Low-carbon liquid fuels: exploring potential ways to contribute to the 2050 EU climate ambition goals

This article presents the findings of a new report which aims to explore the theoretical potential for the production of low-carbon liquid fuels within the European Union refining system, both in terms of total volumes and the number of potential plants required to make a meaningful contribution to climate neutrality in the EU by 2050.

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The context

With the publication of the European Green Deal and the recent legislative proposal from the European Commission to strengthen the 2030 climate-related targets, Europe has made clear its ambition to lead the greenhouse gas (GHG) reduction ambition worldwide, moving towards net-zero GHG emissions and a circular economy by 2050. Transport, which represents about one quarter of total European Union (EU) GHG emissions, is deemed to be one of the sectors in which major efforts should be pursued. In 2017, the road transport sector accounted for 73% of total transport energy demand[1] and, in contrast with other sectors of the economy, average CO_2 emissions from new passenger cars increased during the period from 2017 to 2019.[2] The evolution of the light-duty fleet to create a less GHG-intensive mobility sector is therefore considered to be one of the top priorities for the European Commission towards 2030 and onwards. In addition to the road transport-related targets, proposals for new pieces of legislation, such as the 'ReFuelEU Aviation'[1] and 'FuelEU Maritime'[2] initiatives, are being developed to incentivise the deployment of sustainable fuels to replace fossil-based fuels in these sectors.

In this context and motivated by its role as a major fuel provider, the EU refining system is exploring different plausible and realistic pathways for its own transformation as a way to contribute to this overarching climate ambition goal. However, many questions are still to be answered, and there remains a high degree of uncertainty, for example about the types of energies and powertrains/engines that would be used in 2050 in the different transport segments, as well as the implications in terms of development pace and costs for the different potential routes that would be required to meet a net-zero GHG objective.

A new report,[3] published as part of Concawe's *Low Carbon Pathways/Refinery 2050* series, is now available which, through a scenario analysis exercise, aims to improve understanding of the theoretical potential for the production of low-carbon liquid fuels (LCFs) within the EU refining system, both in terms of total volumes and the number of potential plants required. Aspects such as the relevant impact of LCFs in terms of their contributions to reducing GHG emissions in transport (following a well-to-wheels approach), as well as the level of investment needed for the transformation of the refining industry, are also investigated, providing a quantitative indication over a reference time frame from now until 2050.

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[1] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12303-ReFuelEU-Aviation-Sustainable-Aviation-Fuels_en

[2] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-CO2-emissions-from-shipping-encouraging-the-use-of-low-carbon-fuels_en

Demand scenarios

Looking at the transport sector as a whole, Concawe has explored three 'alternative 1.5°C' scenarios, defining plausible reductions in the demand for liquid fuels in the road, aviation and maritime sectors, as a result of the implementation of energy efficiency measures as well as the penetration of alternative technologies, such as electrification or gaseous fuels in each individual sub-sector. Considering the progressive replacement of fossil-based fuels, different ramp-up scenarios have been defined to assess the potential deployment of low-carbon liquid fuel (LCF)-related technologies within each transport mode during the period 2030–2050. The demand scenarios for LCFs by 2050 are characterised as follows:

- Scenario 1: High demand (all transport modes)

The most challenging scenario in terms of scaling up the production of sustainable LCFs considers that these alternative fuels will penetrate the light- and heavy-duty segments first, to make road fuels climate neutral by 2050, thereby enabling the groundwork for mass deployment of climate-neutral aviation and maritime fuels beyond 2035. This high LCF demand scenario is deemed to be an end-point case under the main assumption that the passenger car segment is not fully electrified by 2050 (i.e. a mixed balance of electrified vehicles (xEVs), hydrogen-powered vehicles and internal combustion engine (ICE)-powered vehicles will still be present in the fleet, leading to a 2050 demand for road transport fuels as defined by the 2050 baseline scenario published in the European Commission's long-term strategy, *A Clean Planet for all*[4]). In this case, the demand for LCFs increases from today, progressively replacing the demand for fossil-based fuels and completely phasing out the use of fossil gasoline/diesel in road transport by 2050.

- Scenario 2: Medium demand (heavy-duty vehicles, aviation and maritime)

The second scenario considers the creation of the LCF market, incentivised initially by road transport (both light- and heavy-duty), moving progressively towards the aviation and maritime sectors. This scenario differs from Scenario 1 in the assumption that, as a result of a more aggressive penetration of xEVs in the passenger car segment (consistent with the 1.5TECH 'climate neutral scenario' presented in *A Clean Planet for all)*, LCFs will only be used in heavy-duty road vehicles and in aviation and maritime in the 2050 time frame (with the total demand for liquid fuels phasing out in the light-duty segment during the 2040–2050 period).

