Concawe
Environmental Science
for European Refining

Report

Report no. 7/21

Transition towards Low Carbon Fuels by 2050: Scenario analysis for the European refining sector

ISBN 978-2-87567-144-8

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Transition towards Low Carbon fuels by 2050: Scenario analysis for the European refining sector

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Brussels
August 2021

ABSTRACT

This report is a theoretical assessment of different potential trajectories (*scenarios*) for the EU refining industry to contribute to EU climate targets. With a wide focus on road, aviation and maritime sectors, three potential demand scenarios show the total volume of low carbon fuels that could be required to contribute to climate neutrality in EU transport by 2050 as well as the number of plants and level of investment required (Volumes ranging from ~70 up to ~160 Mtoe/y with a cumulative ~190-660 B€/y investment at the end of the period). For the purpose of simplification, it includes only a limited number of examples of low carbon feedstocks and technologies (food-crop based, hydrotreated vegetable oils (HVO), Biomass-to-Liquid (BTL), e-fuels, clean hydrogen and Carbon Capture and Storage). A look into sustainable biomass availability identifies no major constrains in the realisation of the scenarios according to a recent publication from Imperial College London Consultants [IC 2021]. This document is not intended to become a roadmap for the industry; other trajectories could be defined or appear depending on the framework conditions as well as the successful development and scale-up of the different technologies and their related value chains.

KEYWORDS

Refining, Energy Transition, Clean fuels, low carbon fuels, low carbon pathways, BTL, e-fuels, CCS, Clean hydrogen, Climate neutrality, Climate ambition, GHG / CO_2 reduction.

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This report is available as an Adobe pdf file on the Concawe website (www.concawe.org).

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SUMMARY

Background

The European Commission has the ambition of reaching climate neutrality in Europe in 2050, as communicated in its new long-term strategy (Green Deal). This will require disruptive changes in the energy mix and the transformation of the industrial manufacturing processes.

To contribute to this ambitious challenge, the European refining industry has embarked in a journey to explore plausible pathways for its own transformation and aiming at understanding the potential and required framework conditions for road-transport fuels to be made climate neutral by 2050, thereby also enabling the groundwork for climate neutral aviation and maritime fuels.

As part of a series of studies in its Concawe's Low Carbon Pathways programme and through a scenario analysis exercise, this report intends to improve the understanding of the theoretical potential, in quantitative terms and over a reference timeline, of the production of low-carbon liquid fuels from now until 2050, its relevant impact for a substantial contribution to the decarbonisation of transport and the order of magnitude of the investments needed for the industry's transformation.

Demand scenarios

This theoretical assessment starts with the definition of '*baseline*' demand scenarios for each transport mode in the period 2030 – 2050 based on:

- **Road transport** (light- and heavy-duty): Both 2030/2050 timeframes include a growing penetration of electrification and other alternative powertrains/fuels and portrays the demand for liquid fuel in transport towards 2050 (Section 2).

  The 2030 energy demand scenario is extracted from the Concawe's demand outlook for road (modelling the evolution of the fleet and penetration of alternative powertrains from today down to 2030 [Concawe 2/2021]).

  2050 is presented as a range of demand scenarios in which, the high end is initially derived from the "2050 baseline" as reported in the 'A Clean Planet for All' (ACP4A) document by DG CLIMA [EU COM 2018], down to a low scenario in which no liquid fuels are consumed in road by 2050.

  It is worth noting that the high end of the baseline also considers that the demand for liquid fuels in road transport gradually decreases from today's levels to ~1/3 towards 2050 as a result of modifications in the EU road fleet (e.g. fuel efficiency measures, hybridisation of internal combustion engines, penetration of alternative powertrains (e.g. Electric vehicles, Fuel cells)/gaseous fuels).

- **Aviation & Maritime**: Both 2030 and 2050 demand scenarios are consistent with the data reported in '*A Clean Planet for All*' [EU COM 2018] with the following considerations:
  - *Aviation*: the penetration of low carbon fuels in the sector is defined by the REFUEL targets for the 2030/2050 period (based on the best available information at the moment of publication of this report). This is also in line with the 1.5TECH scenario reported in 'A Clean planet for all' (~40% of the total demand foreseen to remain as fossil kerosene in 2050).

- *Maritime*: In the absence of a 1.5TECH scenario, the total demand for liquid LCF, diesel-like, is derived from the H2Mar70 scenario [EU COM 2018]. By the integration of LCF with other technologies/energy carriers, this scenario achieves 70% GHG reduction in the maritime sector by 2050 compared to 2008 levels[1].

Based on the above and looking at the transport sector as a whole, this report defines and explores three "***alternative 1.5°C***" Concawe's scenarios, considering a different ramp-up and penetration of Low Carbon Fuels within each transport mode during the period 2030/2050:

1) ***Scenario 1. High demand (All transport modes)***

   The most challenging scenario considers that LCF penetrate in the road transport sector first, growing towards aviation and maritime beyond 2035. This high LCF demand scenario, as described earlier, is deemed an end-point one assuming that the Passenger car segment is not fully electrified (mixed fleet with internal combustion engines still present) and in which LCFs ramp up, progressively replacing the fossil fuel demand by 2050 (2050 demand for Road as defined in the [DG CLIMA 2018] 2050 **baseline scenario**).

2) ***Scenario 2. Medium demand (Heavy-duty, Aviation & Maritime)***

   This scenario considers the creation of the LCF market firstly incentivised by road transport (both light- and heavy-duty), moving progressively towards the aviation and maritime sectors. As a result of a more aggressive penetration of xEVs in the passenger car segment (consistent with the 1.5TECH scenario from *[DG CLIMA 2018])*, LCF will only be used in heavy-duty as well as in aviation and maritime in the 2050 timeframe (with the demand for liquid fuels phasing out in light-duty during the 2040-2050 period).

3) ***Scenario 3. Low demand (Aviation & 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 LCF in road in the first decade of the period, both the LCF market and supply chain creation are less incentivised and, therefore, development and scale-up of the related LCF technology is delayed compared with the previous scenarios. By 2050, all the production of LCF will be used in the aviation and maritime sectors. In this low (end-point) scenario, no additional volumes of Sustainable Aviation Fuels (SAF) have been considered beyond those portrayed in the REFUEL / 1.5TECH (i.e. ~40% remaining fossil kerosene in 2050).

What to find in this report

Within this basis, this report:

- Follows a **Well-to-Wheels approach** to look into opportunities to significantly reduce the carbon intensity of future **low-carbon liquid fuels**, compared to a 100% fossil fuel reference, from the production to the end-use stages.

  To be noted that the term *Well-to-Wheels* (WTW) approach in road is used widely for the purpose of this report, being equivalent to the *Well-to-Propeller* in the maritime sector and *Well-to-Wake* in aviation.

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[1] Higher than 2050 International Maritime Organisation's current ambition levels (50%).

- Analyses the remaining **liquid fuel demand** in **road, aviation and maritime** transport sectors considering the penetration of alternative powertrains / engines and other non-liquid fuels based on **three Concawe's '*Alternative 1.5°C'* demand scenarios (Section 2).**

  These demand scenarios are in alignment with 'A Clean Planet for all' ***assumptions*** for aviation (*1.5TECH*) and maritime transport (*H2Mar70*) investigating different projections for road (both light- and heavy-duty segments).

