sources (DI Fuels study[9] and S&P study commissioned by Concawe[10]) were used to define advanced biofuel demand: for 2030, a single demand was set at 19.3 Mtoe, while for 2050, two scenarios (Low and High demand) were developed due to the larger variability in long-term projections (see Figure 3). Considering two different demand scenarios enables the model to capture the optimal behaviour of the supply chain network under varying demand conditions.

Figure 3: Overview of advanced biofuel and bioenergy (electricity and heat) demand[9,10] considered for the supply chain simulations

Advanced biofuel (Annex IX, Part A)

2030
19.3 Mtoe (based on the 'DI Fuels' study[9] by DG RTD[a])

2050
1) Low demand case = **37.6 Mtoe** (RED Scenario—'DI Fuels' study[9] by DG RTD[a])
2) High demand case = **88.2 Mtoe** (More Molecule Scenario—S&P study[10])

Bioenergy (electricity and heat)[b]

2030
107.3 Mtoe[9]

2050
185.0 Mtoe[9]

[a] DG RTD = European Commission Directorate-General for Research and Innovation
[b] Demand allocated only to lignocellulosic feedstock

[9] EU legislation package designed to enable all sectors of the EU economy to meet at least a 55% reduction in greenhouse gases by 2030.

The total demand was spatially distributed according to projected transport activity per Member State, as reported in the EU Reference Scenario 2020.[11] Refineries were set as the advanced biofuel demand nodes in each country, reflecting their role as existing fuel blending and liquid storage hubs within the supply chain.

For non-transport bioenergy uses (electricity and heat), the latest projections from the PRIMES[10] model were applied (DI Fuels).[9] The allocation of bioenergy demand per country was based on projected bioenergy intensity as indicated in the EU Reference Scenario 2020,[11] with demand nodes assumed to be located in the major cities of each country.

Supply chain modelling results

Overview of simulated scenarios

During the methodology development, a series of scenarios were designed to explore variations in biomass availability, advanced biofuel demand toward 2050, and integration strategies. For each model simulation, different combinations of these scenarios were tested and categorised into base and alternative cases (see Table 4). In the base scenarios, the medium biomass availability case was applied, while different biofuel demand and integration configurations were assessed. In the alternative scenarios, the Low and High biomass availability cases were also simulated to evaluate the model's sensitivity to resource potential.

Table 4: Scenarios run in the optimisation biomass supply chain model

Base scenarios			
Scenarios	**Biomass availability scenario**	**Advanced biofuel demand scenario**	**Integration benefits[a]**
2030	Medium	Default	Default
2050–Low demand	Medium	Low	Default
2050–High demand	Medium	High	Default
2050–Repurpose	Medium	Low	Repurpose for oil refineries — default for the other industrial sites
Alternative scenarios			
Scenarios	**Biomass availability scenario**	**Advanced biofuel demand scenario**	**Integration benefits**
2030–Low	Low	Default	Default
2030–High	High	Default	Default
2050–Low demand (Low)	Low	Low	Default
2050–Low demand (High)	High	Low	Default
2050–High demand (High)	High	High	Default

[a] Default integration strategy refers to the following: terminals (greenfield), biofuel plants and pulp mills (co-location), and refineries (retrofitting).

[10] PRIMES: Price-Induced Market Equilibrium System — an energy system model designed to project the energy demand, supply, prices, trade and emissions for European countries and assess policy impacts.

Optimal technology mix and supply chain configurations

The optimal process technology mix and supply chain configurations derived from the modelling are shown in Figure 4 on page 13, illustrating the capacity allocated to each technology and configuration.

2030

In 2030, the results indicate an optimal balance between centralised GFT facilities and decentralised HTL systems. For large-scale processing, GFT shows better economic performance than centralised HTL and is therefore preferred. However, the economic advantage of large-scale GFT deployment is limited in some regions by biomass supply constraints, which favour the rollout of decentralised HTL configurations.

High-demand countries such as the Netherlands and the United Kingdom have insufficient domestic biomass resources, limiting the feasibility of localised GFT plants. As a result, these regions rely on biomass or biocrude imports from other parts of Europe. This dynamic drives the deployment of decentralised HTL systems in biomass-rich regions (e.g. Scandinavia and the Iberian Peninsula), where feedstocks are converted into biocrude near the source and subsequently transported over long distances to refineries in high-demand areas for final upgrading into drop-in biofuels.

The ranges (error bars) shown on Figure 4 indicate only a small impact from changing biomass availability scenarios. This is because the relative difference between biomass availability and demand in 2030 remains modest, resulting in limited stress on the supply chain network and, therefore, minimal variation in the optimal configuration.

2050

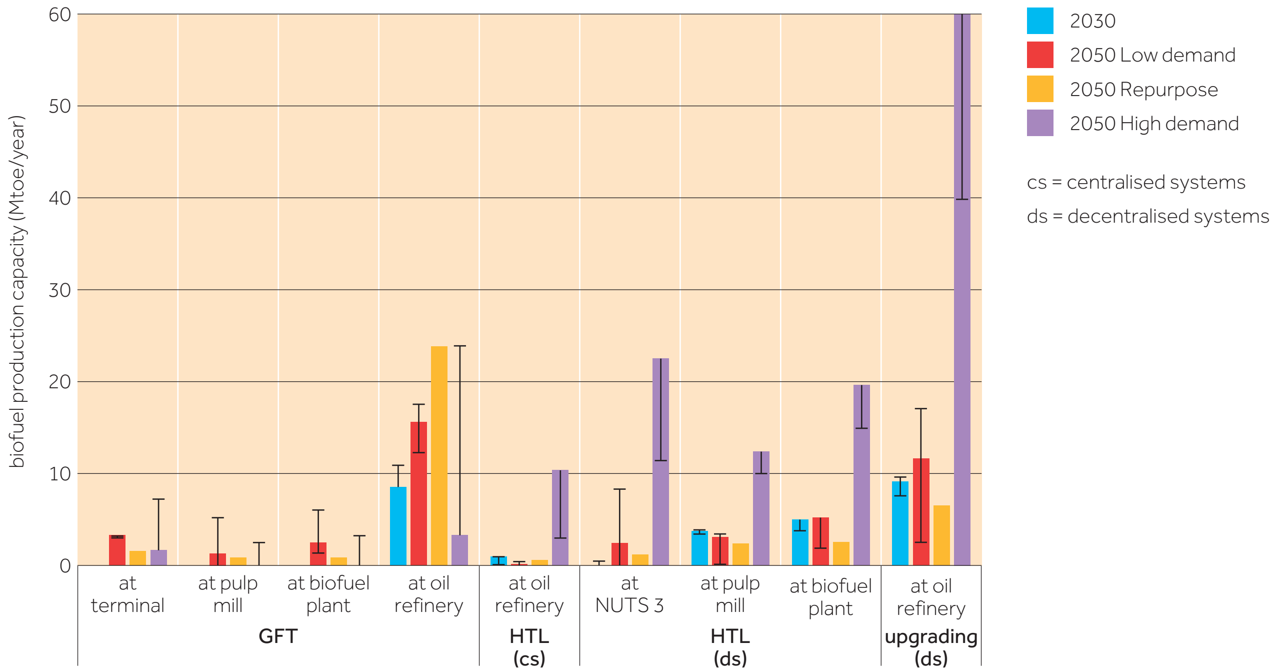
By 2050, the optimal supply chain structure and technology mix become more sensitive to variations in biofuel demand and biomass availability across the different scenarios. In the low-demand case, large-scale centralised GFT plants are strongly favoured over decentralised HTL systems. This reflects both the greater cost advantage of GFT, benefiting from long-term cost reductions through technological learning, and the fact that lower demand levels enable shorter transport distances and sufficient local biomass to meet national needs efficiently. Decentralised HTL and biocrude supply remains advantageous only for countries facing domestic biomass shortages, similar to the cases observed in 2030.

In contrast, under the high-demand scenario, total demand more than doubles, substantially increasing pressure on biomass supply efficiency across Europe. The need to mobilise feedstocks from remote or less accessible areas makes decentralised systems more advantageous, as converting solid biomass into biocrude near the source reduces overall logistics costs and improves supply chain flexibility.

Finally, in the refinery repurposing case, the model indicates a shift toward more centralised GFT facilities compared to the default configuration. This reflects the capital cost synergies achievable through deeper integration with existing refineries, where hydrocracking equipment and related infrastructure can be reused; this is particularly beneficial for GFT, given its high investment intensity in upgrading units.

Figure 4: Advanced biofuel production per plant type (Mtoe/year) in the base scenarios for 2030 and 2050

The error bars show the ranges of the alternative biomass availability scenarios (Low, High).



Geographical distribution of biorefineries

The trends described above, such as the balance between centralised and decentralised configurations in 2030 and the shift toward greater decentralisation under higher demand in 2050, are clearly reflected on the maps in Figures 5 and 6 (page 14) which show the spatial distribution of biocrude and biofuel plants.

Beyond these general trends, several region-specific conclusions can be drawn. North-western European countries, with high transport activity and significant liquid fuel demand but limited biomass availability, emerge as net importers of biocrude from biomass-rich regions, typically hosting upgrading facilities instead of conversion plants. In contrast, biomass-rich regions, most notably Scandinavia and the Iberian Peninsula, consistently appear as key suppliers, producing and exporting biocrude to offset deficits in other parts of Europe.

Large central European countries exhibit a diverse technology mix, as their geographical size and shared borders with multiple regions lead to locally optimised solutions across different areas. Meanwhile, smaller Central and Eastern European countries show greater sensitivity to demand fluctuations, where changes in consumption levels can significantly alter their optimal supply chain configurations.

Another important finding, evident in the maps, is the strategic role of refineries in the biofuel transition. Their existing large-scale infrastructure and compatibility with thermochemical biomass conversion technologies make them ideal integration hotspots for hosting future advanced biorefineries.

Figure 5: Optimal spatial distribution of modelled biocrude and biofuel plants required for advanced biofuels in the EU-27 + UK; Base scenario, 2030

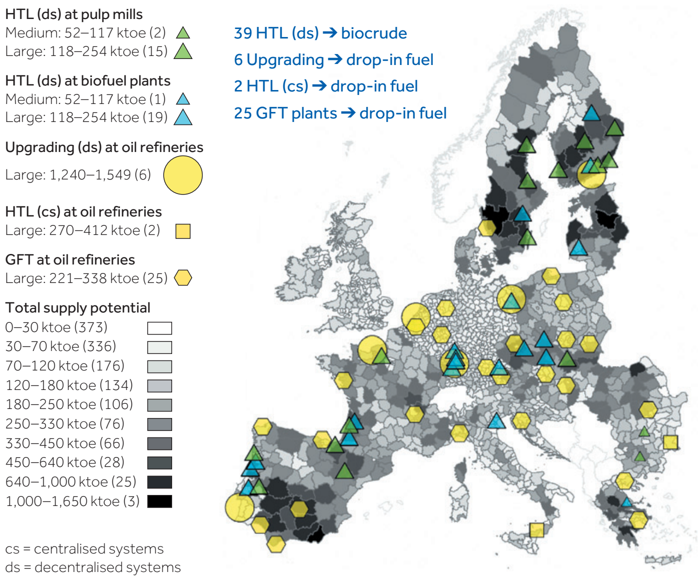
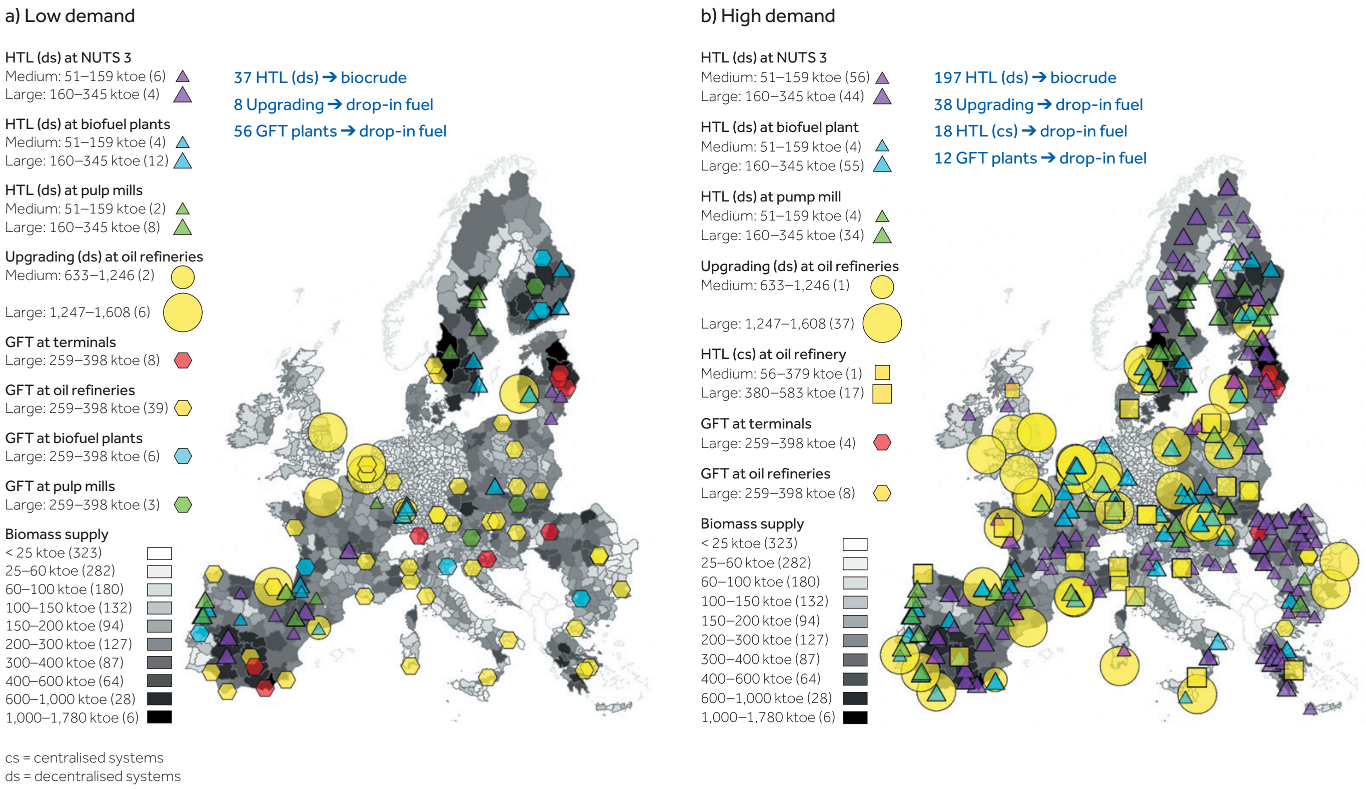


Figure 6: Optimal spatial distribution of modelled biocrude and biofuel plants required for advanced biofuels in the EU-27 + UK; Base scenarios, 2050



Advanced biofuel production costs

The average supply chain costs for all simulated scenarios, along with the breakdown by cost components, are presented in Figure 7.