- Scenario 3: Low demand (aviation and maritime)

This scenario assumes a more aggressive penetration of alternative powertrains in both the light- and heavy-duty segments, leading to a case in which there is no remaining demand for liquid fuels in road transport by 2050. As a consequence of this lower demand for LCFs in road transport in the first decade of the period (2020–2030), both the LCF market and supply chain creation are less incentivised and, therefore, the development and scaling up of LCF technology is delayed compared with the previous scenarios. By 2050, all LCF produced will be used in the aviation and maritime sectors. In this low (end point) demand scenario, no additional volumes of sustainable aviation fuels (SAFs) have been considered beyond those portrayed in the ReFuelEU/1.5TECH scenarios (i.e. ~40% remaining fossil kerosene in 2050).

Tables 1 and 2 present the LCF demand timelines for the aviation and maritime sectors, and for the road transport sector, respectively, according to the Concawe scenarios.

Table 1: Low-carbon liquid fuel demand timeline for the aviation and maritime sectors (Mtoe/year)

Aviation and maritime [a]	**Scenario**	**2030**	**2040**	**2050**
Total demand (liquid fuels)	1, 2	113	108	~100
	3		108	
Low-carbon liquid fuels — total *	1, 2	3	35	67
	3		31	
Aviation	1, 2, 3	3	20	37
Maritime	1, 2	-	15	30
	3		11	30
% LCF vs total liquid fuel demand (maritime and aviation)	1, 2	3%	~32%	68%
	3		30%	

Source: Concawe, based on *A Clean Planet for all* and RefuelEU data

Notes:

[a] Volumes are derived from the SAF mandates for aviation (consistent with the 1.5TECH scenario) and the H2Mar70 scenario[4] for the maritime sector. Without entering into the specific LCF technologies (and qualities/types of specific fuels) that could be used in 2050, the current Concawe estimate is based on an even distribution of drop-in liquid e-fuels and biofuels (assuming the same GHG reduction savings for each category as for road transport). For the aviation sector, the sub-mandate on synthetic fuels from ReFuelEU is deemed to be met by e-fuels.

Table 2: Low-carbon liquid fuel demand timeline for the road transport sector (Mtoe/year)

Road transport [a]	**Scenario**	**2030**	**2040**	**2050**
Total demand [b] (liquid fuels)	1	223	135	93
	2		130	40
	3		100	0
Low-carbon liquid fuels	1	31	62	93
	2			40
	3	19	7	0
% LCF vs total liquid fuel demand	1	14%	46%	~100%
	2		~50% [c]	
	3	9%	7%	N/A

Source: Concawe, based on *A Clean Planet for all* and RefuelEU data

Notes:

[a] Concawe's internal modelling assessment (fleet composition and fuel availability). 2030 data based on Concawe's 2030 Fleet and fuel outlook[5] whereas 2050 data are aligned with the 2050 baseline presented in *A Clean planet for all.* [4] As a simplification, an estimate of the 2040 mid point has been conducted showing a slightly sharper decrease in the 2035+ time frame when compared against a linear interpolation.

[b] The reduction in demand is due to the combined effect of measures such as fuel efficiency improvements in powertrains, implementation of different levels of electrification (hybridisation) in existing ICEs, and penetration of alternative vehicles (e.g. BEVs) or gaseous fuels (e.g. hydrogen).

[c] Low-carbon liquid fuels are diverted to the heavy-duty segment due to the accelerated penetration of xEVs in the passenger car segment (reducing the demand for liquid fuels in this segment).

Low-carbon technologies

With the objective of understanding the potential contribution of the EU refining system to reaching the 1.5°C climate goal while satisfying the three demand scenarios for liquid fuels in the transport sector in a low-carbon-intensive manner, the Concawe study evaluates the potential deployment of some of the most promising GHG reduction technologies from today towards 2050, with a focus on low-carbon liquid fuels and CO_2 reduction technologies as summarised below.

Low-carbon liquid fuels

When the whole well-to-wheels (WTW) cycle is considered, from the production of fuels to their final use in the engines, ~80% of the total GHG emissions are due to the combustion of the fuels onboard the vehicles (i.e. the so-called 'tailpipe emissions').

The production of LCFs targets the replacement of the fossil CO_2 emitted during the combustion of oil-based fuels by biogenic/net carbon-neutral CO_2 released when sustainable biofuels and/or e-fuels are used instead.