- Evaluates the **potential deployment** of some of the **most promising** greenhouse gas **(GHG) reduction technologies (Section 3)** from today towards 2050 to meet the demand for liquid fuels, with a focus on:
  - ***Low Carbon Liquid fuels (LCF)*** including, as selected examples[2], sustainable food-crop based biofuels, biomass & waste-to-liquid (BTL), hydrogenation of vegetable oils/waste & residues and e-fuel technologies, to replace fossil CO_2 by either biogenic or recycled CO_2 from industrial sites (potentially including *Direct Air Capture*) (Section 3.3).
  - Other key mitigation technologies (***key enablers***) such as ***Carbon Capture and Storage* (CCS) and Clean Hydrogen** applied in refineries to reduce the carbon intensity of produced fuels as from today and with clear synergies with alternative feedstock (Section 3.4).

- Provides a quantitative assessment of the **trajectory** of the deployment of these technologies towards 2050 to meet the demand scenarios (Section 4).

  The report explores **how many, and by when**, the different industrial installations of the above-mentioned technologies are needed to progressively replace fossil fuels in aviation and maritime and/or road transport (Section 4). The ultimate objective in all cases is to achieve a similar level of CO_2 emission reduction compatible with the 1.5C ambition in 2050, consistently with the 1.5TECH scenario explored by the EU COM (Section 2).

- For each of the scenarios presented, considers best estimate of the **investment levels** taking in consideration the development scale of the respective technologies.

  As technologies are still to be developed and deployed at industrial scale, the technology development hypotheses are derived from the BTL and e-fuel's current *Technology Readiness Levels* (assuming start of 1st-of-a-kind plants' operation in the mid-2020's according to the announcements and trends currently observed) and based on the current available information, the best available order of magnitude of the investment requirements. EU R&D programs such as the new *Innovation Fund* are expected to trigger further development and investment in the low carbon technologies identified.

- Shows in summary that:
  - The adoption of a mix of electrification and efficient internal combustion engine (ICE) vehicles, together with the progressive replacement of fossil fuels by sustainable biofuels and e-fuels (up to 100% levels in 2050), offers an alternative scenario in terms of greenhouse gas reductions (GHG WTW) for road ***transport*** in 2050 comparable to the '*1.5TECH case*' from ACP4A (which assumes almost complete electrification in the same timeframe).

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[2] For the purpose of simplification, this report focuses only on a limited number of representative examples of low carbon feedstocks and technologies. Advanced biofuels are selected in the basis of their technology readiness levels, potential GHG savings and drop-in characteristics.

- Negative emissions are required to ***reach*** net zero GHG Emissions in transport (as also recognized by DG CLIMA in the *A Clean Planet for all* document).

As a key input complementing this scenario analysis, Concawe performed an initial literature review on feedstock availability concluding that the sources analysed provide different outcomes and show a wide variability in their potential estimate, depending on their underlying assumptions [Concawe Review 27.2, 2020]. A new report commissioned by Concawe to Imperial College London Consultants (IC) assesses the potential availability of sustainable biomass (RED II Annex IX A/B) in the period 2030/2050 (Section 5.2 0). This new Imperial College (IC) report [IC 2021] concludes that significant volumes could potentially satisfy the demand for transport estimated in these Concawe's '*Alternative 1.5°C*' scenarios by 2050 under considerations such as enhanced availability through Research and Innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices.

Concawe 'Alternative 1.5°C' scenarios. Results (Section 4).

As an example of the hypothetical trajectory of the EU refining industry towards 2050, this report shows different intermediate milestones for the three scenarios analysed:

Table 1 Summary of three Concawe LCF scenarios explored

2050	Scenario 1 HIGH	Scenario 2 MEDIUM	Scenario 3 LOW
LCF use in…	All transport	Heavy-duty, Aviation & Maritime	Aviation & Maritime
Total volume LCF (Mtoe)	~ 160	~ 110	~ 70
Total new plants (bio+e-fuels)	~ 150 (2035) ~820 (2050)	~ 150 (2035) ~550 (2050)	~ 35 (2035) ~340 (2050)
Total investment range - cumulative (B€)	~ 450-670	~ 300-450	~190-280
Rate of investment, B€/y	~5 (2020/2030) ~35 (2030-2040) ~30 (2040/2050)	~5 (2020/2030) ~35 (2030-2040) ~10 (2040-2050)	~1 (2020/2030) ~10 (2030-2040) ~15 (2040-2050)

A summary of the main relevant findings for each scenario is described below:

Scenario 1. HIGH (ALL TRANSPORT)

a) Road transport

2030: A 11% overall WTW[3] GHG reduction by 2030

This is the result of a steep curve on technology development and investment accelerated from today's levels towards 2030:

- High investment (30-40 B€) with R&D efforts on technology scale up and high requirements in terms of both engineering and construction resources. Beyond this, it would be essential that a rapid deployment and mobilization of resources across the whole value chain happens in parallel (resulting in high financial risks).
- This trajectory would require the following framework conditions to be realized:
    - Production of ~30 Mtoe/y bio/e-fuels (~70% GHG intensity reduction in average when compared versus a pure fossil reference by 2030)
    - Lignocellulosic based technologies ready for deployment in 2025 moving almost immediately to mass deployment across Europe.
    - Establishment of large lignocellulosic and residue supply chain in line with new plants start-up in 2025+.
    - Due to the current uncertainty, we have imposed an external constraint limiting the domestic European HVO capacity to 10 Mtoe/y in 2030 (conservative approach as a result of the on-going debates in some countries on the feedstock for HVO production). However, based on the current TRL of the lignocellulosic based fuel technologies for BTL production and their current higher costs, it could happen that more investments are diverted towards additional HVO capacity than the one initially considered in this analysis, subject to factors such as availability of sustainable lipid-based sources/waste materials to produce "non-food-crop based" feedstocks for HVO, compliance with the Renewable Energy Directive or potential elimination of the current cap on certain waste-based feedstocks, among others). Additional imports are not included within the scope of the present assessment.
    - E-fuels from renewable electricity scale-up in early 2025+.
    - Potential specification changes in gasoline beyond E10 to allow higher bio-blends.
    - Some of these conditions go beyond the remit of the refining industry, requiring cross-sectorial cooperation as an essential element to enable them to be effectively realised within the given timeframe.
- Within the EU refining system:
    - Efforts to reduce CO_2 emissions in the refining sites are deemed necessary and will allow the deployment of key enabling technologies such as CCS and Clean H_2[4] firstly aiming at reducing fossil-based CO_2 (direct/indirect) emissions, reducing the carbon intensity of conventional fossil fuels, and then potentially used for / applied to

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[3] In the context of this report, WTW terminology refers to *Well-To-Wheels, Well-To-Wake and Well-To-Propeller* depending on the selected segment.

[4] Clean hydrogen can be produced either from renewables or from gas with CCS

  - biofuel and e-fuel production routes once these technologies are progressively deployed within the sites (Refer to Section 3.4).
  - The Well-To-Tank (WTT) reduction in the remaining fossil fuels is limited to only the refining and distribution contribution. The WTT savings are thus limited to ~2% additional GHG WTW reduction in 2030 (As refining representing ~8% of the total 2030 WTW CO_2 intensity).
  - Turn-around timing in refineries can become a limiting factor if needed for implementation of technologies in existing sites (Its economic impact may be significant but not considered in the scope of this assessment).
  - The scenario assumes that CCS is applied to refineries: ~13 new plants in 2030 starting fully deployment in early 2025. This will require wide acceptance across Europe with focus on the more favorable locations in terms of storage.