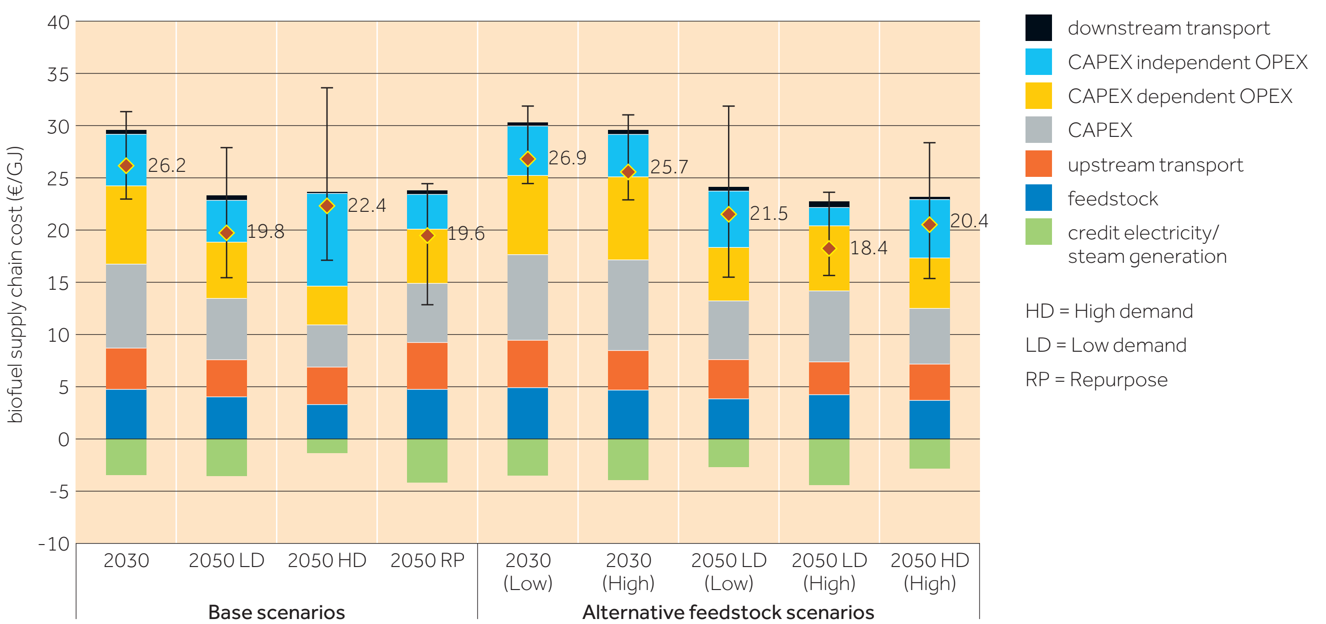
For 2030, the average cost for the base case is 26.2 EUR/$GJ_{biofuel}$. When alternative biomass availability scenarios are applied, only minor cost variations are observed, consistent with the limited structural changes in the optimal supply chain described earlier. The cost range across supply chains in 2030 remains narrow due to the relatively similar cost levels of a mature GFT and HTL process. However, as HTL is currently at a lower TRL, achieving such scales in the short term may be challenging, making GFT a more immediately deployable option.

By 2050, a considerable cost reduction is observed, with average production costs ranging between 19.8 EUR/GJ and 22.4 EUR/GJ. This decline mainly results from technological learning and the associated reduction in capital costs. Unlike 2030, however, larger cost differences appear across scenarios reflecting the need for structural adjustments in the supply chain under higher demand or lower biomass availability conditions.

Across all scenarios, process-related costs (CAPEX and OPEX) remain the dominant cost drivers and thus the most critical area for further cost reductions. Nevertheless, biomass production and transport costs are also non-negligible, as they strongly influence the optimal supply chain configuration, particularly the balance between centralised and decentralised systems under varying demand and biomass availability conditions.

Figure 7: Average biofuel production cost in the base and alternative scenarios

The error bars show the ranges between the minimum and maximum biofuel production costs calculated for each scenario.



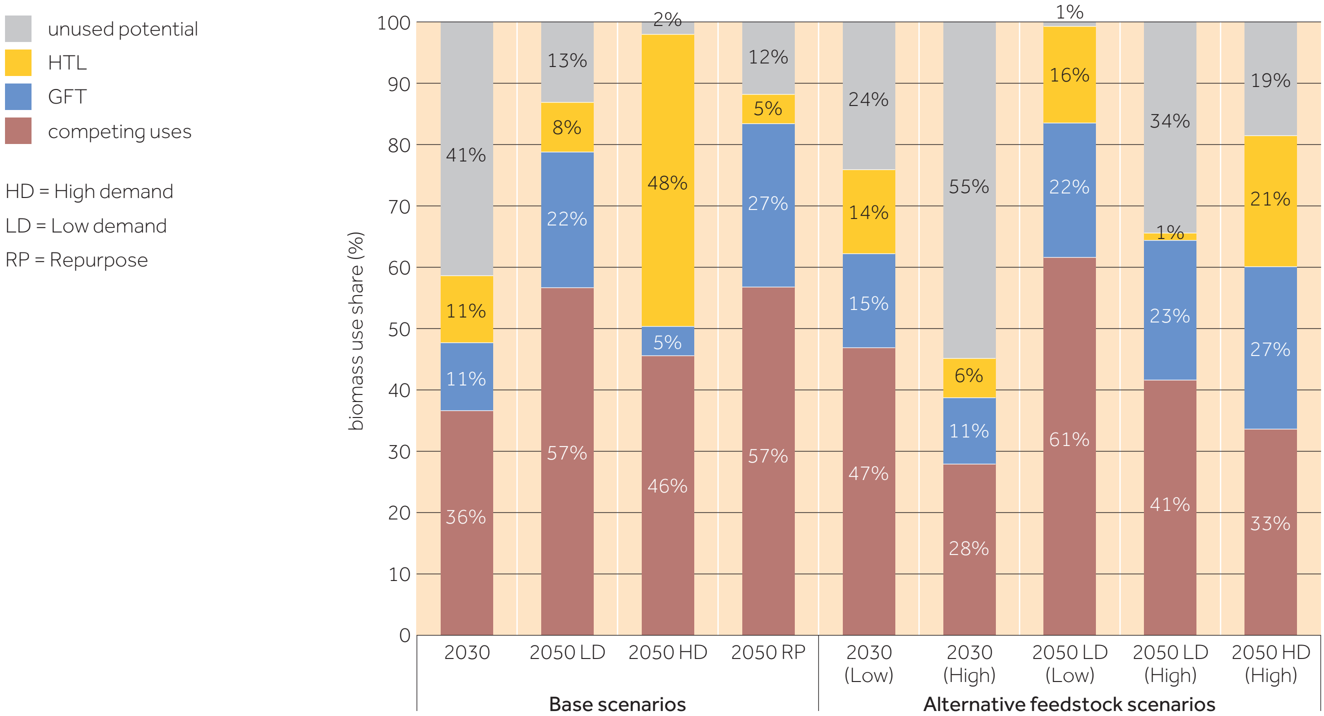
At this point, it should be noted that the calculated process costs are consistent with the values reported in the scientific literature. However, in industrial practice, total project costs are typically higher due to the early commercialisation stage of these technologies and additional factors such as site infrastructure, owner's costs, and financing during construction. Therefore, the results are presented on a comparative basis to assess the impact of different scenarios on supply chain costs and drivers rather than as an absolute cost assessment.

Biomass consumption dynamics

The breakdown of biomass consumption across the different pathways for each scenario, along with the share of domestically available biomass that is not mobilised, is presented in Figure 8.

The results indicate that, in all cases, there is sufficient biomass to meet the advanced biofuel demand. However, under certain combinations of high demand and low biomass availability, such as the High Demand 2050 base scenario, the share of unutilised biomass becomes very small. This highlights the increasing challenges of meeting ambitious future demand levels, as doing so requires near-complete mobilisation of available biomass resources.

Figure 8: Biomass utilisation as a fraction of the total domestic availability potential in the base and alternative scenarios in the EU-27 + UK



However, it should be noted that not all feedstocks listed in Annex IX, Part A were included in this study (see *Biomass availability and production costs* on pages 6–7). Furthermore, the integration of green hydrogen in conversion plants, such as GFT, could significantly increase biofuel yields and reduce biomass consumption, thereby lowering the overall biomass footprint. However, this integration of RFNBOs[11] and biofuel pathways was beyond the scope of the present work.

Conclusions

This study analysed the economically optimal supply chain configurations for advanced biofuel production from lignocellulosic biomass across the EU-27 + UK under varying future scenarios of biomass availability and advanced transport biofuel demand. Using a spatially explicit optimisation model, the analysis accounted for biomass supply and costs, transport networks, conversion technologies (gasification and Fischer-Tropsch—GFT; hydrothermal liquefaction—HTL) and economies of scale.

Centralised vs decentralised systems

Large-scale, centralised GFT plants integrated with industrial assets (especially refineries) are generally more cost-effective when biomass availability is sufficient. However, under high-demand or low-availability conditions, decentralised HTL systems become more efficient, enabling the use of dispersed or remote biomass. The optimal system depends on biofuel demand, local resource availability, and geographic factors such as inland versus port access.

Geographic patterns and trade

Geography decisively determines the optimal supply chain selection. Western European countries with limited biomass, such as the UK, Belgium and the Netherlands, emerge as import and upgrading hubs thanks to their port and refinery networks. Scandinavia and the Iberian Peninsula act as biocrude exporters, while Germany and France require hybrid systems combining both strategies. As biomass availability tightens relative to demand, cross-border trade intensifies, favouring biocrude and drop-in fuels over solid biomass for their higher energy density and transport efficiency.

Biomass demand vs availability

Europe's domestic biomass is sufficient to meet demand through 2030 and 2050, but by 2050 the availability-to-demand ratio narrows considerably in scenarios of high biofuel demand or low biomass availability. This strains the supply chain, requiring wider deployment of decentralised HTL plants to reach scattered resources. Future targets will rely on better biomass management practices and innovations.

[11] Renewable fuels of non-biological origin

Advanced biofuel supply chain costs

In 2030, cost differences between scenarios are small (< 10%), suggesting that early deployment will depend more on commercial readiness than intrinsic cost advantages. By 2050, learning effects reduce process costs substantially and GFT becomes more favourable when biomass availability is high or demand is low, while HTL gains ground when resources are limited and decentralised collection is required.

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Algae-to-liquid biofuel pathways — a literature review of technology, techno-economics and sustainability

Algae have long been considered as a potential novel biofeedstock for advanced biofuel production, but challenges associated mostly with cultivation and processing present barriers to realising its potential on a commercial scale. This article summarises the results of a literature review undertaken by Concawe to assess the latest data on technical progress, and to highlight both recent advances and remaining barriers.

Author

Themistoklis Neokosmidis (Concawe)

Introduction

Over the past two decades, algae have emerged as a promising biofeedstock, particularly when cultivated in controlled artificial environments that allow production management and avoid competition with food resources. Classified as aquatic biomass, algae are included in Annex IX, Part A of the Renewable Energy Directive (RED) as eligible feedstocks for advanced biofuel production without any restrictions on the amount that can be used.

The initial wave of enthusiasm for algae, reflected in a surge of start-ups and scientific publications, has since diminished, with most companies, including major refiners, withdrawing investment from this pathway.[1,2] Early studies suggested that algae could achieve productivities 5–45 times higher than terrestrial crops; however, these estimates proved overly optimistic and have not been realised due to persistent technical and economic challenges in cultivation and processing.[3]

The most recent comprehensive review of algae for biofuel applications was published by the IEA in 2017.[3] Nevertheless, algae continue to be cited as the primary feedstock candidate for long-term biofuel production, and are often referred to as third-generation biofuels. In this context, Concawe has undertaken a literature review to compile updated information and data on technological progress in algae-based advanced biofuel production, with the objective of highlighting both recent advancements and the remaining barriers.