To illustrate the importance of replacing fossil-based fuels with these alternative options, it is worth mentioning that, in the case of advanced biofuels, the amount of CO_2 emitted to the atmosphere when combusted in an engine is the same as that originating in the agricultural residue (i.e. the CO_2 captured from the atmosphere during its growing stages). For e-fuels produced in conjunction with carbon capture, utilisation and storage (CCUS) schemes, CO_2 is captured directly and converted into a fuel with the same characteristics as conventional fuels. When combusted, those e-fuels emit an equivalent amount of CO_2 to that which was initially captured, thereby closing the loop for a potential net-zero impact if renewable energy sources are used in their production.

The concept of LCFs in this assessment includes, as selected examples, sustainable food crop-based biofuels, biomass (and waste)-to-liquid (BTL), hydrogenation of non-food/crop-based vegetable oils/waste and residues, and e-fuel technologies, using either biogenic or recycled CO_2 from industrial sites; there is also the potential to consider direct air capture as this technology develops and becomes available at a more competitive cost.

The GHG savings shown in Table 3 on page 25 are derived from the GHG savings thresholds (minimum values) in the EU Renewable Energy Directive (RED II), and were considered in the assessment of the different types of LCFs selected.

Table 3: Assumed well-to-wheels GHG reduction (end points) for LCFs versus reference fossil fuel (diesel)

	2030 RED II / SGAB[c] / JEC[d] WTW v5[6]	**2050** Concawe[3]
Food-crop biofuels (conventional, i.e. first generation (1G))[a]	65%	70%
Advanced biofuels/ non-food-crop	75%	85%
e-fuels[b]	~95%	

Notes:

[a] In the absence of an approved legislation beyond 2030, a 7% cap as defined in RED II for food-crop biofuels has been applied and kept constant (% vs total energy) in this assessment, progressively limiting the volume of this type of LCF towards 2050 as the energy demand in transport is reduced.

[b] Renewable electricity is used at the production stage.

[c] SGAB — Sub-Group on Advanced Biofuels, European Commission Sustainable Transport Forum

[d] JEC — Consortium of the EU Commission's Joint Research Centre (JRC), EUCAR and CONCAWE.

CO_2 reduction technologies

Other key CO_2 reduction technologies such as carbon capture and storage (CCS) and clean hydrogen (H_2) installed or linked to the refineries could help to reduce the carbon intensity of the fuels produced today (mostly from fossil origin) as well as moving forward, as they have clear synergies with the production of LCFs. Clean H_2 and CCS are deemed to be key enablers of the 2050 climate objectives: clean H_2 is one of the main feedstocks for the production of e-fuels, and their use could also maximise the conversion of biomass into advanced fuels in a low GHG-intensive manner. Furthermore, when CCS is applied to certain biofuel production pathways, it can capture and store biogenic CO_2 underground, which is recognised as a way of removing net CO_2 from the atmosphere to generate so-called 'negative emissions' (as, for example, in the case of bioenergy with CCS (BECCS) schemes).

Figure 1 on page 26 summarises the range of low-carbon technologies explored in the Concawe report.

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[3] Potential GHG reductions in production processes due to additional energy efficiency measures and electrification of processes (e.g. replacement of H_2 production by 'clean H_2'), reductions in emissions in the transport step, etc.

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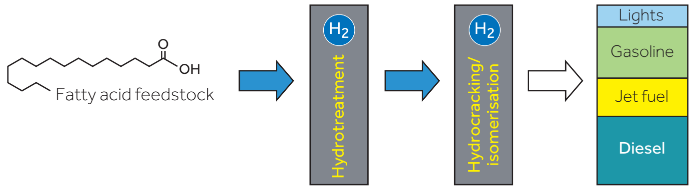
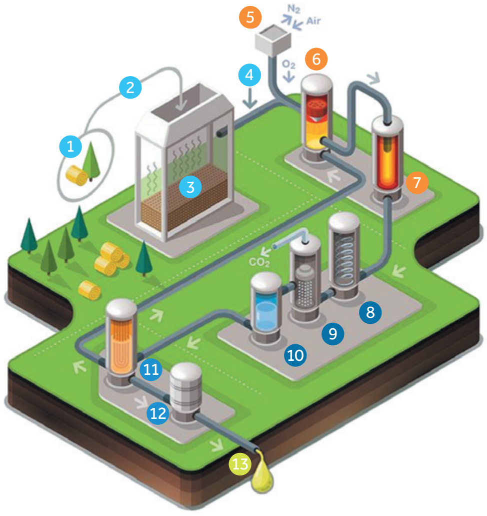
Figure 1: Examples of low-carbon technologies explored in the Concawe report

a) Hydrogenated vegetable oil (HVO)



b) Biomass to liquids (BTL)