<u>2040: 40% GHG reduction</u>

Compared to 2030 baseline, a higher level of ambition is explored in 2040 (reaching 40% WTW reduction) with additional investment in low carbon fuels (assuming a further reduction in demand based on the A Clean Planet for All baseline scenario). The estimated investment ranges between 150 and 220 B€ (cumulative in the 2020-2040 period).

<u>2050: ~90% GHG reduction</u>

Approaching zero-GHG in road transport in 2050 would imply that:

- All remaining fossil fuels are replaced by biofuels/e-fuels. The total amount of Low Carbon fuels required for road transport is ~90 Mtoe/y.
- The previously installed CCS plants, when coupled with the newly deployed technologies, would allow to achieve additional negative emissions (around -30 Mt CO_2/y) that could be added to the 90% GHG savings estimated which will allow to reach ~net zero.
- The estimated investment ranges between 250-360 B€ (cumulative in the 2020-2050 period).

b) Aviation & Maritime Transport

The demand scenarios for low carbon fuels from 2030 onwards provided to the aviation and maritime sector are in line with the ones defined in ‘A Clean Planet for all’:

- This alignment with the REFUEL and ACP4A scenarios will ensure that the Concawe’s 2050 endpoint scenario explored in this report (‘1.5 alternative’ scenario) is compatible with the EU Commission’s goal of reaching net zero GHG emissions by 2050 (whole EU economy level).
- As a result of this, for both sectors:
  - Overall, the contribution of low carbon fuels is estimated to represent > 50% of the total energy demand in 2050 when each sector is individually considered. In total, at least 70% of the liquid fuel demand is deemed to be satisfied by LCF when both aviation and maritime are jointly reported (Table A.4.1).
  - Contributing to cut up to 60% of CO_2 emissions by 2050 in those sectors (Compared to a 100% fossil reference to meet the liquid fuel demand in the scenario analysed).

  - Up to ~70 Mtoe/y additional biofuels/e-fuels may be required in 2050 for aviation/marine (derived from the 1.5 scenario in the *A Clean Planet for All* demand forecast).
  - When this is added to the road estimate reported above, this would represent a total volume of ~160 Mtoe/y of low carbon fuels corresponding to a minimum investment between 440-670 B€ in the whole 2020-2050 timeframe, requiring an aggressive and maintained annual investment ratio in the last two decades (~35 B€/y in 2030-2040 and ~30 in 2040-2050) far beyond the traditional ones from the industry[5].

Scenario 2. MEDIUM (Heavy-duty, Aviation & Maritime)

- This scenario maintains the early development and subsequent fast deployment of LCF in the 2020-2030 timeframe due to the market volume creation across all transport sector.
- However, as a consequence of the penetration of alternative powertrains in the passenger car segment, this scenario foresees a reduction in the demand for liquid fuels (and therefore, for LCF) in the 2035+ period, reaching a minimum point in 2050, where liquid fuels in passenger cars are deemed to have been completely phased out. Under these conditions, LCF are therefore diverted progressively from road transport sector towards aviation and maritime in the 2040-2050 decade (maintaining the penetration in the heavy-duty segment as in Scenario 1).
- As a result, LCF demand is estimated as ~110 Mtoe/y in 2050, with a cumulative investment of ~300-450 B€ to satisfy the whole transport sector (The CO_2 emission reduction remaining similar to the ones in Scenario 1).

Scenario 3. LOW (LCF Aviation & Maritime)

- As an end-point case, this scenario explores an extreme low liquid demand case for road (completely phased out by 2050) in which there is little incentive for LCF to penetrate into both light- and heavy-duty segment in the 2020-2030 timeframe. Therefore, the development of LCFs is mainly driven by both aviation and maritime segment giving a less strong market signal to the R&D activities versus the previously described scenarios. As a consequence, the mass deployment of LCF plants is delayed: half of the volume foreseen in Scenario 1&2 in 2035) reaching a volume of ~70 Mtoe/y of LCF by 2050. As a result, the CO_2 emission reduction in the 2035 period due to LCF is ~5% lower than in the other scenarios analysed.
- The annual investment ratio remains similar across the 2030-2050 period, in the order of magnitude of ~10-15 B€/y with a total cumulative investment of ~190-280 B€/y (60% lower than in Scenario 1).
- Should the economic/market conditions be in place, there could be a potential for the EU refining industry to maximise the level of investment rate up to the levels defined in Scenario 1 (HIGH), equivalent to ~30 B€/y in the period 2040-2050, potentially replacing all the remaining fossil liquid fuels in aviation and maritime. This assumption will portray a sensitivity case around this scenario 3 in which the total level of LCF could reach ~100 Mtoe with a level of cumulative

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[5] OPEC World Oil Outlook 2018 foresees a potential investment of ~110 B$ (2017) in EU refining related projects in the 2018-2040 period following a business-as-usual scenario (with no LCF replacement). This would be equivalent to ~5 B$/y (mostly on maintenance).

investment ranging between 280-420 B€ (~500 new plants) in the period 2020-2050, similar to the levels reached in Scenario 2.

Feedstock availability issues

Complementing this scenario analysis, Concawe has commissioned a study on the maximum sustainable availability for the feedstocks considered in RED II Annex IX A/B to verify that the volumes of biofuels required in the different scenarios were compatible with Europe's potential of sustainable biomass. Conducted by Imperial College London Consultants (IC) [IC 2021], the total estimated net biomass that can be used for biofuel production, including imports and taking into account the use of biomass for other purposes non-transport related (power, industry, service, agriculture and residential), is estimated to be equivalent to an advanced biofuel production of ~**45 to 100 Mtoe for 2030** and ~**70 to 180 Mtoe for 2050** by selectively choosing the value chain and conversion technology that results in the highest production of biofuel, and considering the increase of biofuel production yields due to renewable hydrogen.

When this availability is compared to the Concawe "*1.5°C alternative*" scenarios portrayed in this report, it can be concluded that:

- The high sustainability biomass scenario estimates sufficient sustainable biomass for advanced biofuels in 2030 and 2050, even with the EU Commission high allocation of biomass to non-transport sectors, such as power, industry and residential sectors.
- Considering the total biomass availability for bioenergy and a maximum set of yields, the maximum potential availability for advanced biofuel production is notably higher than Concawe's advanced biofuels demand in 2030 and 2050.
    - The high-end case (Scenario 1) would require the realisation of the high availability scenario portrayed by Imperial College (IC) and a potential small adjustment (10 Mtoe/y) in terms of the biofuel/e-fuel ratio (assuming a conservative picture regarding the competition among bio-energy sectors).
    - Different type of feedstocks beyond the ones currently listed in RED II Annex IX A/B could provide additional flexibility beyond the bio-sources considered by IC.
- The availability of sustainable biomass is not deemed as a barrier per-se. However, additional R&D efforts together with the implementation of improved management strategies and development of the whole supply chain would be essential elements to realise the potential identified by IC.

This analysis is to be considered as a theoretical assessment on potential scenarios to contribute to EU climate targets and, as such, only a limited number of low carbon feedstock and technologies with different TRLs have been chosen for the purpose of simplification. This document is not intended to become a roadmap for the industry. Other trajectories could be defined or appear depending on the framework conditions and successful development and scale-up of the different technologies presented and their related value chains.

Concawe's ambition is to maintain this analysis alive, being conveniently updated as new demonstration and commercial plants are deployed and penetrate into the market.

1. INTRODUCTION

The long-term European strategy (Green Deal) states the ambition of reaching climate neutrality in Europe in 2050.