Types of algae and biofuel pathways

Algae can be broadly classified into two main groups based on cellular structure: macroalgae and microalgae. Macroalgae are multicellular aquatic plants, commonly referred to as seaweed, and can be further subdivided, according to pigmentation, into green, red and brown macroalgae. This distinction is important because each subgroup differs in its biomolecular composition. Microalgae, by contrast, are unicellular organisms found in both freshwater and marine environments. They have attracted far greater research attention for biofuel production, primarily because they can be cultivated in artificial environments where growth conditions are controlled.[4]

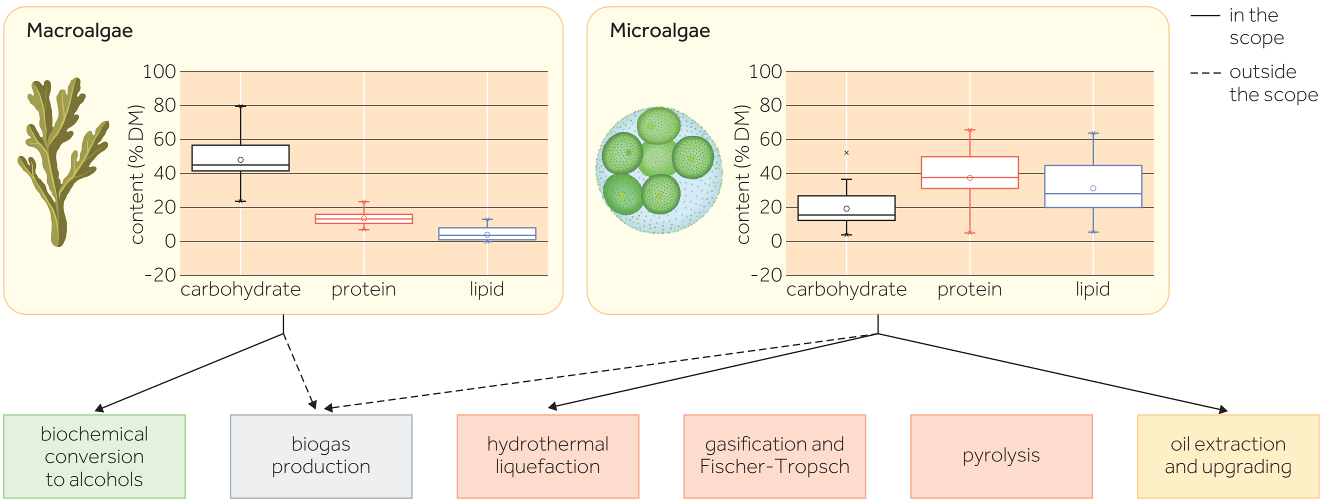
A key factor driving biofuel industry interest in microalgae is their potentially high lipid content, which can be extracted and processed in existing refinery facilities, similar to established pathways for vegetable oils and used cooking oil (UCO). As shown in Figure 1 on page 20, the lipid composition of microalgae is highly variable depending on the species and cultivation conditions. The prevalence of lipid-rich species has motivated extensive research into biofuel production pathways based on lipid extraction and upgrading.

Conversely, any application of conventional thermochemical processes, such as gasification and pyrolysis, is limited. This limitation arises because harvested microalgae typically have very high water content (> 99%), making such processes both energy and cost-intensive.[3,5] An exception is hydrothermal liquefaction (HTL), which can efficiently process wet feedstocks and has therefore received growing research interest as an alternative route for microalgae-based biofuels.[3]

Macroalgae, although also variable in composition depending on species, season and climate, are generally characterised by significantly lower lipid concentrations and higher carbohydrate levels.[3] Consequently, research into lipid extraction has been limited, while thermochemical processing of macroalgae has also been limited due to their high water content as feedstock. The most investigated conversion pathway for macroalgae has been carbohydrates utilisation through conversion to alcohols, particularly ethanol.

Both microalgae and macroalgae can be processed for biogas production, but research in this area has been comparatively limited and, given the stronger focus of this study on liquid biofuels, this pathway is considered to be outside the scope of the present review.

Figure 1: Biochemical composition of macroalgae and microalgae, and an overview of the most compatible and extensively researched pathways for biofuel production from each group (indicated by the arrows)
(box plots showing molecular composition are adapted from Gao *et al.*, 2020[6])



Industry status

According to FAO[1] data (2021), Europe accounts for only 0.8% of global algae production, with the vast majority located in Asia, where seaweed is primarily cultivated for food and pharmaceutical applications.[7] Notably, none of the algae currently produced at commercial scale are used for biofuels. For Europe, recent data collection and mapping exercises indicate that 67% of European production consists of seaweed, while the remaining 33% is microalgae;[8] the geographical distribution is illustrated in Figure 2 on page 21. In terms of end uses, the primary markets are human food, nutritional supplements and cosmetics.

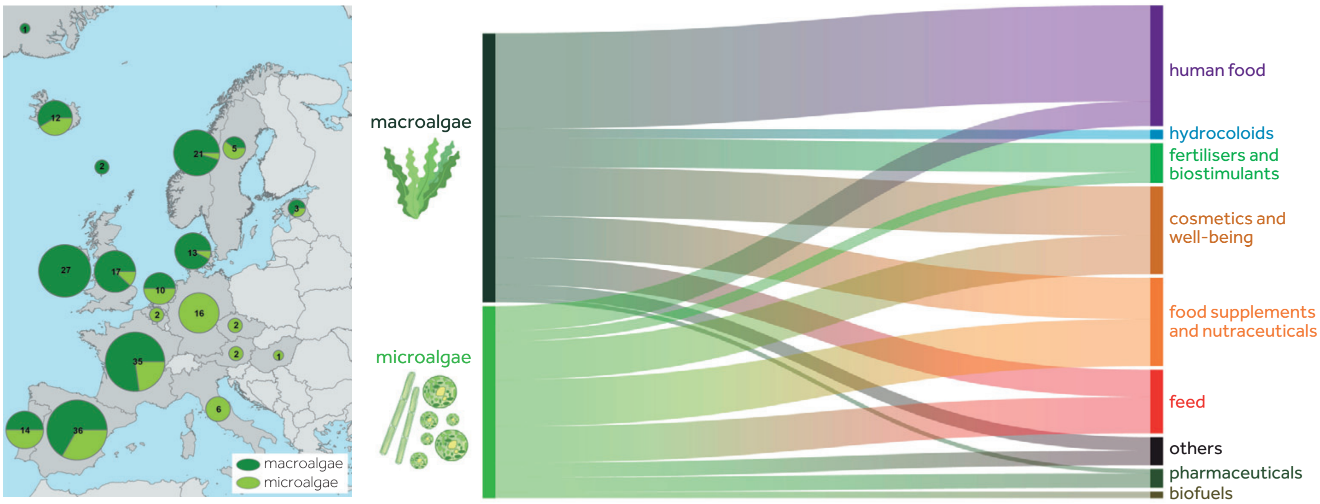
1 Food and Agriculture Organization of the United Nations

Industrial interest in biofuel from algae production within Europe has declined sharply in recent years. While numerous EU projects were launched in the previous decade, today only two projects are active: FUELGAE and SusAlgaeFuel. Despite this downturn, the European Commission has signalled its intention to strengthen algae production across the EU through the EU Algae Initiative.[9] Although addressing biofuel challenges is explicitly mentioned among the targeted actions, the main emphasis of the initiative is expected to remain on food and feed applications.

Figure 2: Distribution of macroalgae and microalgae production facilities, and flows of algae to different applications in Europe
(adapted from Araujo *et al.*, 2021[8])

Distribution of companies producing algae

Flows of algae to various applications



Algae production systems

Algae production lies at the core of algae-to-biofuel pathways, as most of the associated technical and economic challenges are concentrated at this stage. At present, seaweed supply mainly comes from direct harvesting of wild stocks.[8] However, under the RED, algae derived from wild stocks are not considered eligible, and only algae cultivated in ponds or bioreactors qualify. This requirement has not yet been widely applied for seaweed, which therefore remains dependent on natural harvesting.

By contrast, microalgae have attracted greater interest due to their properties and potential for cultivation in controlled environments such as open ponds or photobioreactors. Key parameters influencing microalgae growth include sunlight, temperature, pH, and nutrients supply. Although microalgae generally exhibit higher productivities than terrestrial plants, large-scale artificial production faces significant spatial constraints. For example, utilising a CO_2 emissions stream of 100 kt CO_2/year to feed algae ponds would require ponds covering an area of around 1,000 hectares.

Figure 3: Examples of microalgae production systems[10,11]

Open pond system

Tubular photobioreactor

The question of which microalgae production system is most suitable and efficient has been the subject of ongoing debate. Open ponds are the most common and least costly option, but they offer limited controllability, are highly sensitive to weather fluctuations, and are vulnerable to contamination. Closed photobioreactor (PBR) systems provide much better control of growth conditions, but at the expense of substantially higher capital and energy costs.[12] While PBRs may be viable for high-value products such as pharmaceuticals, they remain cost-challenging for biofuels, where open ponds are generally preferred.

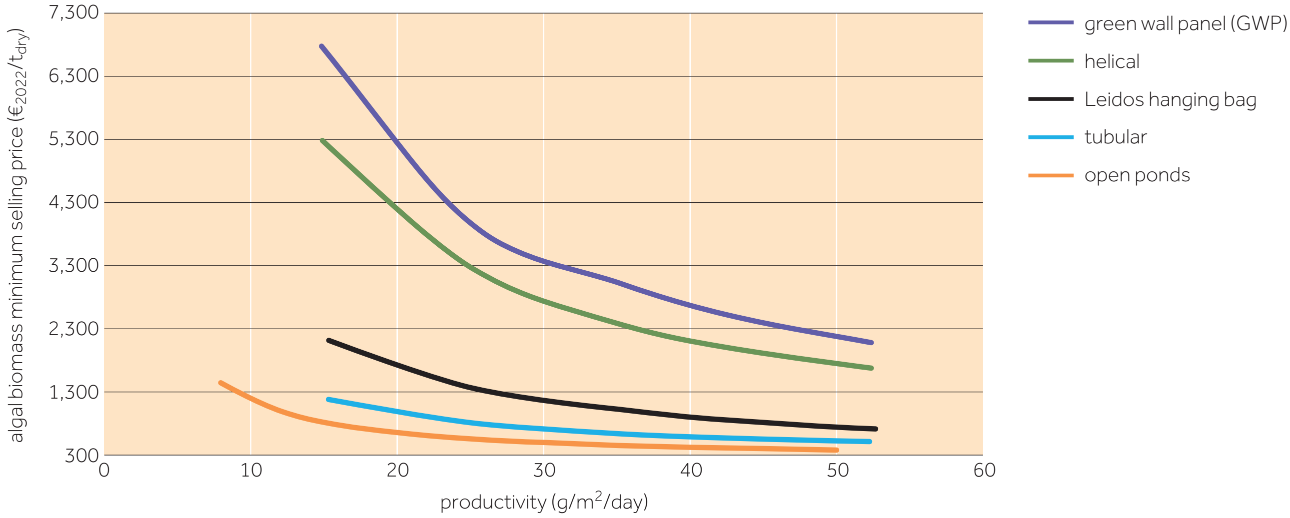
The state-of-the-art annual average biomass productivity in open ponds, based on experimental trials at AzCATI,[2] is 18.6 $g{\cdot}m^{-2}{\cdot}d^{-1}$.[13] This is considerably lower than the projections made by NREL[3] a decade ago, which anticipated reaching 25–30 $g{\cdot}m^{-2}{\cdot}d^{-1}$ by 2022.[12] Based on the latest advances, expectations have now been revised, with a productivity target of 25 $g{\cdot}m^{-2}{\cdot}d^{-1}$ by 2030.[14] A persistent challenge in these systems is the trade-off between biomass growth and lipid productivity: strains and conditions that favour high lipid accumulation often inhibit overall biomass yields, complicating scale-up under favourable cost and output conditions.

Closed systems can achieve higher production rates; however, their costs are significantly higher (see Figure 4 on page 23). They may only become comparatively efficient in regions with limited sunlight, such as Central and Northern Europe, where open pond productivities cannot exceed 15 $g{\cdot}m^{-2}{\cdot}d^{-1}$.

[2] Arizona Center for Algae Technology and Innovation, azcati.asu.edu

[3] National Renewable Energy Laboratory, www.nrel.gov

Figure 4: The biomass minimum selling price[4] for open ponds and different closed photobioreactor designs[15]
(prices were indexed to 2022 and converted from USD to EUR)



Biofuels from algae: economics

The biofuel minimum selling price (MSP)[5] was used as the indicator for reviewing the economic performance of algae-to-biofuel pathways, as it is the most frequently reported metric in the literature. The review concentrated on the pathways that have received the most attention across the techno-economic studies in the literature:

For macroalgae:

- bioethanol (BioEtOH) production

For microalgae:

- lipid extraction and processing (LE);
- hydrothermal liquefaction and processing (HTL); and
- combined algae processing (CAP) targeting the co-production of fuels and chemicals.