PRETREATMENT

1. Lignocellulosic feedstock
2. Initial grinding and drying
3. Torrefaction
4. Hydrocarbon feedstock (if co-processed)

GASIFICATION

5. Air separator
6. Input, gasifier
7. Quench chamber

SYNGAS CONDITIONING

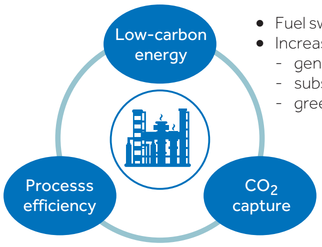
8. H_2/CO ratio adjustment
9. Cleaning with physical or chemical solvents
10. Final purification

FISCHER TROPSCH PROCESS AND UPGRADING

11. Fischer Tropsch plant
12. Hydrotreating/hydrocracking
13. Biodiesel/biojet fuel

The BTL illustration is adapted from: https://www.total.com/en/energy-expertise/projects/bioenergies/biotfuel-converting-plant-wastes-into-fuel

c) CO_2 reduction technologies

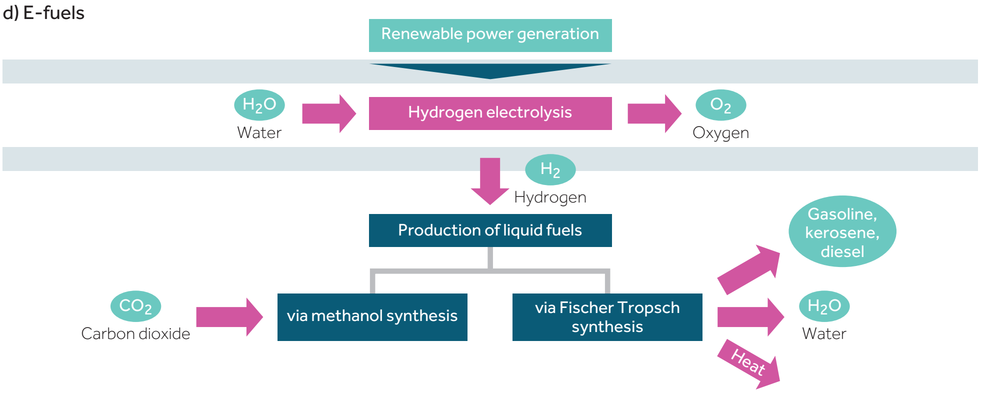


- Fuel switch
- Increased use of imported low-carbon electricity:
  - general electrification
  - substitution of fired boilers and heaters
  - green hydrogen

- Continuous improvement
- Energy management
- Major capital projects

- 'Easy-to-capture' (H_2 production)
- Other plants

d) E-fuels



Based on the current status of development of each of these technologies, from pilot plants to fully operational commercial facilities, the Concawe report provides a quantitative assessment of the trajectory towards a plausible, still ambitious, deployment of these technologies towards 2050 to meet the three demand scenarios foreseen, while answering the following key questions:

- How many industrial installations of the above-mentioned technologies will be needed, and by when will they be required, to progressively replace fossil fuels in the aviation and maritime and/or road transport sectors (with the ultimate objective in all cases of achieving a similar level of reductions in CO_2 emissions compatible with the 1.5°C ambition in 2050 explored by the European Commission)?
- How much will the transition of the industry towards these technologies cost?
  For each of the scenarios considered, best estimates of the order of magnitude of investment levels are presented, taking into consideration the development and scaling up of the respective technologies. As technologies are still to be developed and deployed at an industrial scale, the technology development hypotheses are derived from the current technology readiness levels (TRLs) for BTL and e-fuels (assuming that 'first-of-a-kind' plants will begin operating in the mid-2020s, according to announcements and trends currently observed) and are based on currently available information. EU research and development programmes such as the new Innovation Fund[4] are expected to trigger further development and investment in the low-carbon technologies identified, potentially reducing the production costs in the coming years. As a simplification, in all cases, the potential CAPEX reduction due to the development and scaling up of the technologies, as well as non-negligible OPEX aspects (e.g. feedstock costs), have not been considered.

Table 4 provides details of the capacity and CAPEX assumptions for new-build plants towards 2050.