Reaching climate neutrality in this timeframe requires disruptive and immediate changes in the energy mix and the transformation of the industrial manufacturing processes. To contribute to this ambitious challenge, the European refining industry as a whole has embarked in a journey to explore plausible pathways for its own transformation, aiming to understand the potential and required framework conditions for road-transport fuels to be made climate neutral by 2050 (thereby also enabling the groundwork for climate neutral aviation and maritime fuels).

Concawe, as the scientific body of the European Refining association, started its Low Carbon Pathways programme in 2018 to conduct specific assessments in this regard. A number of publications have been issued since then[6], diving into the key technologies which could effectively contribute to reduce the Green House Gas Emissions (GHG) linked to both the production sites (refineries) and the use of the products/fuels at the end point.

1.1. BACKGROUND: PREVIOUS CONCAWE’S DEEP DIVES ON ROAD TRANSPORT

This assessment is inspired and also builds on the outcome of two previous key reports commissioned by Concawe on light-duty segment [Ricardo 2018] and heavy-duty [FEV 2019] to inform our Concawe’s Low Carbon Pathways’ programme:

1.1.1. Light-duty Vehicles: Passenger cars and Light commercial Vehicles

Impact analysis of mass EV adoption and low-carbon intensity fuels scenarios [Ricardo 2018]

In this deep dive, Ricardo carried out an extensive study to examine a scenario involving the near-complete electrification of passenger cars and light commercial vehicles in the EU by 2050 (the ‘*High EV scenario*’) and to compare this scenario with the combined use of electrification and low-carbon liquid fuels (e-fuels and sustainable biofuels replacing fossil-based up to ≈95% in 2050) in highly efficient internal combustion engines (ICE)-based vehicles (the ‘*Low Carbon Fuels scenario*’). This in-depth study includes the quantification of greenhouse gas (GHG) reductions (in terms of CO_2 equivalent), total parc annual cost and total cost of ownership for final users as well as the cost of infrastructure, resources and power requirements. The study also sets out the challenges and opportunities associated with such a range of alternative options.

The results of the analysis show that both scenarios demonstrate broadly similar reductions in total GHG emissions by 2050.

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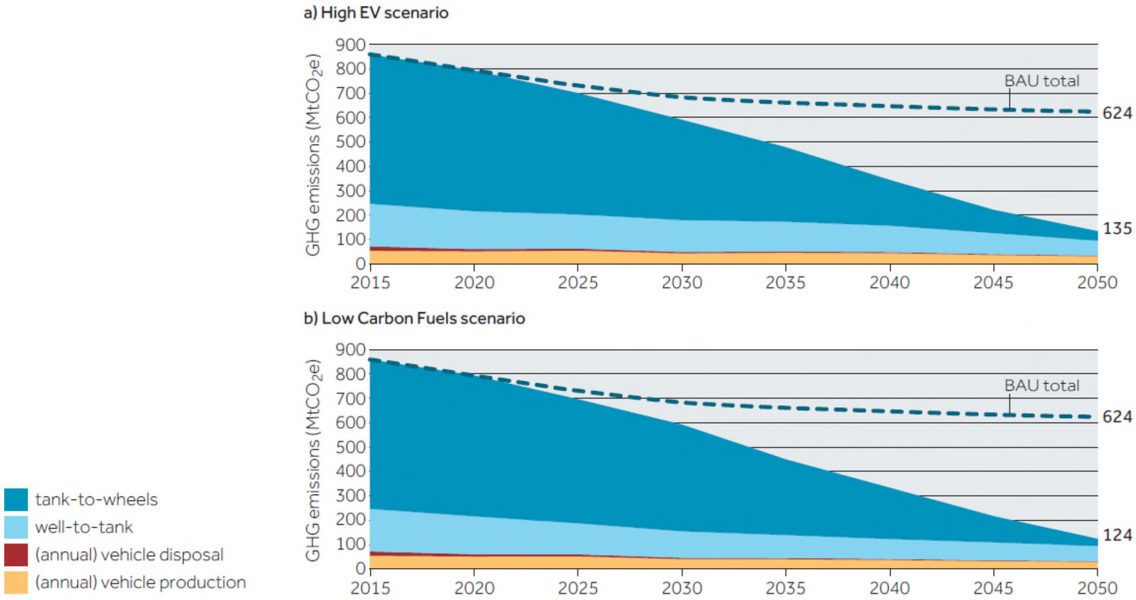
[6] https://www.concawe.eu/low-carbon-pathways/

Figure 1 Comparison of GHG emissions on a life-cycle basis for the EU light-duty fleet [Ricardo 2018].



Note. BAU refers in **Figure 1** to a business-as-usual scenario defined as a reference by Ricardo in which limited penetration of alternative powertrains or low carbon fuels is considered with minor energy efficiency improvement (This is not to be considered as a projection or compared with the ACP4A baseline which assumes a more diversified mix leading to a lower GHG emissions for the car segment).

When costs are compared, it can be seen that, while costs for the High EV scenario are higher in the period to 2035, the net costs are ≈€70 billion lower per year than for the *Low Carbon fuels* scenario up to 2050. Including the Net Fiscal Revenue (NFR) loss versus a business-as-usual scenario, closes the gap to ≈€9 billion. When the total car parc end-user annual costs of vehicles are compared under the High EV scenario or the Low Carbon Fuels one, the results are similar with no competitive advantage for the EV versus the ICE. The implications in terms of raw material requirements (e.g. Lithium/Cobalt for battery manufacturing) is also explored in both scenarios.

As one of the main takeaways of the study, it is shown how **both electrification and low-carbon fuel technologies are complementary**, helping to mitigate the risk in terms of key factors such as feedstock and raw material availability or new infrastructure development / investment or fleet turn-over.

1.1.2. Heavy-duty Vehicles.

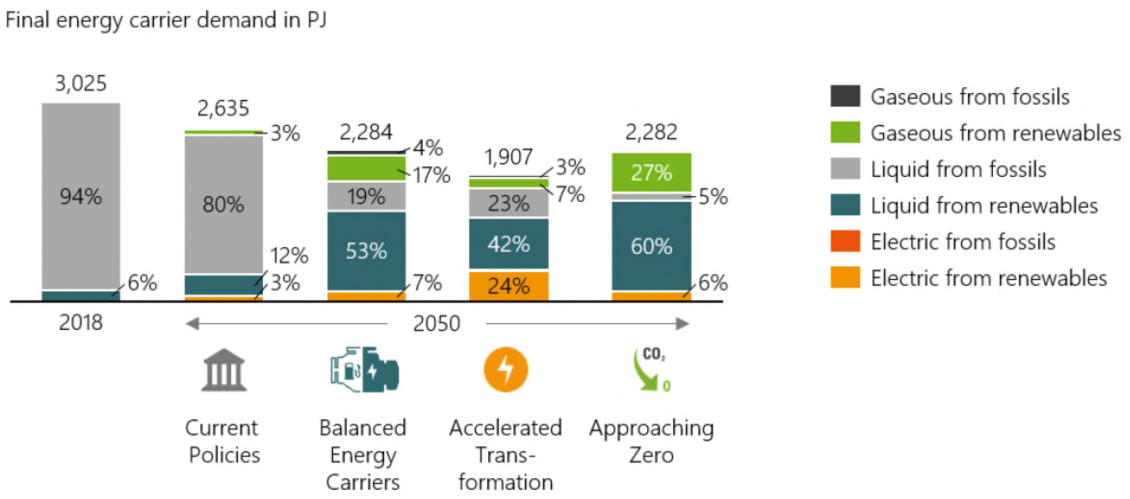
Low Carbon pathways until 2050 – Deep dive on Heavy-duty transportation **[FEV 2019]**

In the FEV’s analysis, three low carbon pathways are explored which achieve GHG emission reductions of 80% to 95% by 2050 versus 1990 through the application of four main blocks of measures:

- **Optimisation of usage** is identified as an important aspect of the CO_2 emission reduction, mitigating the emissions added by the higher transport demand in the future. This is enabled by an uptake of connected and automated trucks which results in an increased truck utilisation.