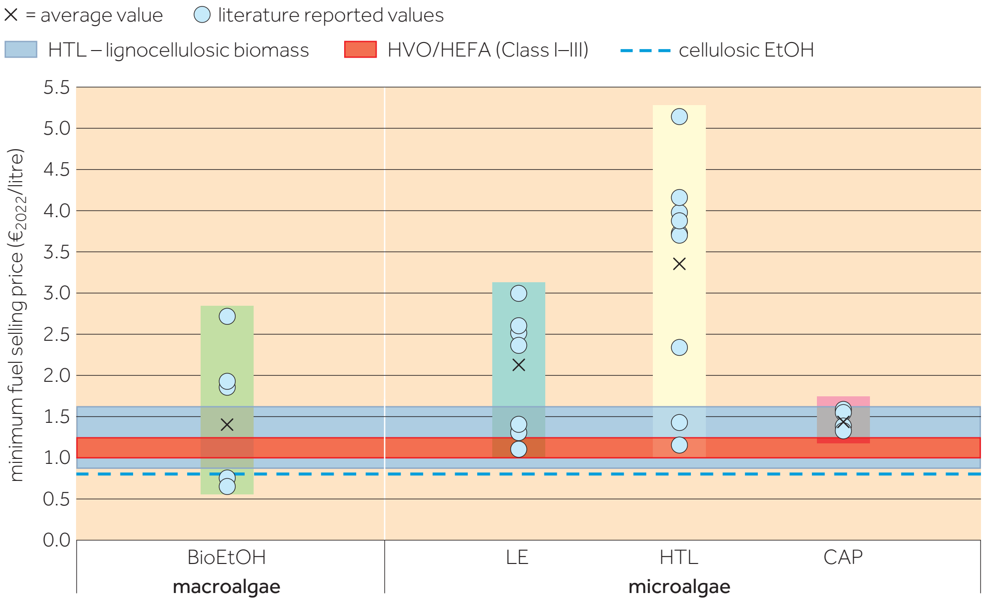
The results of this review are summarised in Figure 5 on page 24.

[4] The minimum price at which algal biomass must be sold in order to cover the total production costs, including capital investment and operating expenses, under assumed process and economic conditions.

[5] The minimum price at which biofuel must be sold in order to cover the total production costs, including capital investment and operating expenses, under assumed process and economic conditions.

Figure 5: Distribution of literature-reported values for the minimum fuel selling price across various algae-to-biofuel pathways explored

(Minimum fuel selling price of biofuel alternatives)



Notes:

Pathways included:

- BioEtOH = biochemical pathway to ethanol
- LE = lipid extraction for renewable diesel or biodiesel
- HTL = hydrothermal liquefaction to renewable diesel
- CAP = combined algae processing-multiproduct biorefinery (e.g. polyurethane co-production)

The coloured boxes represent the economic ranges reported across studies.

For macroalgae, the number of economic studies is relatively small, and the assumptions applied vary widely. This leads to significant variability in the results and makes drawing firm conclusions difficult. Reported MSP values for ethanol range from 0.66 to 2.71 EUR/litre, with a statistical average of 1.30 EUR/litre. The lower end of this range generally reflects highly optimistic assumptions, such as near-ideal conversion yields, which are not representative of the current technological status. Conversely, studies that rely on more realistic assumptions typically present less favourable results. Across all studies, a consistent conclusion is that achieving feedstock supply costs below ~80 EUR/tonne, coupled with improvements in conversion efficiency from biomass to ethanol, will be critical to achieving economic competitiveness for macroalgae-derived ethanol.

For microalgae, the results are more consistent across the literature, as they are based on the harmonisation performed by Cruce *et al.* (2021) for key parameters such as biomass productivity (set at 25 $g \cdot m^{-2} \cdot d^{-1}$ representing a future target higher than the current maximum reported productivity of 18.6 $g \cdot m^{-2} \cdot d^{-1}$).[16] Within these assumptions, lipid extraction (LE) pathways demonstrate lower costs than hydrothermal liquefaction (HTL), with the statistical average MSP calculated at 2.2 EUR/litre compared to 3.4 EUR/litre for HTL. Notably, the HTL pathway exhibits a much wider cost range, coming from the lower technology readiness level (TRL) and higher uncertainty in conversion yields relative to the more established oil extraction and upgrading routes. In both pathways, energy consumption and the capital investment for pond systems are consistently identified as the dominant cost drivers, underlining the importance of improvements in upstream cultivation systems to achieve meaningful cost reductions.

Another important conclusion concerns the potential of multi-product biorefineries designed to maximise the value of algal components. In particular, the co-production of polyurethanes, primarily studied by NREL, has been shown to significantly improve the economics of algae-to-fuel pathways.[13] However, the relatively smaller market size for such co-products poses a potential bottleneck for large-scale deployment of this concept.

When compared with alternative biofuel options, algae-derived biofuels remain a significantly more expensive route. Even under optimistic assumptions, such as achieving productivities of 25 $g \cdot m^{-2} \cdot d^{-1}$, which reflects future targets, algae-based fuels are estimated to be considerably costlier than advanced biofuels produced from lignocellulosic feedstocks (eligible in Annex IX) or HEFA/HVO[6] pathways from used oils and fats.

To improve the economics of algal biofuels, technological advancements in upstream cultivation are essential. The development of systems capable of sustaining annual average biomass productivities in the range of 25–30 $g \cdot m^{-2} \cdot d^{-1}$ represents an important step, but this alone is insufficient to offset the high production costs. These productivity gains must be coupled with increased lipid yields in algal cells (approaching 50%), since lipids constitute the feedstock for lipid extraction pathways and also enhance conversion efficiencies in HTL processes. However, achieving both high biomass growth and elevated lipid contents simultaneously remains a major bottleneck, as these two factors are generally counteractive.[3]

Biofuels from algae: sustainability

The sustainability of algae-to-biofuel pathways was assessed through a literature review of reported greenhouse gas (GHG) intensities ($gCO_2eq/MJfuel$). Results were grouped according to the GHG accounting methodology applied in each study, such as allocation or system expansion.[7] Data for macroalgae-to-ethanol are limited, whereas microalgae pathways have been more extensively examined. For the latter, the study by Cruce *et al.* was used as the reference basis, as it applied harmonisation of system boundaries across different LCA assessments, thereby providing a more consistent basis for comparison.[16]

The results nevertheless show significant divergence, reflecting the range of assumptions and GHG methodologies employed (see Figure 6 on page 26). For example, studies employing system expansion, where credits are granted for co-products such as electricity or fertiliser that displace fossil-based equivalents, report much lower GHG intensities than those applying allocation methods (no displacement credit). These differences highlight both the sensitivity of outcomes to methodological choices and the role of process configuration and targeted co-products in achieving low GHG emissions.

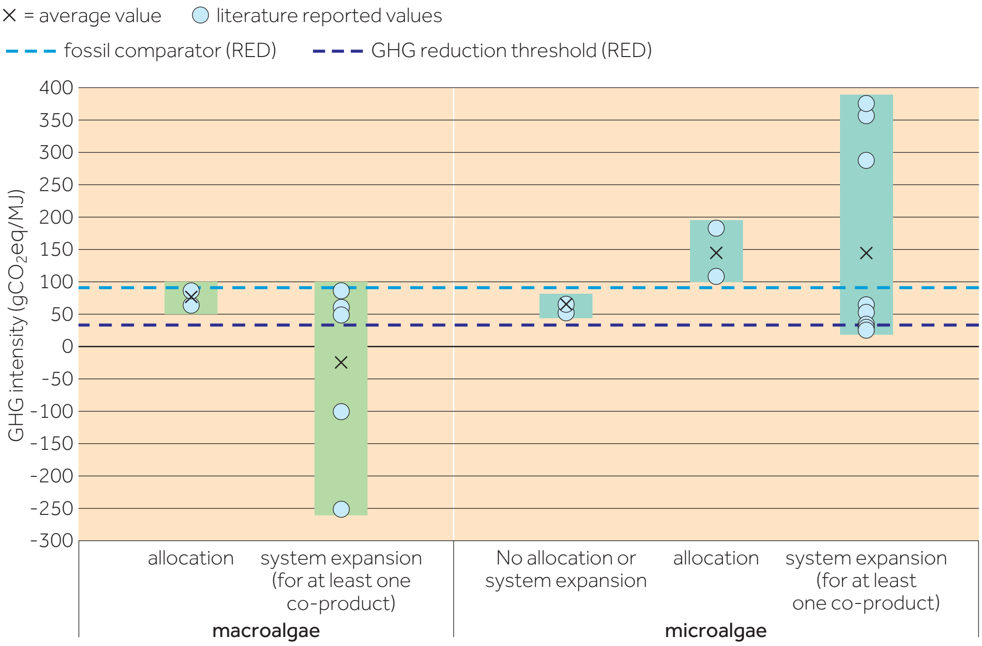
[6] Hydroprocessed esters and fatty acids/hydrotreated vegetable oil

[7] Allocation refers to distributing environmental impacts proportionally among the main product and co-products of a process (e.g. based on energy content, mass or price). System expansion attributes credits for co-products by accounting for the displacement of equivalent fossil-based products (e.g. electricity, fertiliser), thereby lowering the overall GHG intensity of the biofuel pathway.

Despite such opportunities, even under consistent calculation frameworks, achieving GHG intensities comparable to other advanced biofuels (e.g. via lignocellulosic pathways) remains challenging for algae-based systems. This is largely due to the high energy demand of upstream processes, particularly for microalgae cultivation and harvesting. The lack of a harmonised methodology for GHG accounting across studies further complicates comparison and points to the need for alignment with frameworks such as the RED methodology.

Future research should also focus on updated case studies that better reflect sustainable frameworks. For example, accounting for the projected decarbonisation of electricity grids, or integrating more sustainable energy and material inputs, could provide a clearer view of the long-term potential for algal biofuels to deliver meaningful GHG reductions—an aspect that remains underexplored.

Figure 6: Distribution of literature-reported values for the GHG intensity of the different algae-to-biofuel pathways explored



Notes:

The fossil comparator and GHG reduction threshold set in RED III are disclosed. It is important to clarify that the presented GHG reduction threshold and fossil comparator refer to the values given in RED III. To compare these values with the corresponding values for biofuels, RED discloses a specific GHG accounting methodology (allocation based on energy content), which often differs from those used in algae studies (e.g. accounting displacements credits from electricity surplus). Nonetheless, these figures remain a useful reference point for evaluating the sustainability of algal biofuels.

The results are categorised based on the GHG accounting methodology (allocation, system expansion) used in each study.

Conclusions

Over the past two decades, algae have attracted significant interest as a potential biofuel feedstock, owing to their ability to be cultivated in artificial environments. However, despite the early enthusiasm, the technological and economic challenges of scaling up algae production have led many companies to scale back or redirect their investments away from algal biofuels. Both major groups of algae, macroalgae (or seaweed) and microalgae, have been studied for biofuel applications, though research has primarily focused on microalgae due to their potentially high lipid content and their suitability for production in industrial facilities. For macroalgae, which are typically rich in carbohydrates, ethanol production is the most widely examined pathway. For microalgae, lipid extraction and upgrading to drop-in biofuels is the dominant route, followed by hydrothermal liquefaction (HTL). Other thermochemical pathways have received limited attention, as the high water content of algae renders them both energy and cost-intensive.

At present, macroalgae production is dominated by wild stock harvesting, with biomass directed to non-energy applications while microalgae production is small. Regarding microalgae production, two types of systems are available: open ponds and closed photobioreactors (PBRs). Closed systems allow tighter control of growth conditions and product characteristics, and they achieve higher biomass productivities, but their capital and energy requirements are substantial. Open ponds, by comparison, are more economically favourable for biofuel production, whereas PBRs are better suited to contexts where natural limitations, such as low sunlight, make open ponds inefficient.

From an economic standpoint, data for macroalgae-to-biofuel pathways are limited, and the studies with realistic technological assumptions report costs higher than for other biofeedstocks. For microalgae, lipid extraction generally appears more cost-effective than HTL, but both remain considerably more expensive than biofuels from lignocellulosic biomass or used oil and fat feedstocks (e.g. UCO). The high capital investment and operating costs associated with open and PBR systems are consistently identified as the main barriers. Current peak productivity for microalgae in open ponds is 18.6 $g \cdot m^{-2} \cdot d^{-1}$, with targets of 25 $g \cdot m^{-2} \cdot d^{-1}$ by 2030, though even such improvements are unlikely to ensure competitiveness. Increasing lipid content is also critical, but the inverse relationship between lipid accumulation and biomass growth creates a biological trade-off that has yet to be resolved.

From a sustainability perspective, algal biofuels face further challenges. Producing large quantities of algal biomass requires significant energy inputs, often resulting in GHG intensities exceeding those of fossil fuels or failing to meet EU reduction thresholds for eligible biofuels. Moreover, differences in assumptions and GHG accounting methodologies across studies complicate comparisons. Applying a harmonised framework, such as the RED GHG methodology, and exploring more sustainable production solutions (e.g. renewable energy integration) are critical steps that need to be further explored.

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Overview of non-CO_2 emissions from aircraft and fuel composition effects

Aviation's climate impact extends beyond CO_2. Non-CO_2 effects, especially contrails and contrail cirrus, are contributors to aviation radiative forcing, though uncertainties remain high. This article outlines the main non-CO_2 emissions from aircraft and explains contrail formation. It also reviews how fuel composition can affect particulate emissions and contrail properties, with a focus on sustainable aviation fuel (SAF) and the trade-offs of further hydroprocessing in existing European refineries.