Table 4: New-build plants:[a] capacity and CAPEX assumptions (see notes on the right)

Basis (per plant)	**Capacity — industrial scale**[b]	**CAPEX (M€)**	**CAPEX intensity (M€/ktoe/year)**
New-build HVO plant	0.5 Mtoe/year	275	0.55
BTL plants[c] (lignocellulosic)	0.15 Mtoe/year	610–900	4.0–6.0
e-fuels	0.2 Mtoe/year	400–650[d]	2.0–3.3
Clean H_2 (e.g. electrolyser)[e]	0.3 Mt CO_2/year	~150	-
CCS[e]	1.0 Mt CO_2/year	~500	-

Notes on Table 4:

[a] Due to the cap on food crop-based biofuels as well as on used cooking oil and animal fat, no investment in additional capacity is envisaged towards 2050, increasing the utilisation rate of existing plants when required.

[b] In the absence of commercial plants, the capacity of the future industrial units is uncertain. Factors such as the availability and accessibility of local resources in a sustainable way, as well as decentralised versus centralised models (with or without integration/co-locations within the refinery site), may have a severe impact on economies of scale.

[c] As an example of the potential technologies to process lignocellulosic/waste-like feedstocks, the BTL technology has been chosen based on Fischer-Tropsch technology already developed at a much bigger commercial scale for gas-to-liquid (GTL) processes. Other technologies also in development, such as the pyrolysis or thermal liquefaction processes, are deemed to offer less CAPEX-intense routes (up to ~50%[7] and could also be deployed in parallel to this BTL route (for simplification, these technologies are not included in this analysis because of their lower TRLs). Higher-capacity plants could also be foreseen, benefiting from some CAPEX optimisation, but may be limited by the high amount of biomass to be supplied. For the purpose of this assessment, and due to the uncertainty around these assumptions, a more conservative approach (e.g. in terms of plant capacity and CAPEX) was preferred, with an impact on a higher number of plants/investment requirements by 2050.

[d] In the case of the future size of the e-fuels plants (grid-connected), some bigger units integrated within the refining sites or as part of an industrial hub could be envisaged, taking advantage of additional CAPEX reductions (see Figure 5.4.2-1 on page 46 of Concawe report 9/19). As an initial estimate, this assessment is based on smaller-size units connected to the grid, and certifying the renewability content of electricity either by direct purchase agreements or other certification mechanisms (therefore, CAPEX due to the installation of renewable electricity capacity is not included and the electricity consumption is considered as OPEX).

[e] Summary of calculations based on Concawe, 2019b.[8]

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[4] https://ec.europa.eu/clima/policies/innovation-fund_en

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Results

Based on the assumptions described, and considering the TRLs of the different technologies and feedstocks analysed, as well as the time to develop, construct and start up new plants, different theoretical pathways with an associated timeline have been explored to meet the estimated demand scenarios for LCFs by 2050. As an example of the work conducted, Figure 2 illustrates the scaling up of new plant from today through to 2050 for demand Scenario 1.

Figure 2: New plant scale-up and time frame towards mass deployment
(Scenario 1 selected as an illustrative example)

Concawe's three 'Alternative 1.5°C' scenarios are summarised in Table 5 on page 30 and represent examples of the hypothetical trajectory of the contribution of the European refining industry towards the EU 2050 climate ambition goals.

	2030 vs 2020	2050 vs 2020
	~16 Mtoe 0 M€ No additional plants Utilisation ratio maximised (7% cap 1 G)	No additional plants vs 2030 (7% cap 1 G <> 9 Mtoe/year)
	Total: ~13 Mtoe Total: 16 new plants Total: ~4.4 B€	No additional plants vs 2030
	Total: ~4 Mtoe Total: 27 new plants Total: ~25 B€	Total: ~60 Mtoe Total: ~410 new plants Total: ~370 B€
	Total: ~1.5 Mtoe Total: 7 new plants Total: ~4.5 B€	Total: ~80 Mtoe Total: ~380 new plants Total: ~250 B€
CCS	Total: 13 new plants Total: ~6.5 B€ Total 13 Mt CO_2/year storage capacity	Total: CCS: 36 plants (28 B€) Clean H_2: 12 plants (1.9 B€)
Clean H_2	Total: 6 new plants (0.9 B€) (4 Mt CO_2/year reduced (EU level))	

Source: Concawe's theoretical assessment, 'Alternative 1.5°C' scenario for transport (road, aviation and maritime)