- **Electrification of powertrains** includes hybrid, battery and fuel cell electric powertrains, using renewable sources, representing more than 25% of the vehicle stock in all the low carbon pathways.
- **Efficiency increase** of the vehicles is a strong contributor to lower CO_2 emissions enabled by improved gliders (reduction of aerodynamic drag, rolling resistance and weight) and improved powertrains (e.g. engine efficiency measures).
  - **The adaptation of energy carriers including more low carbon intensity fuels** is also identified as a key element (**Figure 2**). In all scenarios, combustion engines stay relevant and represent at least ~50% of the vehicle stock in 2050 many of them with different levels of hybridisation. In the three low carbon pathways, renewable sources account for more than 70% of the final energy demand, reaching ~95% in the approaching zero scenario.

Figure 2 Final energy demand of heavy-duty trucks in EU (PJ) by energy carrier type and source.



Note. Description of scenarios (%GHG reduction versus 1990):
(*) *Current policies* includes announced policies as of today towards 2050 with no further tightening considered (this leads to CO_2 emission reduction below 10%).
(**) The *Balanced Energy Carriers* scenario assumes the electrification of heavy-duty vehicles in selected use-cases only. Efficiency measures will be introduced at the current pace and energy carriers from renewable sources ensure 80% GHG emission reduction levels. The *Accelerated Transformation* reaches the same level of reduction by a faster development of automation and battery technology assuming that charging is cheaper and infrastructure is built-up rapidly.
(***) *Approaching Zero* scenario achieves 95% lower CO_2 emissions by 2050. Developments and trends are like in the Balanced Energy Carriers scenario, but the contribution of electrification and energy carriers from renewable sources is higher.

As for the light-duty segment, one of the key findings of the report is that a combination of different technologies and measures are required to achieve the level of CO_2 reduction ambition, including a high share of energy carriers from renewable sources (including low carbon liquid and gaseous fuels) emphasizing the strong interdependency of stakeholders (fleet operators, vehicle manufacturers, technology suppliers and energy providers) to define an aligned strategy enabling the required shift of the industry.

1.2. SCOPE OF THIS REPORT

This new Concawe report:

- Builds on the previously commissioned deep dives into transport (Section 1.1) where it is shown that same CO_2 emission reduction in road transport (light-duty vehicles and heavy-duty vehicles) can be achieved by full electrification of the powertrains or by a combination of electrification and improved Internal Combustion Engines fed with Low Carbon Fuels [Ricardo 2018][7] [FEV 2019][8].
- Complements our previous analysis on the subject [CO_2 technologies, Concawe 8/19]; [Refinery 2050, Concawe 9/19] and [Refineries in the *A Clean Planet for all*, Concawe 20/20] investigating a **potential timeline** for some key low carbon liquid fuel related technologies to be scaled up and extensively deployed across Europe.
- Explores key alternative feedstocks / production routes: **food-crop based biofuels** (capped accordingly to RED II criteria), sustainable **vegetable oils**, advanced **lignocellulosic/waste**-based fuels and **e-fuels** (Power-to-fuels).
- Includes additional key industrial mitigation technologies such as ***Clean hydrogen*** (including both **renewable and low carbon hydrogen[9])** and **Carbon Capture and Storage** solutions, with clear synergies with other energy intensive industries when looking into climate change mitigation options.

As a result, an initial assessment on the accelerated penetration of the technologies towards 2050 through a three-scenario analysis is presented, including the impact of such a transformation of the European refining system in terms of both GHG emission reduction and volumes, number of new plants as well as level of investment required. A revision on the available outlooks on biomass availability is also included.

It is worth highlighting that this assessment explores end-corner scenarios in which the penetration of alternative low carbon liquid fuels (LCLF) into **road transport** is considered as a lead mass market for the timely development and scale-up of the related technologies (Scenario 1 & 2). Once the commercial readiness level is reached, an estimate on the additional requirements to make these low carbon fuels mass deployed across the whole transport sector (road, aviation and maritime) is also presented. A low case scenario (Scenario 3) portrays a case in which no incentives are given to the penetration of LCLF in road, aviation and maritime are the only drivers for the development & deployment of these technologies.

1.3. DETAILED ASSESSMENT - CONTENT

This assessment explores the possibility to supply low carbon liquid fuels in transport as a complementary alternative to other pillars of transport decarbonisation such as fuel efficiency measures, penetration of alternative powertrains or different forms of electrification in internal combustion engines.

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[7] https://www.concawe.eu/wp-content/uploads/Mass-EV-Adoption-and-Low-Carbon-Fuels-Scenarios.pdf

[8] https://www.concawe.eu/wp-content/uploads/Low-Carbon-Pathways-Until-2050-Deep-Dive-on-Heavy-Duty-Transportation-FEV-report-Concawe.htm

[9] *Renewable hydrogen* refers to hydrogen produced from either water electrolysis with renewable electricity or from biomass/biogas. *Low carbon hydrogen* refers to natural gas reforming (SMR) coupled with Carbon Capture and Storage schemes.

As a result of the combined effect in those areas, the demand for transport fuels is expected to significantly decline mainly due to a lower demand in road transport, with a steeper effect foreseen in the 2030-2050 timeframe ([A Clean Planet for all, 2018]).

For the 2030, 2040 and 2050 timeframes, this study:

- Explores the decline in **total fuel demand** in **road transport** (regardless the origin of the fuel) in diversified scenarios where both electrification and low carbon fuels are complementary solutions to reduce GHG emissions (Section 2)[10]:
  - Both **Light-duty** (Passenger Cars and Vans) and **Heavy-duty** segments of road transport are included in the scope.
  - The impact of the penetration of alternative powertrains (e.g. Battery Electric Vehicles (BEVs), Fuel Cell Hydrogen Vehicles (FCHV)) is also considered within the demand scenario.
- Analyses the fuel demand in aviation and maritime transport sectors with a limited penetration of alternative powertrains / engines.
- Defines a potential timeline for the progressive development, scale-up and deployment of key production technologies (**new plants**) to bring **low carbon liquid fuels** into the market (Section 4.1).
- Estimates the impact of this accelerated scale-up in terms of **volumes** of low carbon liquid fuels available to progressively substitute fossil-based fuels for a given demand (Section 4.1).
- Provides a quantitative assessment of the order of magnitude of the **investment** requirements and potential **GHG reduction savings** in a **Well-To-Wheels (WTW) basis** (Section 3.3.2 and 3.4.3).

Complemented by information published in external sources, this report also compares the feedstock requirements with the **maximum potential availability in 2050**[11] (See Section 50).

Within this context, three scenarios are presented considering a different penetration of Low Carbon Fuels within each transport mode in the 2030/2050 period (Section 2):

1) ***Scenario 1. High (All transport modes)***

   The most challenging scenario considers that LCF penetrate in the road transport sector first, growing towards aviation and maritime beyond 2035. This high LCF demand scenario is deemed as an end-point scenario assuming a mixed fleet for Passenger cars, where LCF will progressively meet the remaining demand for liquids, replacing fossil fuels by 2050 (2050 demand for Road as defined in the [DG CLIMA 2018] 2050 **baseline scenario**).