Authors

Athanasios Megaritis and Adrian Velaers (Concawe)

Introduction

Aviation is one of the most important global economic activities in the modern world, with an extremely high increasing activity trend over the past 50 years.[1] Aviation emissions can have an impact on surface air quality[2,3] as well as on climate change via a complex set of processes.[4] From a climate perspective, the most important radiative forcing components of aviation are carbon dioxide (CO_2), oxides of nitrogen (NO_x), water vapour (H_2O), aerosol (soot, sulphates, nitrates), and condensation trails (contrails). The latter in particular, based on an evaluation of global aviation activity in 2018, was estimated to be among the largest contributors to annual mean radiative forcing due to aviation, albeit subject to a high degree of uncertainty, followed by aviation's cumulative CO_2 and annual NO_x emissions.[1] This article provides an overview of non-CO_2 emissions from aircraft and fuel composition effects based on recent studies conducted by Concawe.

Non-CO_2 emissions from aircraft

Aircraft emit several non-CO_2 species that influence climate and, in the landing and take-off regime, local air quality.[5,6] Beyond CO_2, the most consequential climate impact is the formation of contrails and contrail cirrus from exhaust water vapour interacting with ambient cold, humid air; their radiative impact depends on the initial ice crystal number, size, optical depth and lifetime. Combustion also releases: NO_x, which perturbs upper tropospheric ozone (warming) and methane (cooling) with a net positive effect on most decadal timescales; SO_x that oxidises to sulphuric acid; non-volatile particulate matter (nvPM, soot) that seeds droplet/ice formation; volatile PM (vPM) that forms as sulphuric acid and organics that condense in the cooling plume; and small amounts of CO and unburned hydrocarbons. Together, these species and the meteorology at cruise altitudes determine whether contrails form and persist. Near airports, the same emissions—especially nvPM and NO_x—drive air quality concerns, motivating tighter certification and operational controls.[5]

The different gases and particulate matter emitted by aircraft engines remain in the atmosphere for different lengths of time. Consequently, their radiative forcing and the subsequent climate impacts also occur on different timescales. CO_2 is removed slowly, so it accumulates in the atmosphere over periods ranging from decades to millennia. During that time, it exerts a radiative forcing on the climate system. Therefore, a substantial fraction of past aviation CO_2 emissions continues to exert a radiative forcing today and will continue to do so in the future. The residence time of non-CO_2 emissions is much shorter, so non-CO_2 radiative forcing is exerted by recent emissions. In particular:

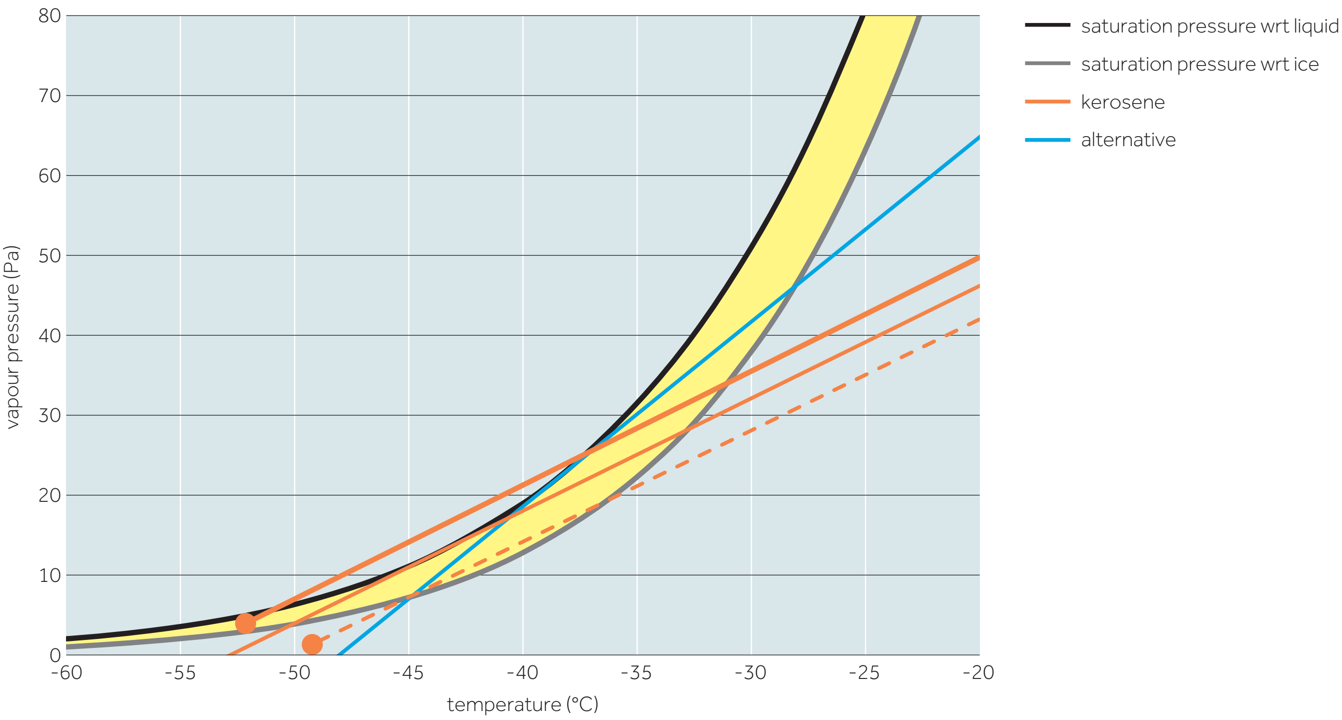
- Aviation PM can be involved in forming contrails, which last up to several hours. During that time, contrails exert a radiative forcing through both their own greenhouse effect (warming), and by reflecting sunlight (cooling), with the net effect depending on atmospheric conditions.
- Aviation PM remains in the atmosphere for days to weeks. During that time, it exerts a radiative forcing by interacting with sunlight and terrestrial radiation, and in some cases by interacting with clouds.
- Aviation NO_x remains in the atmosphere for several weeks. It triggers perturbations to ozone and methane concentrations that last for months to decades, during which they exert a radiative forcing.

The influence of aviation on climate is shown to be greater than that from its CO_2 emissions alone, but with large uncertainties on the non-CO_2 effects.[1,6,7] The aviation non-CO_2 effects comprise: changes in the atmospheric concentrations of O_3, CH_4 and H_2O resulting from NO_x emissions; the formation of contrails and contrail cirrus; the direct emission of H_2O; the emission of aerosols and aerosol precursors with their direct radiative effects; and the indirect cloud effects resulting from aviation-induced aerosols.[1,6,7,8] Recent studies have shown that non-CO_2 effects contributed two thirds of total aviation effective radiative forcing (ERF) between 1940 and 2018, with CO_2 contributing the remaining third. From all non-CO_2 components, contrails and contrail cirrus were found to be the largest contributors.

What are contrails and why do they form?

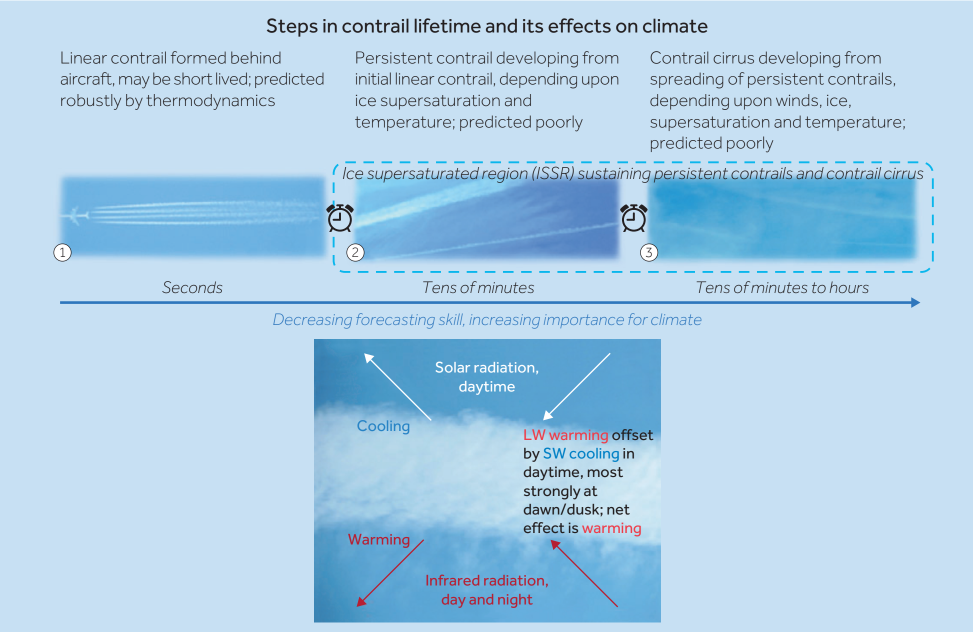
Contrails are line-shaped ice clouds triggered by the emission of water vapour by aircraft engines under specific atmospheric conditions within the atmosphere, in particular in sufficiently cold air (specified in the so-called Schmidt-Appleman criterion—see Figure 1). Persistent contrails can spread horizontally in the air, such that they no longer appear line-shaped after a short while. These clouds are termed contrail cirrus.

Figure 1: Typical T-e (temperature vs. vapour pressure) diagram of water showing fuel-specific contrail thresholds



The principle behind contrail formation is that the mixing of two air masses that are both subsaturated (i.e. their relative humidity is below 100%) can result in a supersaturated state (i.e. the relative humidity of the mixture exceeds 100%) (Figure 2). In the case of contrail formation, the two air masses are the exhaust gases, which are emitted hot and with high vapour pressure, and the ambient air, which is cold and has low vapour pressure. After emission, the mixture immediately attains ambient pressure, so the mixing and contrail formation process is isobaric. Mixing more and more ambient air into the exhaust gases allows them to cool down, and lets the vapour pressure approach the ambient value. If, during this process, the vapour pressure transiently reaches values above the saturation vapour pressure, condensation sets in and liquid droplets form that freeze instantaneously in the cold ambient air. Hence, a contrail forms. A contrail does not form if the mixture never becomes supersaturated (i.e. if the vapour pressure of the mixture remains below the saturation pressure).

Figure 2: Illustration of the formation and evolution of contrails, and their impact on radiative fluxes[9]

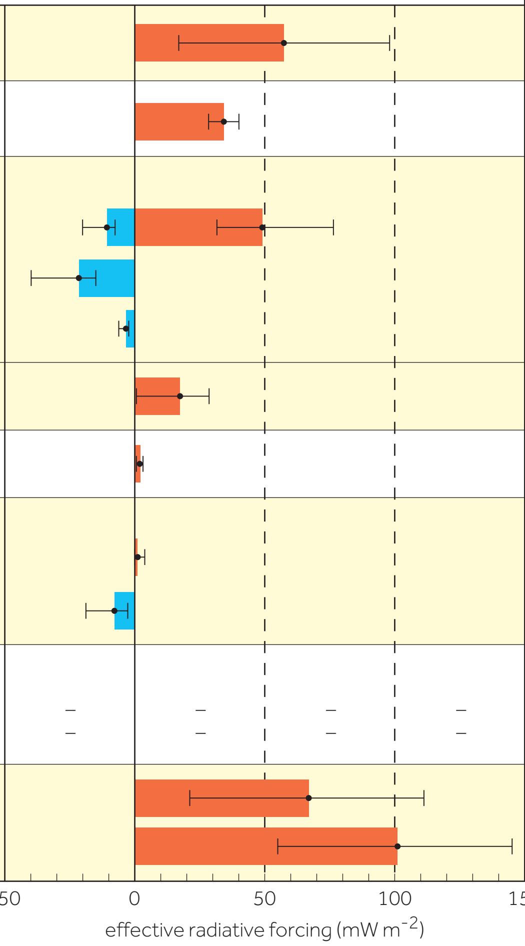


Climate impact of contrails

Figure 3 on page 33 shows the various contributions of aviation to climate change in terms of ERF as presented in a recent paper by Lee *et al.*[1] The results show that contrails and contrail cirrus, while short-lived relative to CO_2, are currently among the largest contributors to total radiative forcing (RF) and ERF, respectively, from aviation if the best estimates are considered. Nevertheless, the uncertainty of the magnitude of the contrail- (and contrail cirrus-) induced RF and ERF is large in comparison to CO_2. The uncertainty further increases if RF or ERF are to be transferred into climate change effects, e.g. in terms of global mean temperature change due to the associated efficacy. Note that the efficacy of contrails and contrail cirrus is significantly smaller than 1, i.e. the temperature response is smaller than would be expected from RF or ERF.[10,11,12,13]

Figure 3: Best-estimates for climate forcing terms from global aviation from 1940 to 2018

best estimates (blue = cooling, red = warming) | 5–95% confidence



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Confidence levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36 (23, 56)	1.37	Medium
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Medium
Stratospheric water vapour decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for (NO_x) emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	–	Low
Water vapour emissions in the stratosphere	2.0 (0.8, 3.2)	2.8 (0.8, 3.2)	[1]	Medium
Aerosol-radiation interactions				
From soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
From sulphur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
From sulphur emissions	No best estimates	No best estimates	–	Very low
From soot emissions			–	
Net aviation (non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	–	–
Net aviation (all terms)	100.9 (55, 145)	149.1 (70, 229)	–	–

Contrails interact with both solar (short-wave) and terrestrial (long-wave) radiation. They generally cool in sunlight by reflecting solar radiation, but warm during both day and night by trapping outgoing long-wave radiation; on average the long-wave effect dominates, yielding a net warming. The magnitude depends on optical depth, ice crystal size, and lifetime—all of which are influenced by initial ice number and ambient supersaturation and dynamics. In addition to the impact of atmospheric conditions, the magnitude of the RF and ERF from contrails and contrail cirrus depends on fuel composition, engine type, and consequential soot emissions—effects which require improved quantification.[14] The following sections provide further insights into these aspects.