Table 5: Summary of the three LCF scenarios explored in the Concawe report

	Year/ period	Scenario 1 High demand	Scenario 2 Medium demand	Scenario 3 Low demand
Sector in which LCFs are used		*All transport*	*Heavy-duty, aviation and maritime*	*Aviation and maritime*
Total volume of LCF (Mtoe)		~ 160	~ 110	~ 70
Total new plants (bio + e-fuels)	**2035:**	~ 150	~ 150	~ 35
	2050:	~820	~550	~340
GHG reduction ($Mt\ CO_2$/year) / GHG reduction in transport,[a] LCF vs fossil reference (%)	**2030:**	100 / 10%	100 / 10%	50 / 5%
	2040:	300 / 35%	300 / 35%	100 / 20%
	2050:	490 / 75%	325 / 70%	190 / 60%
Total investment range — cumulative (billion €)		~ 450–670	~ 300–450	~190–280
Rate of investment (billion €/year)	**2020–2030:**	~5	~5	~1
	2030–2040:	~35	~35	~10
	2040–2050:	~30	~10	~15

[a] Note that the demand for liquid fuels varies depending on each scenario, hence the % reduction refers to each individual basis.

Figure 3 on page 31 builds on the data presented in Table 5 and illustrates the three scenarios graphically. Note that the grey text on each chart indicates the WTW GHG savings in Mtoe/year, while the figures in the blue ovals indicate the percentage reductions in GHG emissions compared to a 100% fossil fuel baseline.

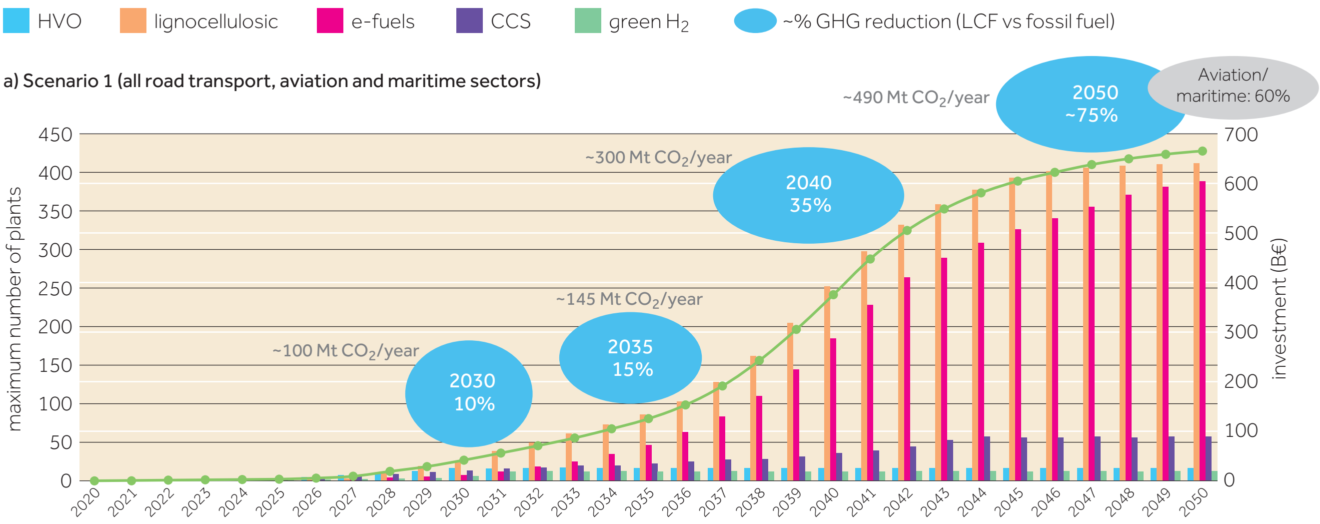
Figure 3a (Scenario 1) illustrates the level of investment, new biofuel/e-fuel plants and additional CO_2 reduction levels that could be achieved when the road, aviation and maritime sectors are integrated in a holistic picture.

Figure 3b (Scenario 2) assumes a penetration of LCFs only in the heavy-duty road, aviation and maritime sectors. Due to the smaller market volume compared to Scenario 1, the mass deployment of the related technologies is slowed down.