2) ***Scenario 2. Medium (Heavy-duty, Aviation & Maritime)***

   This scenario considers the creation of the LCF market, firstly incentivised by road transport (both light- and heavy-duty), progressively moving towards aviation and maritime. As a result of a more aggressive penetration of xEVs in the passenger car segment (consistent with the 1.5TECH scenario from *[DG*

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[10] As a simplification, the **2030 baseline** assumes that all the remaining liquid fuel demand is satisfied by fossil fuels.

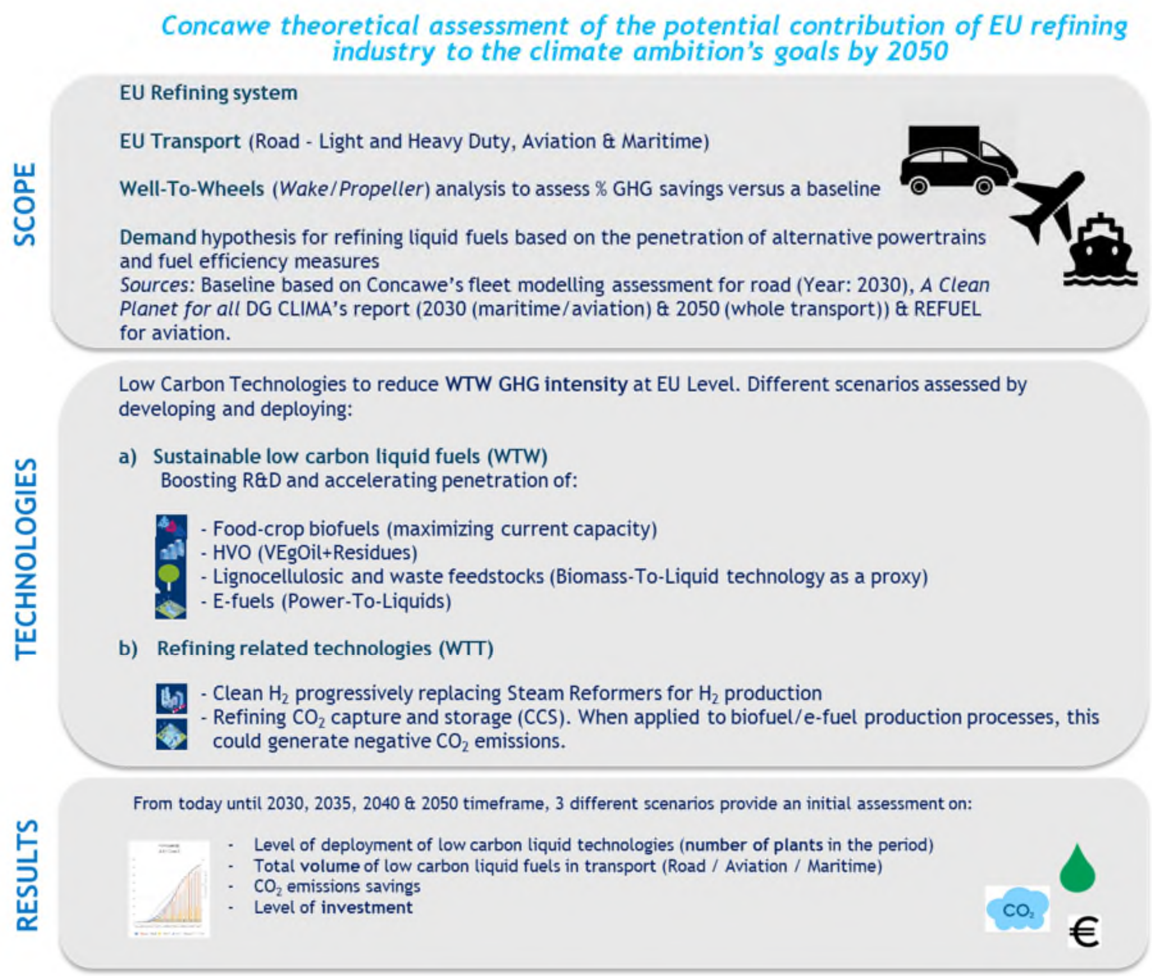
[11] [JRC ENSPRESO, 2019] [DG RTD / ECORYS, 2017]

CLIMA 2018]), LCF will only be used in heavy-duty as well as in aviation and maritime in the 2050 timeframe (with the demand for liquid fuels phasing out in light-duty during the 2040-2050 period).

3) ***Scenario 3. Low (Aviation & Maritime)***

This scenario assumes a more aggressive penetration of alternative powertrains in both light- and heavy-duty segments, leading to a case in which there is no remaining demand for liquid fuels in road by 2050. As a consequence of this lower demand for LCF in road, both the LCF market and supply chain creation are less incentivised and, therefore, the related LCF technology development and scale-up is delayed versus the previous scenarios. By 2050, all LCF will be used in the aviation and maritime sectors. In this low (end-point) scenario, no additional volumes of Sustainable Aviation Fuels (SAF) have been considered beyond what REFUEL / 1.5TECH portray.

Figure 3 Concawe theoretical assessment – What to find in this report.



Concawe theoretical assessment of the potential contribution of EU refining industry to the climate ambition's goals by 2050

SCOPE

EU Refining system

EU Transport (Road - Light and Heavy Duty, Aviation & Maritime)

Well-To-Wheels (*Wake/Propeller*) analysis to assess % GHG savings versus a baseline

Demand hypothesis for refining liquid fuels based on the penetration of alternative powertrains and fuel efficiency measures
Sources: Baseline based on Concawe's fleet modelling assessment for road (Year: 2030), *A Clean Planet for all* DG CLIMA's report (2030 (maritime/aviation) & 2050 (whole transport)) & REFUEL for aviation.

TECHNOLOGIES

Low Carbon Technologies to reduce **WTW GHG intensity** at EU Level. Different scenarios assessed by developing and deploying:

a) **Sustainable low carbon liquid fuels (WTW)**
Boosting R&D and accelerating penetration of:

- Food-crop biofuels (maximizing current capacity)
- HVO (VEgOil+Residues)
- Lignocellulosic and waste feedstocks (Biomass-To-Liquid technology as a proxy)
- E-fuels (Power-To-Liquids)

b) **Refining related technologies (WTT)**

- Clean H_2 progressively replacing Steam Reformers for H_2 production
- Refining CO_2 capture and storage (CCS). When applied to biofuel/e-fuel production processes, this could generate negative CO_2 emissions.