Notes on Figure 3:

- The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively.
- Red bars indicate warming terms and blue bars indicate cooling terms.
- Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels.
- RF values are multiplied by the respective ERF/RF ratio to yield ERF values.
- ERF/RF values designated as '[1]' indicate that no estimate is currently available.[1]

Effects of changes in fuel composition on non-CO_2 emissions from aviation

Fuel composition and fuel source

One proposed way to achieve a reduction in non-CO_2 emissions is by changing the composition of aviation fuel. Sustainable aviation fuel (SAF) has been the primary focus of recent discussions on the impact of fuel composition on non-CO_2 emissions for two reasons:

- First, because SAF plays a central role in aviation decarbonisation plans. The production process for SAF, when using CO_2 taken directly from the atmosphere or by using various bio or waste feedstocks, can provide reductions in net CO_2 emissions from aviation, depending on the feedstock and production process used. Hence, the possibility of decreasing both CO_2 and non-CO_2 emissions with the same fuel change is worthy of consideration.
- Second, because flight tests have to date focused on one of the SAF types, HEFA-SPK.[1] Hence, scientific evidence is most extensive for this fuel source.

Recent research suggests that some of the non-CO_2 emissions of aircraft engines can be reduced by increasing the hydrogen content of the fuel. The hydrogen content is increased by saturating aromatic molecules, and decreasing total aromatic and naphthalene content. In a conventional refinery, this could be done by hydrotreating which will also decrease the sulphur content of the fuel.[15] This processing is, however, expensive and CO_2 intensive, but SAF blending with conventional jet fuel would provide these benefits as SAF, including HEFA-SPK, naturally has very low sulphur, aromatic and naphthalene content, and therefore a high hydrogen content. Other fuel sources (fossil, bio-co-processing, etc.)[15] could also have high hydrogen content and ultra-low sulphur, aromatic and naphthalene content, although these would require severe hydrotreatment in the refinery, which is not possible with most current refinery configurations, hence this would require additional capital investment. It would also require additional hydrogen production and more energy, with the associated higher GHG costs. Some refineries are not able to hydrotreat jet fuel but only use a sweetening process, transforming mercaptans in disulphides, which has no impact on sulphur or aromatics content. Typical kerosene hydrotreating units, when available, are designed for sulphur removal, with little aromatics saturation. As such, most refineries would require substantial capital investment for significant aromatic reduction. However, the economic impact on resources for such units could reduce the funds available for refiners to invest in the development of SAF production, or accelerate refinery shut-down and reduce jet fuel supply.

[1] HEFA-SPK = hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (straight paraffinic jet fuel)

What are the impacts of fuel composition on non-CO_2 emissions of aircraft engines?

Different categories of non-CO_2 emissions respond differently to changes in fuel composition, and are discussed in turn below.

Nitrogen oxides (NO_x): Fuel composition has minimal impact on ground-based and cruise NO_x emission indices,[16] which primarily depend on engine and combustor design, and on operating conditions.

Water vapour (H_2O): The use of fuels with high hydrogen content increases water vapour emissions. Flight tests powered by 100% HEFA-SPK SAF measured an increase in the water vapour emission index by about 10%.[17] This could increase the number of ice crystals in contrails.

Non-volatile particulate matter (nvPM, also called soot): Petroleum-based Jet A/A-1 fuels have a hydrogen content range of around 13.5–14.5% by mass, depending on the crude oil origin and the degree of hydrotreatment. The use of fuels with higher hydrogen content, up to around 15% by mass, including fully paraffinic SAF, leads to reductions in nvPM emissions in certain engine types and operating points. That reduction is expected because a high hydrogen content is associated with the saturation of aromatic molecules and desulphurised fuel, which in turn reduces nvPM formation in the primary zone of the combustor where the fuel-to-air ratio is high to ensure a stable combustion. As a general principle, paraffinic molecules will combust more readily than aromatic molecules, thereby reducing the chance of soot formation caused by incomplete combustion. The hydrogen content of the fuel is, therefore, a simplified directional predictor of nvPM emissions. Individual fuel properties such as sulphur, aromatics and napthalenes content, carbon number distribution and the distillation curve will each affect nvPM emissions to varying degrees. Reduced soot emissions from combustion of 100% SAF (HEFA-SPK) and different blends of fossil-based Jet A-1 and HEFA-SPK or FT-SPK[2] have been confirmed by ground and airborne measurements, with a reduction in soot particle number of 20% to 80%, depending on the fuel tested, engine type, combustor design and engine power settings.[18,19,20,21,22,23] The highest reductions appear at engine idle, at the lowest combustion temperatures, however this is not relevant to the operating conditions of aircraft in flight. In high-thrust conditions, fuel effects are generally less apparent.

Lean-burn combustion technology, which is used on most modern narrow body aircraft representing approximately 16% of the total fleet and growing with aircraft renewal, substantially reduces soot emissions when engines run between medium to high thrust. Recent in-flight soot measurements have indicated very low (near-ambient) levels of soot emissions when burning Jet A/A-1.[24] A combination of high hydrogen content fuels and lean-burn combustion technology will minimise soot particle number emissions at the lower thrust range (idle and taxi), and have a small effect on already very low emissions at higher thrust ranges (take-off and flight). This result is a logical consequence of the combined effects of fuel and engine technology, although the low thrust range has a negligible impact on non-CO_2 emissions as this operating point is seldom used in flight. At medium to high thrust, lean burn systems are combusting lean, with close to zero nvPM formation even with low-hydrogen content jet fuels. It would therefore be expected that fuel hydrogen content will have little effect on nvPM in lean burn engines when operating at altitude cruising conditions, where contrails are formed.

[2] FT-SPK = Fischer-Tropsch straight paraffinic jet fuel

Volatile particulate matter (vPM): The impact of fuel composition on the number of emitted vPM particles is more complex. vPM form from precursor gaseous emissions from the aircraft engines, in amounts that also depend on external factors such as weather conditions, or from lubricating oil emissions. The sulphur content of the fuel is important because sulphur oxidises into sulphur dioxide, one of the precursor gases for vPM. Petroleum-based Jet A/A-1 typically contains a range from fifty to several hundred parts per million of sulphur by mass. In contrast, HEFA-SPK does not contain sulphur. The number of formed vPM particles also depends on nvPM (soot) number[25] because soot scavenges the volatile molecules from the engine plume, especially organics, including oil vapours and sulphur oxides, thus preventing them from forming vPM. Therefore, when nvPM numbers remain relatively large, in the so-called 'soot-rich regime' associated with rich-burn, quick-mix, lean-burn (RQL)[3] combustion, sulphur has a limited impact on vPM number but might play a role in 'activating' the hydrophobic nvPM particles to allow water to condense on them,[26] leading to the formation of ice crystals, contrails and cirrus clouds. Conversely, in the so-called 'soot-poor regime', achieved by some advanced RQL and lean-burn combustors, theoretical calculations predict that the lack of nvPM limits the scavenging of vPM precursors and opens previously suppressed pathways of volatile particle formation.[25,27,28] Flight tests in the soot-rich regime using fuels with different sulphur contents confirmed the expected reduction in vPM with decreasing fuel sulphur content.[29] The extent to which oil droplets, nitric acid or organic compounds would drive volatile particle formation in soot-poor, ultra-low sulphur conditions remains an open question.

Note that hydrogen content is not currently measured or reported in commercial aviation fuel specifications, nor are there any limits on hydrogen content. This is because aromatics, naphthalenes and sulphur are individually measured and each have their associated limits. It follows that lower levels of these three properties would result in higher hydrogen content. Hydrogen content is a useful indicator for research purposes and can be easily calculated from the current Jet A/A-1 certificate of analysis (COA) using the method ASTM D3343 (Standard Test Method for Estimation of Hydrogen Content of Aviation Fuels).

What does the use of SAF or fuels of similar composition mean for contrail formation and the climate impact of contrails?

The previous section concluded that fuels with high hydrogen content and low sulphur content, such as, but not limited to, SAF, can reduce the number of particles generated by aircraft engines. This number of particles is one of the factors, along with, more significantly, atmospheric conditions, that determines the initial number of ice crystals in contrails. Contrail ice crystals form when water vapour condenses onto the particles emitted or formed in the aircraft engine exhaust plume, forming liquid water droplets that quickly freeze. It is expected that the emission of fewer particles will lead to the formation of fewer ice crystals.[25] Recent research stresses that the reduction should be in total particle emissions, not just nvPM emissions, because from a thermodynamics perspective, ice crystals will form if there are particles available.

[3] RQL = Rich-burn, quick-quench, lean burn combustion technology

Several in-flight measurements taken behind aircraft burning fuels with varying hydrogen and sulphur contents confirm the formation of fewer ice crystals from reduced soot particle numbers and/or reduced volatile particle numbers.[24] Most recently, reduced ice crystal numbers have been observed in the case of SAF and desulphurised Jet A / A-1.[29]

Climate modelling suggests that a reduced ice crystal number translates into reduced radiative forcing by contrails and contrail cirrus, thanks to smaller contrail optical depths and shorter lifetimes.[4] [14] Simulations using the Schmidt-Appleman criterion to determine conditions favourable to contrail formation find that the use of SAF slightly increases the extent of the regions of formation of persistent contrails because of its higher water vapour emission index compared to Jet A-1. However, this effect is small and, consequently, models still find a net reduction in contrail-cirrus radiative effect, driven by decreases in contrail optical properties and lifetime.[17,30] There is however more uncertainty as to the extent that radiative forcing causes climate temperature variations.

It should also be taken into account that increasing hydrogen content will first remove sulphur from jet fuel. Reducing sulphur in jet fuel will reduce the sulphate emissions which slowly form sulphuric acid in the atmosphere. The interaction between sulphuric acid and low-level clouds has the effect of cloud brightening, which is known to have a significant atmospheric cooling effect. Hence, there is a trade-off between increasing hydrogen content which may reduce contrails, and losing the sulphur which provides this cooling effect.[31,32] The net effect on global cooling/warming could well be unchanged compared to current aviation fuel composition; however, the scientific literature currently lacks the confidence level to draw net temperature conclusions. For this reason, a production process that emits large additional amounts of CO_2 to achieve higher hydrogen content would be unlikely to yield a net benefit; however, SAF blending would be a more neutral way to achieve higher hydrogen content.

A change to current Jet A / A-1 aviation fuel specifications would require additional hydroprocessing at existing refineries, which will come at a substantial cost in terms of invested capital, hydrogen consumption and additional CO_2 emissions from production. Furthermore, over 30% of European refineries do not have any installed hydrotreating capacity for jet fuel. The business case required to fund large capital investments would be unlikely in an environment of overall demand reduction for petroleum products, so tighter specifications would most likely accelerate refinery closure rather than improve jet fuel quality. Security of supply is a concern in this scenario as Europe is already a net jet fuel importer for 40% of its needs. Imported products are also less likely to comply with tighter European specifications at competitive pricing. The quantification of European refinery impacts is the subject of a Concawe study entitled *Aviation fuel composition effects on non-CO_2 emissions: European refinery impacts & effects on fuel quality*.

[4] Note that Bier, A. *et al.* (2017) shows that this reduction in climate impact is due to the reduction in the radiative forcing of long-lived contrails. The reduction in ice crystal numbers is negligible for short-lived contrails.

It is therefore an open question whether the net effect of the various fuel property-related trade-offs on non-CO_2 emissions would be enough to justify the additional GHG emissions required to further hydroprocess conventional jet fuel. However, if SAF mandates are achieved in the coming years, the hydrogen content will naturally increase proportionally in the final fuel blends used in the market.

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Decarbonising Europe's refining and liquid fuel production — insights from the Concawe-S&P Global study

Introduction

Europe's 2050 climate neutrality ambition is inducing a profound transformation of the petroleum refining and renewable fuel manufacturing sectors. This article summarises key findings from the S&P Global Commodity Insights (SPGCI) study[1] commissioned by Concawe to assess the potential evolution of refining and liquid fuel production in Europe to 2050 under two pathways achieving the European Union's (EU's) 2050 net-zero greenhouse gas (GHG) emissions target through contrasting technology and energy-system strategies.

This article presents a technical synthesis of an S&P Global Commodity Insights study commissioned by Concawe on the evolution of Europe's refining and liquid fuel manufacturing sectors to 2050. Two illustrative net-zero pathways are assessed: 'Max Electron', characterised by accelerated electrification, and 'More Molecule', which places greater emphasis on low-carbon fuels. Both pathways indicate a substantial decline in fossil fuel demand and refining capacity, alongside significant growth in biofuels, hydrogen and e-fuels, requiring coordinated policy support and investment.