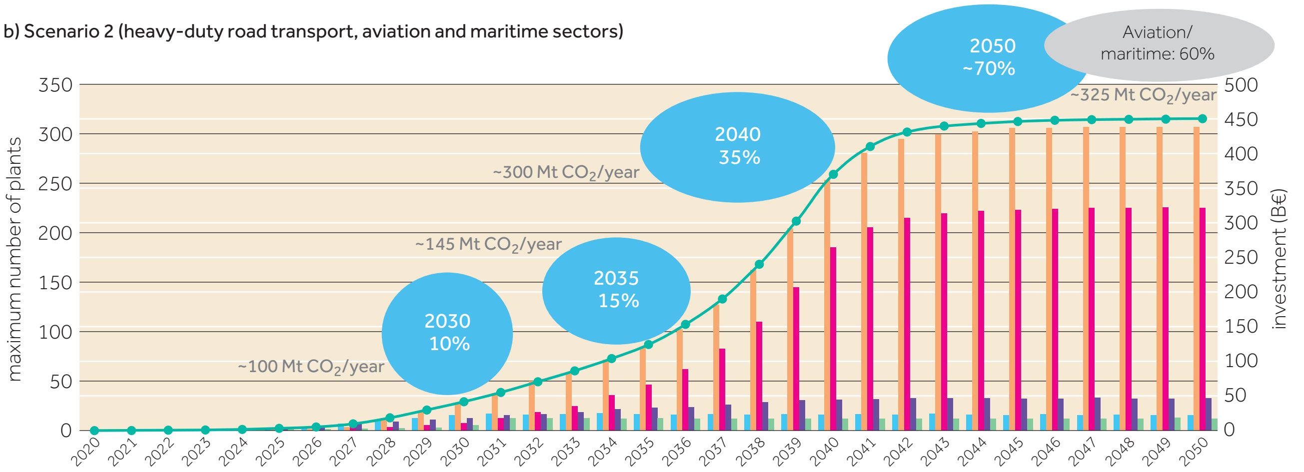
Figure 3c (Scenario 3) assumes a penetration of LCFs only in the aviation and maritime sectors. Due to the smaller market volume compared to Scenarios 1 and 2, the mass deployment of the related technologies is slowed down.

Figure 3: The evolution of new plants and investment, and potential WTW GHG savings (vs 100% fossil fuel) from 2020 towards 2050

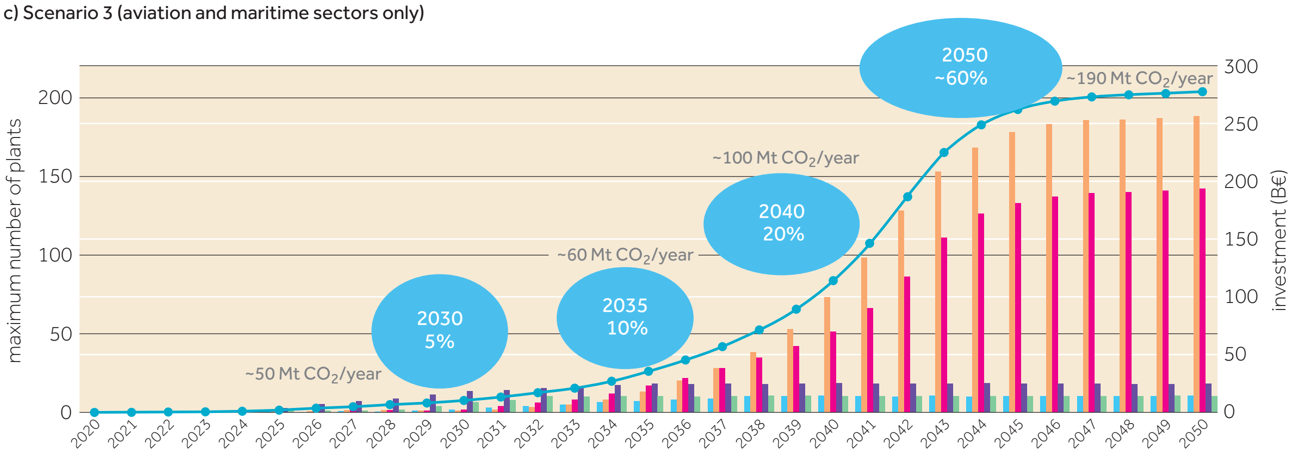
a) Scenario 1 (all road transport, aviation and maritime sectors)



b) Scenario 2 (heavy-duty road transport, aviation and maritime sectors)



c) Scenario 3 (aviation and maritime sectors only)



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A look into feedstock availability