RESULTS

From today until 2030, 2035, 2040 & 2050 timeframe, 3 different scenarios provide an initial assessment on:

- Level of deployment of low carbon liquid technologies (number of plants in the period)
- Total volume of low carbon liquid fuels in transport (Road / Aviation / Maritime)
- CO_2 emissions savings
- Level of investment

2. DEMAND SCENARIOS

2.1. ROAD TRANSPORT

2.1.1. Concawe’s baseline towards 2030

From today up to 2030, the demand of liquid fuels for road transport is expected to decline due to the combination of different factors:

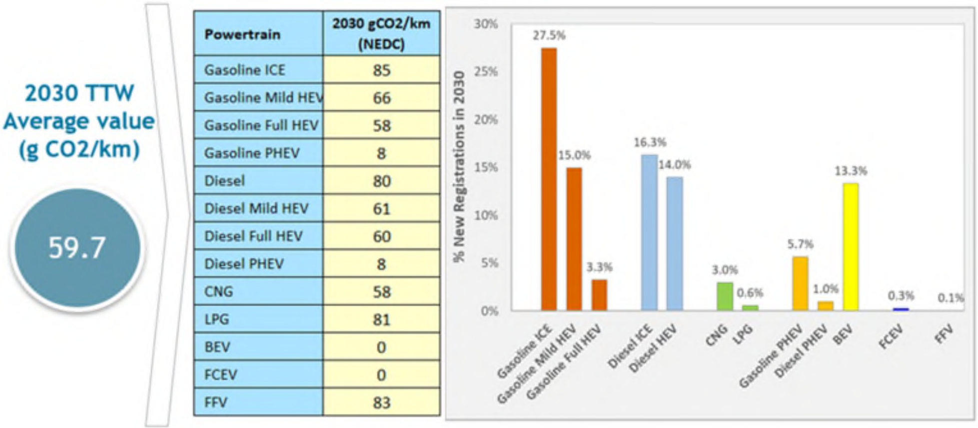
- **New sales:** The improvement in fuel efficiency and hybridization of internal combustion vehicles as well as the increasing penetration of alternative powertrains such as BEVs, FCHVs or gaseous fuels (e.g. CNG).
- **Old vehicles** replacement: Scrappage of old and less efficient vehicles.

The Concawe’s baseline [Concawe 2/2021], investigates the combination of these effects through a detailed model that projects the evolution of the fuels demand & fleet at European level based on relevant publications (e.g. Eurostat, JEC WTW v5), market outlook and Concawe’s internal expert judgment. This analysis defines the fuel efficiency and the market penetration (composition of new sales mix and impact on total fleet) per type of vehicle for road transport in 2030 (see **Figure 4**, **Figure 5** and **Figure 6**) and estimates the decline in liquid fuel demand (~20% in the period 2017-2030) as a result of the two factors described above (See additional details in **Appendix 3**). It is important to note that the basis for this modelling exercise includes the current 2030 CO_2 standards in vehicles and not the potential revision as a result of the new *2030 Impact Assessment* [IA 2020] recently published by the EU COM[12] nor the new targets proposed by the Commission in its *Fit-for-55* publication on 14/07/2021.

Both the basis for the modelling and the summary of the total demand are summarized as follows:

(i) Details of the fuel efficiency and share of new registrations (%) for the different sub-segments (Passenger cars, Vans and Heavy-duty).

Figure 4 Fuel efficiency and share of new registration – Passenger cars (2030).



2030 TTW Average value (g CO2/km)

59.7

Powertrain	2030 gCO2/km (NEDC)
Gasoline ICE	85
Gasoline Mild HEV	66
Gasoline Full HEV	58
Gasoline PHEV	8
Diesel	80
Diesel Mild HEV	61
Diesel Full HEV	60
Diesel PHEV	8
CNG	58
LPG	81
BEV	0
FCEV	0
FFV	83

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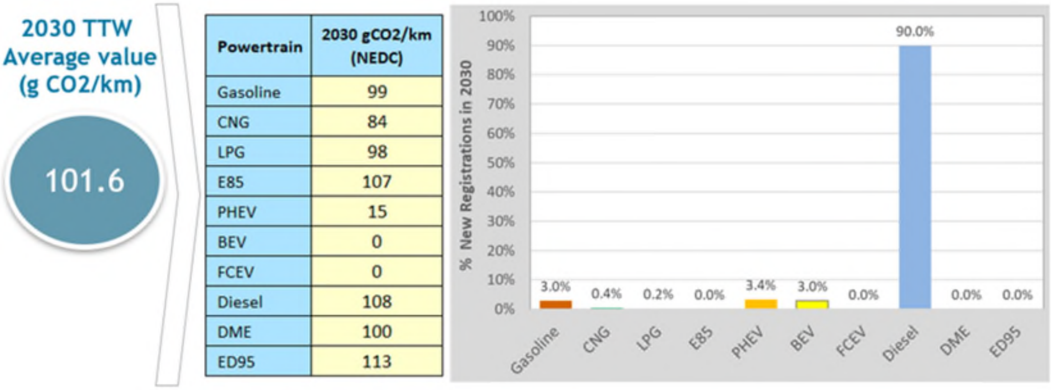
[12] Proposal for amending Regulation (EU) 2019/631 as regards strengthening the CO_2 emission performance standards for new passenger cars and new light commercial vehicles; see https://ec.europa.eu/info/sites/default/files/amendment-regulation-CO2-emission-standards-cars-vans-with-annexes_en.pdf.

In this proposal, targets have been recently revised for further tightening to 55% (cars) and 50% (vans) reaching 100% tailpipe emissions reductions by 2035 [EU COM (2021)]

Note. Modelling work conducted using a C-segment passenger car as the reference vehicle [JEC TTW v5]. New vehicle CO_2 standard of 59.7 g CO_2/km (equivalent to 37.5% reduction compared to 2021 (95.5 gCO_2/km) as defined in current Regulation (EU) 2019/631).

Figure 5 Fuel efficiency and share of new registration – Vans (light-duty commercial vehicles) (2030). [JEC TTW v5]



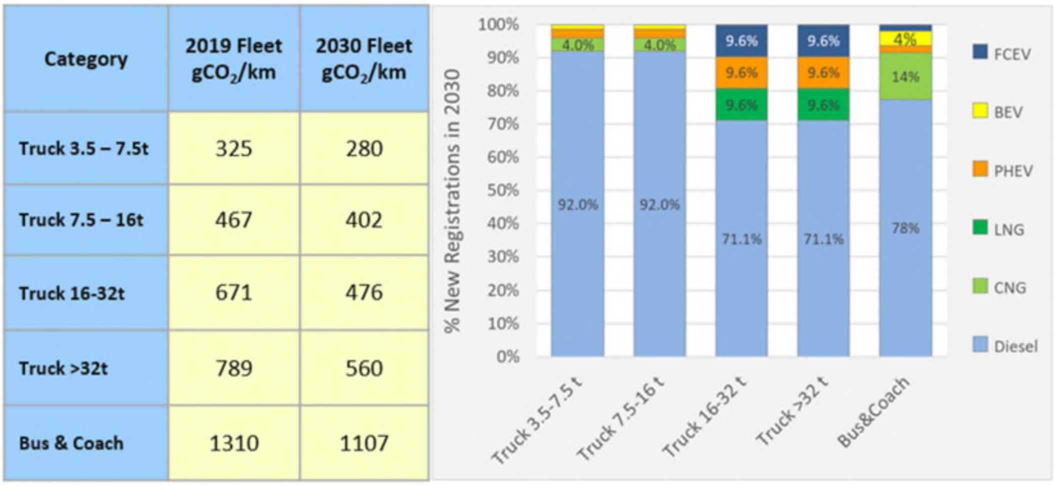
2030 TTW Average value (g CO2/km)

101.6

Powertrain	2030 gCO2/km (NEDC)
Gasoline	99
CNG	84
LPG	98
E85	107
PHEV	15
BEV	0
FCEV	0
Diesel	108
DME	100
ED95	113

Note. Based on current CO_2 standards in 2030: 31% less than 2021 value (147 g CO_{2eq}/km).

Figure 6 Fuel efficiency and share of new registration – Heavy-duty vehicles (2030).