Author

Johan Dekeyser (Concawe)

Concawe has already studied opportunities and challenges with regard to the future of the EU refining industry amid the ongoing transition to a low CO_2-intensive economy up to 2030 and 2050, and published different scenarios, including considering an increase in the production of low-carbon fuels, such as sustainable biofuels and e-fuels, in its 'Refinery 2050' report.[2]

The objective of this study is to assist stakeholders to better understand the possible impact on the refining industry of two different scenarios, regarding mobility and energy supply, meeting the net-zero greenhouse gas emission target in 2050 with segregation by clusters of European states.

This will provide European states with a deeper understanding of the impacts of different ways to achieve climate neutrality on their economies and on the security of supply of fuels and other refinery products of key importance for the economic value chain of EU-27 + 3 states.1 It also addresses potential fuel supply issues that could impact fuel security during the energy transition phase.

Context and methodology

EU legislation review

The European Green Deal,2 presented by the European Commission in December 2019, is a set of policy measures aimed at promoting environmentally sustainable development and economic growth across the EU with the overarching goal of achieving climate neutrality by 2050. It covers all sectors of the economy, including transport, energy, agriculture and industry, with actionable policies aimed at reducing emissions and promoting energy transition.

The European Climate Law3 transforms the European Green Deal's political commitment into a legal obligation and details the necessary steps to get there. EU Member States and the European Parliament approved the European Climate Law on 29 July 2021. By adopting it, the EU and its Member States committed to the intermediate target of cutting net GHG emissions in the EU by at least 55% by 2030, compared with 1990 levels. This 55% reduction is covered by the Fit for 55 package,4 proposed in July 2021.

1 The 27 member countries of the European Union, plus Norway, Switzerland and the UK (also 'EU+')

2 European Green Deal

3 European Climate Law

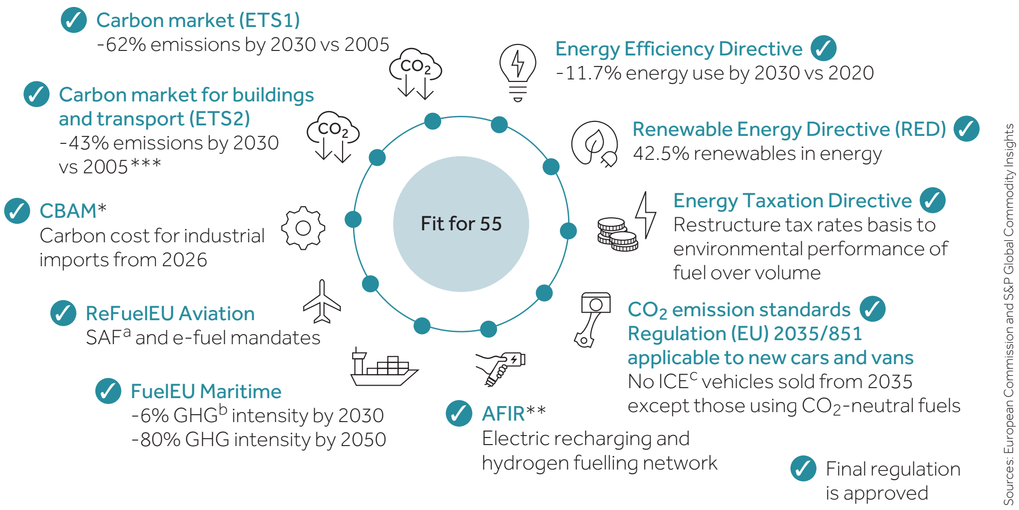
4 'Fit for 55: Delivering on the proposals' (online).

European policy framework

The transformation takes place within a demanding regulatory landscape shaped by the European Green Deal, Fit for 55 package (see Figure 1) and Renewable Energy Directive III (RED III).

These measures accelerate decarbonisation across transport, power and industry. Carbon prices are assumed to rise steadily, reaching EUR 350–400/t CO_2 by 2050.

Figure 1: Fit for 55 policy initiatives



[a] SAF = sustainable aviation fuel [b] GHG = greenhouse gas [c] ICE = internal combustion engine

* CBAM: carbon border adjustment mechanism

** AFIR: alternative fuels infrastructure regulation

*** The release for consumption of fuels for which the emission factor is zero is not considered in the scope of ETS and ETS2. Under the ETS Monitoring and Reporting Regulation (MRR), the zero rating applies to renewable fuels compliant with the RED (biofuels, RFNBOs and recycled carbon fuels (RCFs)), as well as low-carbon fuels defined in Article 2 (13) of the EU Gas Directive (Directive (EU) 2024/1788) and certified according to the provisions set by Article 9.

Scenario modelling by SPGCI

The Energy and Climate Scenarios are typically used by clients of SPGCI for creating and testing their strategy. SPGCI's Green Rules scenario represents the current view of the fastest plausible energy transition, but it is not net zero globally, and results in a global temperature rise of +1.7°C by 2100. Green Rules is, however, essentially net zero when looking at Europe by 2050.

For this study, S&P Global created two bespoke scenarios — 'Max Electron' and 'More Molecule'. Both used the Green Rules scenario from the SPGCI Energy and Climate Scenario service as a starting point.

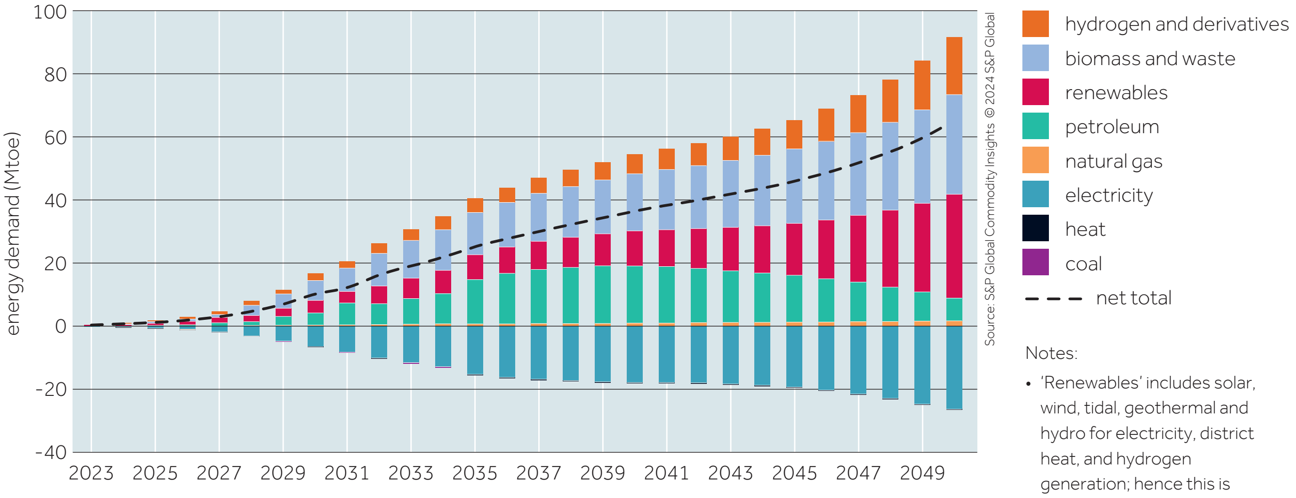
The first, the Max Electron scenario, meets all requirements of the Fit for 55 package while surpassing the requirements of the EU's CO_2 standards regulation for HDVs[5] by assuming zero sales of ICE vehicles after 2035. It assumes an accelerated and unprecedented rate of electrification across various modes of transportation, with widespread use of renewable electricity, heat pumps and hydrogen.

The second, the More Molecule scenario, was derived from the Max Electron scenario by relaxing the requirements of the LDV and HDV vehicle standards and allowing sales of some new internal combustion engine cars and vans after 2035, and postponing any electrification in the aviation and marine sectors until after 2050. This scenario achieves net zero in 2050 by complementing electrification with an increased use of low-carbon and renewable fuels, relying more heavily on biofuels and RFNBOs.

Both scenarios rely on an important shift of road and aviation transport to rail. The increase in rail activity required to meet the net-zero emission objective in 2050 represents a major challenge, which will require significant investment in the rail infrastructure. Both pathways were built using the S&P Global Integrated Energy Model and detailed refinery-level LP modelling.

Comparing the overall total energy demand for the More Molecule and More Electron scenarios by 2050, the More Molecule scenario requires 65 Mtoe more energy demand as compared to the Max Electron scenario by 2050 (see Figure 2).

Figure 2: Delta total energy demand outlook: More Molecule minus Max Electron (Mtoe)
(for the EU-27 plus Norway, Switzerland and the UK)



Notes:
- 'Renewables' includes solar, wind, tidal, geothermal and hydro for electricity, district heat, and hydrogen generation; hence this is renewables input to the production of electricity, heat and hydrogen/hydrogen derivatives.
- Values greater than zero reflect a greater demand in the More Molecule scenario compared to the Max Electron scenario.

[5] Regulation (EU) 2024/1610

Decarbonising Europe's refining and liquid fuel production — insights from the Concawe-S&P Global study

Linear programming analysis

The Max Electron and More Molecule scenarios present a significant modification in the EU+ region's refinery landscape, driven by S&P Global's proprietary forecast of industrial and transport activity, by the adoption of e-mobility, and by the transition to low-carbon fuels. These transformations are poised to reshape liquid fuel demand, traditional refining capacities and product balances, necessitating strategic adaptations from the refining industry, and its transition to low-carbon fuels manufacturing.

S&P Global developed a linear program (LP) model, in which all EU+ refineries are represented.

The declining local market demand for fossil products impacts conventional refinery viability, with LP model outputs showing increasing numbers of EU+ refineries projected to have negative margins over time under both scenarios. Refineries showing negative margins in 2024, 2030, 2040 and 2050 are deemed to stop operations.

Existing refineries will have to align their capacities with lower margins resulting from decreasing market demand for fossil fuels. Conventional refining capacity is projected to decrease from 13 Mbbl/d in 2024 to 2.1 Mbbl/day in More Molecule and 1.7 Mbbl/day in Max Electron by 2050. This significant reduction reflects the negative margins due to the declining fossil fuels demand and the corresponding need for refineries to adjust their operations to match market dynamics.

Figure 3: Numbers of refineries remaining in 2024, 2030, 2040 and 2050 in the Max Electron and More Molecule scenarios

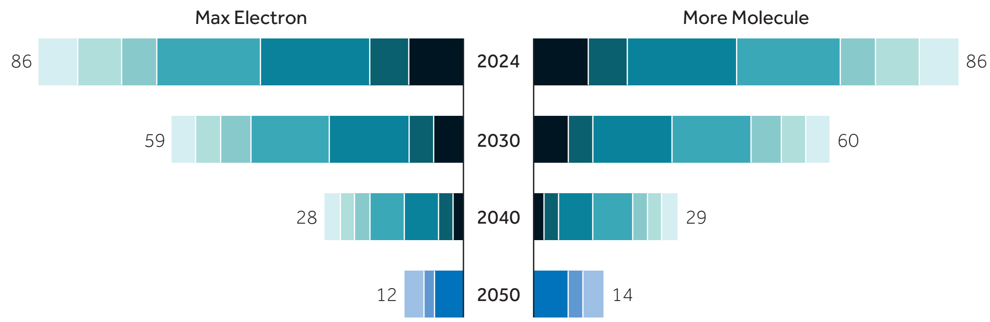
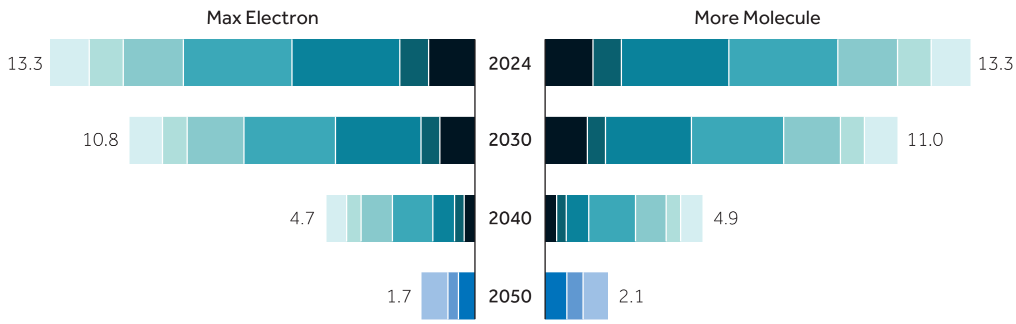


Figure 4: Refining capacities remaining in 2024, 2030, 2040 and 2050 in the Max Electron and More Molecule scenarios (million barrels of oil per day)



In both cases, significant conventional refinery closures are expected. However, the demand for low-carbon fuels is higher in the More Molecule scenario, which creates greater opportunity for traditional refineries to be transformed to produce low-carbon fuels rather than being fully closed in this scenario.

Supply and demand

In both scenarios, EU+ demand for conventional hydrocarbons falls and the region enters a sustained period of having an excess of crude oil refining capacity. However, expected poor refining economics restricts the operating rate of conventional refineries and, as a result, refining cover for most fuels reduces over the period from 2024 to 2040. The demand for renewable liquid fuels increases, which provides some refineries with the opportunity to integrate more renewable feedstocks in the replacement of petroleum, and to transition to bio- or e-refineries.