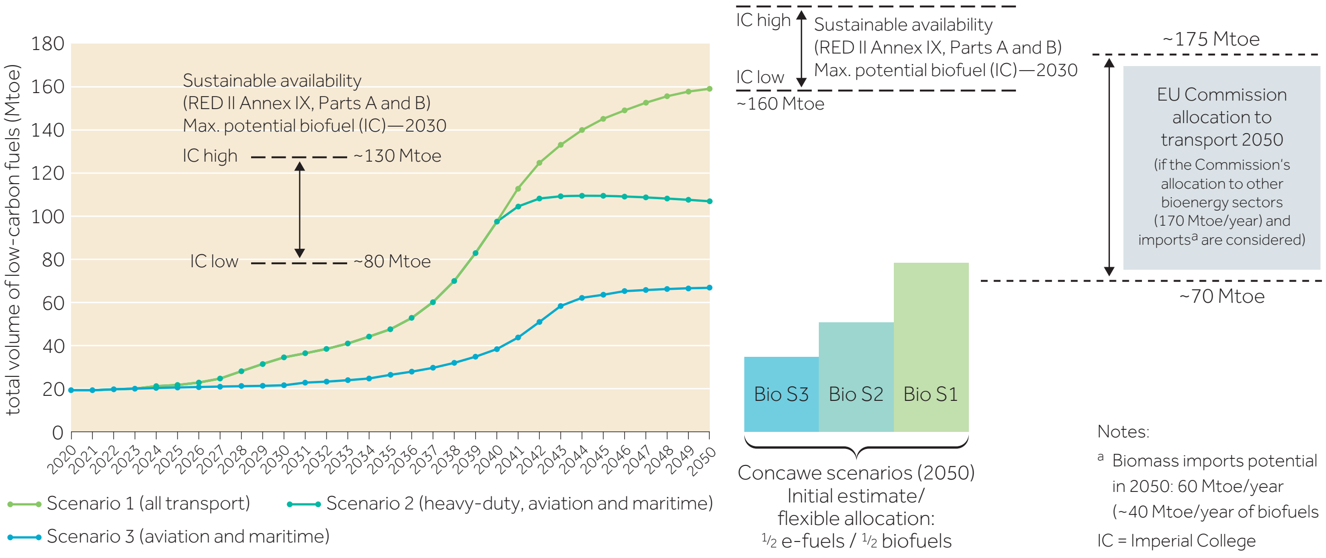
Complementing this study, a report recently published by Imperial College London[9] allows the comparison between the demand for LCF (assessed in the three scenarios described above) with the maximum potential sustainable feedstock availability for the bioenergy sector, with respect to the transport sector.

With a focus on agricultural and forestry residues and bio-waste materials that could potentially be used as feedstocks for the production of advanced biofuels, limited to the list of feedstocks reported in RED II Annex IX Parts A and B, the Imperial College study explores low, medium and high scenarios, assuming enhanced availability through research and innovation measures, as well as improved mobilisation due to improvements in cropping and forest management practices.

The comparison of the potential availability of feedstocks (and their conversion into advanced biofuels) versus the potential requirement for LCF production (the biofuel portion) shows the following:

- The high biomass scenarios of the Imperial College study estimate that there is sufficient sustainable biomass for advanced biofuels to cover all the demand trajectories presented in 2030 and 2050, even if the high allocation of biomass to non-transport sectors (especially to the power sector) presented in *A Clean Planet for all* is considered.
- Taking into account the total biomass availability for bioenergy and a maximum set of conversion yields, the maximum potential availability for advanced biofuel production is notably higher than Concawe's total biofuel demand in 2030 and 2050 (between 70 and 75 Mtoe/year of advanced biofuels by 2050, as a conservative approach considering the above-mentioned allocation to non-transport sectors presented in *A Clean Planet for all*, as well as the estimated import levels from recent statistics and other relevant sources).

Figure 4: Total low-carbon fuel demand scenarios (biofuel + e-fuel)



Notes:

[a] Biomass imports potential in 2050: 60 Mtoe/year (~40 Mtoe/year of biofuels

IC = Imperial College

Overall it can be concluded that there is sufficient sustainable biomass to meet the three Concawe scenarios in 2030 and 2050. There is a caveat around Scenario 1 (high demand) when the 2050 time frame and the low biomass availability scenario are considered, in which a small adjustment of the e-fuel production of ~10 Mtoe/year versus the foreseen equal distribution with advanced biofuel would be required to meet the total anticipated demand for LCF.

It is also important to highlight that the potential biomass availability estimated in this study is based on what the Imperial College believes to be a set of conservative assumptions regarding the maximum potential. Furthermore, the potential of algal biofuels plus other sustainable biomass feedstocks that are not included in RED II Annex IX have not been taken into consideration at all in the above calculations; taking these into account would provide additional flexibility and a higher level of availability than the amounts foreseen in the Imperial College study.

Important note

It is important to emphasise that the analysis described in this article should be considered as a theoretical assessment of a potential trajectory to contribute to EU climate targets and, for simplification, only a limited number of low-carbon feedstocks and technologies with different TRLs have been chosen. This article is not, therefore, intended to provide a roadmap for the industry, and different trajectories could be defined depending on the framework conditions, the specific country-level conditions, and successful development and scaling up of the different technologies presented and their related value chains. The assessment provides one example of a potential accelerated trajectory that could contribute to reaching climate neutrality in transport by 2050.

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