Food and feed crop-based biofuels production capacity will enter long-term decline in line with falling fuel demand regardless of the scenario. Furthermore, it will fall to zero by 2050 to meet net-zero emissions because of the higher embedded CO_2 content of food and feed crop-based biofuels. RED Annex IX, Part B biofuels production capacity will also decline in line with falling fuel demand; in 2050, production is 5.2 Mtoe in Max Electron and 5.7 Mtoe in More Molecule.

In both scenarios, production capacity for Annex IX, Part A biofuels needs to increase in the long term to meet the rising demand for advanced biofuels. By 2050, in the Max Electron scenario, production capacity needs to rise to ±57 Mtoe, and to ±88 Mtoe in the More Molecule scenario.

A 2021 study on sustainable biomass availability in the EU, undertaken by Imperial College London at the request of Concawe, showed that the potential availability of advanced and waste-based biofuels (through EU domestic production) in 2050 can reach 137 Mtoe with some progress in biomass collection and research and development in yield improvement.[3] The demand for biofuels in the Max Electron scenario falls within the low to middle of sustainable biofuel potential availability, whereas the More Molecule scenario approaches the upper range of this estimate. This implies that improvement measures detailed in the Imperial College London study will be required to realise the higher mobilisation of biomass required.

SPGCI maintains a database of fatty acid methyl esters (FAME) plants, fuel ethanol plants and biorefineries which is updated by the SPGCI Biofuels Value Chain Service (BVCS) team of researchers and analysts. This database records global biofuel plants that are operating, and the projects that have been announced publicly by companies in the industry up to 2030. Collectively between the FAME plants, fuel ethanol plants and biorefineries—considering both current operational capacity and firm projects—EU+ biofuel production capacity is forecast at 33 Mtoe in 2030. It is assumed that two-thirds of this capacity could remain operational in 2040 and 2050.

As fossil fuel demand reduces, the use of spare capacity in the remaining refining infrastructure provides a useful path for producing biofuels. Our analysis allows spare capacity on operational diesel/kerosene hydrotreaters to be used to produce biofuels, either by co-processing or produced in batch with fossil fuels.

We also assume that refineries that are stopping their fossil operations can be repurposed to produce advanced biofuels. This greatly reduces the requirement for investment in new stand-alone biofuel or e-fuel plants, and would likely reduce overall investment costs as the repurposed plant could take advantage of existing infrastructure and units, and access existing fuel distribution networks.

By 2050, assuming a standard capacity for a biorefinery of 1 Mtoe per year, the EU+ would require 22 repurposed or new biorefineries in the Max Electron scenario and 48 in the More Molecule scenario to supply the required biofuel demand. This is in addition to co-processing biofuels at any remaining operational conventional refineries.

In addition, in both scenarios, the demand for renewable fuels of non-biological origin (RFNBOs)—hydrogen and e-fuels—grows in the long term as a solution for emissions reduction in hard-to-abate sectors. RFNBO demand in the More Molecule scenario is 11% higher than in the Max Electron scenario by 2050. The overall possible supply of RFNBOs in the EU+ is 111 Mtoe by 2050 in the More Molecule case.

Excluding drop-in e-fuels, the emergence of RFNBOs as a green energy carrier requires development of specific transportation infrastructure for import and use. Multiple hydrogen carriers exist (hydrogen gas, ammonia, methanol, etc.), each with different transportation economics. In the Max Electron scenario, non-e-fuel RFNBO demand is 151 Mtoe, and in the More Molecule scenario it is 160 Mtoe in 2050.

RFNBO demand will come from the hard-to-abate sectors such as industrial, power, refinery use and transport. Overall, the EU+ industrial hydrogen demand for RFNBOs will be based on the target defined by the EU, i.e. 42% by 2030 and, by 2050, an assumed 100% of overall industrial hydrogen demand (excluding the production of hydrogen as a by-product from processes such as reforming and steam cracking, which must be consumed). Demand in the transport sector will come from direct hydrogen use by the ICE and fuel-cell electric vehicle (FCEV) fleet, and from the use of hydrogen to produce e-fuels.

Given the expected maximum possible renewable power capacity by 2050 under the SPGCI Green Rules scenario, and with strong demand for renewable power coming from power, transport and other sectors, the EU+ would have limited renewable power capacity available to meet the expected overall demand for RFNBOs. The EU will therefore need to import more than 50% of its e-fuel requirements in both scenarios.

Table 1 on page 47 shows the evolution of fuel manufacturing plants in Europe. While the number of traditional refineries reduces from 86 to 12 and 14, respectively, in the Max Electron and More Molecule scenarios, the increased demand for liquid fuels in the More Molecule scenario allows 92% of current EU refineries to be retained or repurposed, whereas in the Max Electron scenario 41 refineries would have to be closed without further utilisation.

Table 1: Number of refineries, biorefineries and e-fuel plants in the Max Electron and More Molecule scenarios

a) Max Electron

	Number of conventional refineries running	Number of new biorefineries required	Number of e-fuel plants required	Total
2024	86			86
2030	58	0	1	59
2040	28	0	2	30
2050	12	22	11	45

b) More Molecule

	Number of conventional refineries running	Number of new biorefineries required	Number of e-fuel plants required	Total
2024	86			86
2030	59	0	1	60
2040	29	8	3	40
2050	14	48	17	79

Security of supply

Based on SPGCI analysis, the EU+ maximum potential for additional renewable electricity production from 2024 is estimated at ±3,712 TWh in 2050, of which 51% will be used for hydrogen production in 2050. Domestic generation of RFNBOs (hydrogen and e-fuels) requires additional renewable electricity of more than 1,884 TWh in 2050, which will be a challenge—for context, the total EU+ electricity consumption in 2022 was 2,895 TWh.

In the Max Electron scenario, the total liquid biofuel demand for bio-gasoline, biodiesel, biojet and bioLPG reaches 62 Mtoe by 2050. In the More Molecule scenario, total liquid biofuel demand reaches 94 Mtoe. There is sufficient biomass available in the EU+[3] to meet Annex IX, Part A and Part B biofuels demand, hence there could be sufficient domestic production to meet these requirements without imports by 2050 under both the Max Electron and More Molecule scenarios. Such a demand for biofuels would enhance EU+ fuel security.

In the More Molecule scenario, by 2050, the demand for e-fuels—which includes e-SAF,[6] e-gasoline and e-diesel—is 39.5 Mtoe, and 23.6 Mtoe in the Max Electron scenario. Overall supply capacity for e-fuels in the EU+ grows to 16.0 Mtoe in the More Molecule case and 10 Mtoe in the Max Electron case.

RFNBO production requires large amounts of renewable electricity produced by a combination of wind and solar power; and as mentioned above, the supply of renewable electricity is estimated by SPGCI to be limited. Therefore, the EU+ remains a net importer of RFNBOs and e-fuels in both scenarios. By 2050, RFNBO import volumes vary from 32% of total RFNBO demand in the Max Electron scenario to 39% of total demand in the More Molecule scenario.

In 2030 and 2040, the imbalances between supply and demand of liquid fuels (fossil, bio- and e-fuels) in the EU+ remain relatively similar in both scenarios: a significant excess of gasoline and deficit of diesel in 2030, somewhat reduced in 2040 but countered by a significant deficit in jet/kerosene (approximately a third of the demand will have to be imported).

[6] e-SAF: electro-Sustainable Aviation Fuel—a synthetic jet fuel offering a 90%+ reduction in carbon footprint compared to conventional jet fuel.

The EU+ will have to rely on imports to cover 56% of its e-fuel demand in 2050 in the Max Electron scenario, and 59% in the More Molecule scenario. It is expected that e-fuel imports will come from regions with a high number of sunlight days and low population density, such as the Middle East, North Africa, Chile, Australia and the US Gulf Coast. Imports of e-fuels could include either finished products or e-crude to be refined in EU refineries, depending on the business model of the international e-fuel producers.

In 2050, both scenarios show a similar excess of gasoline, albeit at a much reduced volume. A deficit of jet/kerosene will represent 25% of the demand in the More Molecule scenario, and 33% of the demand in the Max Electron scenario. Diesel will have to rely on the export of approximately 20% of its production, and residual fuel oil and LPG on imports of approximately 50% of the demand in the Max Electron scenario, while the supply and demand of these products are almost equilibrated in the More Molecule scenario, leaving the EU+ almost self-sufficient for these products.

The transition from fossil fuel refining results in a decline in EU+ supply of crude-derived speciality products such as bitumen, petcoke, base oils, and petrochemical feedstocks such as naphtha, propylene and aromatics. Bitumen and petcoke cannot be cost-effectively produced from renewable feedstocks, and the EU+ will have to rely on imports for the majority of the supply in 2050. Approximately 50% of base oil demand will have to be imported in the Max Electron scenario (1.7 Mtoe), while these imports are reduced to approximately 35% of the demand in the More Molecule scenario (1.2 Mtoe).

The reduction in propylene and aromatics production from conventional refineries could be replaced by additional production from the petrochemical industry, which would require additional naphtha supply for steam crackers. This additional 12 Mtoe naphtha demand could be met in 2050 in the More Molecule scenario, while it would have to rely on imports in the Max Electron scenario.

Conclusions

The Max Electron scenario requires an unprecedented expansion of renewable electricity infrastructure, while the More Molecule scenario relies on an important development of sustainable feedstock availability. Both scenarios demand sustained policy clarity, supportive carbon pricing, and cross-sectoral cooperation. A hybrid path combining electrons and molecules appears most robust for security of supply and industrial competitiveness and resilience.

The Concawe-SPGCI study shows that both pathways can deliver net-zero emissions by 2050. The transition will reshape Europe's refining industry into a low-carbon ecosystem anchored by innovation, hydrogen and carbon management.

Report-specific disclaimer

Neither scenario is intended as a forecast or a validation of the probability or feasibility of realising the various assumptions in the study, such as the rate of electrification or availability of renewable energy and green hydrogen for the transport sector, nor do they assess the impact on competitiveness of the

European economy or the affordability for consumers or industries. These scenarios are two theoretical cases for meeting the EU's 2050 net-zero objective.

The choice of these two theoretical scenarios should not be considered as exhaustive for meeting the 2050 net-zero emission objective, as this study does not include other scenarios that could potentially achieve the objective by modifying other key decarbonisation opportunities such as, for example, greater uptake of carbon capture and storage (CCS), additional bioenergy carbon capture and storage (BECCS), blue hydrogen or other technological advancements in sectors other than transport.

Furthermore, the economic modelling behind the scenarios did not take into account refinery-specific parameters such as petrochemical integration, individual refinery energy efficiency, etc. The conclusions regarding the necessary reduction of refining capacity should therefore not be interpreted as an indication of the level of any individual European refinery.

Acknowledgement

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Abbreviations and terms

AFIR	Alternative Fuels Infrastructure Regulation
ASTM	ASTM International—formerly known as the American Society for Testing and Materials
AZCATI	Arizona Center for Algae Technology and Innovation
BECCS	BioEnergy Carbon Capture and Storage
BVCS	Biofuels Value Chain Service
CAP	Combined Algae Processing
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
COA	Certificate Of Analysis
CS	Centralised Systems
DS	Decentralised Systems
e-SAF	electro-Sustainable Aviation Fuel
E/H	Electric power and Heat
ERF	Effective Radiative Forcing
EtOH	Ethanol
ETS1 (also ETS)	The European Union Emissions Trading System (also known as the EU ETS)
ETS2	A proposed new Emissions Trading System that addresses the CO_2 emissions from fuel combustion in buildings, road transport and additional sectors not covered by ETS1 (the existing EU ETS); ETS2 is due to become operational in 2027.
EU	European Union
EU-27	The 27 member countries of the European Union
EU-27 + 3 (also EU+)	The 27 member countries of the European Union plus Norway, Switzerland and the UK
FAME	Fatty Acid Methyl Esters
FAO	Food and Agriculture Organization of the United Nations
GFT	Gasification and Fischer-Tropsch
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Green Wall Panel
H_2O	Water
HD	High Demand
HDV	Heavy-Duty Vehicle
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	HydroThermal Liquefaction
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
ICL	Imperial College London
IEA	International Energy Agency
LD	Low Demand
LE	Lipid Extraction
LP	Linear Program
LPG	Liquefied Petroleum Gas
MILP	Mixed-Integer Linear Programming
MSP	Minimum Selling Price
Mt	Million Metric Tonnes
Mtoe	Million tonnes of oil equivalent
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NUTS	Nomenclature des Unités Territoriales Statistiques (Nomenclature of Territorial Units for Statistics)
nvPM	Non-Volatile Particulate Matter
O_3	Ozone
OPEX	Operating Expenditure
PBR	PhotoBioReactor
PM	Particulate Matter
PRIMES	Price-Induced Market Equilibrium System
RED	Renewable Energy Directive
RF	Radiative Forcing
RFNBO	Renewable Fuels of Non-Biological Origin
RP	Repurpose
RQL	Rich-burn, Quick-quench, Lean burn (combustion technology)
SAF	Sustainable Aviation Fuel
SO_x	Sulphur Oxides
SPGCI	S&P Global Commodity Insights
SPK	Synthetic Paraffinic Kerosene
TRL	Technology Readiness Level
UCO	Used Cooking Oil
vPM	Volatile Particulate Matter
WRT	With Respect To

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Concawe
Avenue des Nerviens 85
1040 Brussels (Etterbeek)
Belgium

Telephone: +32-2 566 91 60
Fax: +32-2 566 91 81
info@concawe.eu
www.concawe.eu