Category	2019 Fleet gCO_2/km	2030 Fleet gCO_2/km
Truck 3.5 – 7.5t	325	280
Truck 7.5 – 16t	467	402
Truck 16-32t	671	476
Truck >32t	789	560
Bus & Coach	1310	1107

Note. Based on current CO_2 standards: 30% emissions reduction by 2030, compared to 2019, for Trucks>16t.

(ii) Details of the total demand - Concawe's fleet and fuel baseline [Concawe Outlook, 2021] (Basis of this current Concawe's assessment).

Table 2 Details of 2015/2030 demand for liquid fuels per sub-segments

Total demand final fuel (Mtoe)	JRC - IDEES 2015	Concawe's baseline (*)	
		2015	2030
Passenger Cars	D: 91.7	D: 92.6	D: 58.7
	G: 74.1	G: 78.2	G: 51.4
Light Commercial	D: 32.0	D: 34.8	D: 25.4
	G: 1.7	G: 2.0	G: 1.3
HD 3.5 – 7.5t	68.7	7.0	9.7
HD 7.5 – 16t		9.8	13.5
HD 16-32t		15.8	15.4
HD >32t		34.2	34.6
Buses and Coaches	13.9	41.4	12.6
TOTAL	**282.1**	**288.7**	**222.6(**)**

Note. D = diesel; G= gasoline

(*) Concawe's assessment based on the modelling of the EU fleet and alternative fuel market-based approach (aligned to the JEC TTW v5 fuel efficiency for different powertrains, using a C-segment vehicle in the modelling as representative of the passenger car fleet). The results show a good alignment with the road transport demand as reported by JRC-IDEES [IDEES 2018].

(**) Concawe's prediction of total energy demand from the model, including rail, aviation and maritime (318 Mtoe) is also in line with the European Commission baseline in the A Clean Planet for all document (330 Mtoe) [EU COM, 2018].

Note that, as mentioned earlier, this does not include the potential impact of the revision of the current *2030 CO_2 standards* in vehicles as a result of the 2030 Impact Assessment (proposal from EU COM published in July 2021 – see footnote 12).

Table 3 Summary of 2017 and 2030 demand for liquid fuels in road transport

	LDVs		HDVs		ROAD (Total)	
(Mtoe)	2017	2030	2017	2030	**2017**	**2030**
Gasoline	80.2	52.7	0	0	**80.2**	**52.7**
Diesel	127.4	84.1	81.2	85.8	**208.6**	**169.9**
Total demand	**207.6**	**136.8**	**81.2**	**85.8**	**288.8**	**222.6**

2.1.2. Concawe's Alternative scenarios towards 2050

The Concawe's 2050 demand is based on the main 1.5°C related scenarios as reported by the European Commission:

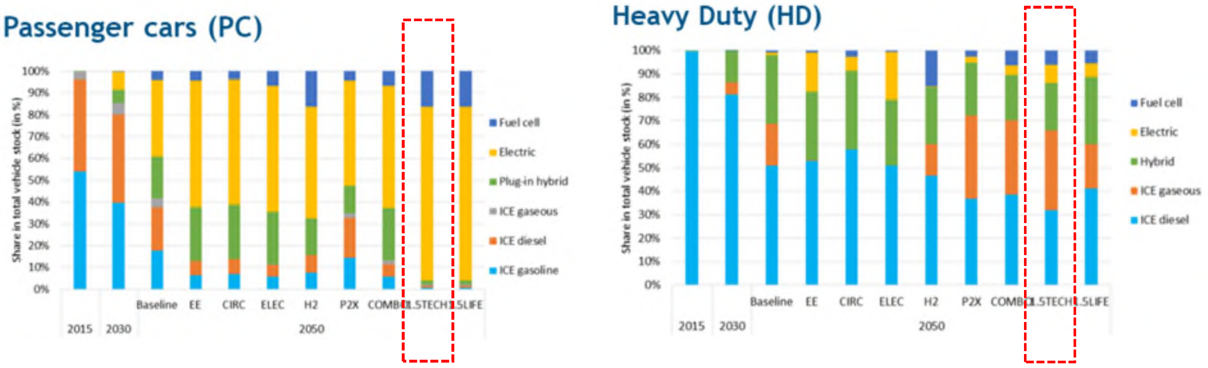
a) Background – 1.5TECH scenario

Forward-looking into the 2050 timeframe, the total energy demand in transport is derived from the figures reported in the long-term strategy *A Clean Planet for All* document [EU COM, 2018], which are well aligned with the overall demand considered in the updated related publication: EU COM's *2030 Impact Assessment* document [IA 2020]. Besides the **2050 baseline scenario** (a continuation of the *2030 policies baseline*), the European Commission explored the implications of eight different scenarios with different focus on the penetration of certain technologies (e.g. energy efficiency, electrification, Power-to-products (PtX)) to inform long-term climate-related policy options. From these scenarios, the 1.5TECH[13] has been chosen as the reference one for the low case scenario, as it aims to achieve net -100% GHG reductions (including sinks) by 2050 vs 1990, through:

- The combination of different technology solutions in transport (electricity, hydrogen, liquid and gaseous biofuels, e-liquid/gases and some remaining oil products)
- With CCS and BECCS (Bioenergy coupled with Carbon Capture and Storage (CCS), allowing negative emissions) implemented across the EU Economy.

In terms of fuel demand, the *A Clean Planet for All*'s 1.5TECH strategic vision requires fossil energy in transport to reduce significantly. This is achieved through a heavily electrified road transport (**Figure 7)** with a very limited contribution of internal combustion engines, mainly in the heavy-duty transport.

Figure 7 Shares in total cars / heavy-duty stocks by powertrain technology in the baseline and scenarios [EU COM, 2018]



As a result of this 1.5TECH scenario, the demand for liquid fuels in the transport sector is significantly reduced (~85% versus the 2050 baseline) with some remaining fuel consumption mainly for aviation and maritime sectors (**Figure 9**).

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[13] 1.5TECH scenario has been chosen as the reference one for our assessment as the 1.5LIFE implies societal changes in consumer choice towards more "sustainable lifestyles" including, for example, transport activity reduction (e.g. taking less flights) or food consumer preferences changes.

b) Concawe's 'alternative 1.5°C' - 2050 scenarios

Building on these long-term scenarios, three 'alternative *1.5°C*' scenarios, aiming to achieve the same net GHG reduction levels as the 1.5TECH scenario, are explored in this Concawe report:

b.1) Scenario 1 (High end – All transport)

This scenario considers:

- Future demand: a balanced-powertrain mix

  The penetration of the different alternative powertrains in the total fleet (Figure 7**) as well as the improvement in fuel efficiency measures** will ultimately define the basis for the remaining demand of liquid fuels in 2050.

  Therefore, the more **balanced** penetration of electric driven vehicles (xEVs) and efficient internal combustion engines (ICEs) in road transport, as defined in the **2050 baseline** scenario from *A Clean Planet for all*, has been chosen to determine the demand for liquid fuels in the present Concawe assessment.

  The *2050 Baseline* scenario still implies a significant penetration of electrified vehicles in the total road fleet (e.g. - ~60% BEVs (Battery Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles) in passenger cars).

- Fuel composition: The role of Low carbon liquid fuels (LCLF)

  Once the 2050 demand is defined, this Concawe study explores an accelerated **substitution of fossil-derived fuels** towards 2050, **progressively replaced by low carbon liquid fuels** with much lower GHG intensity values (see **Figure 10**), to achieve the same GHG emission reduction as the *A Clean Planet for All* 1.5TECH scenario.

b.2) Scenario 2 (Medium – Heavy-duty, Aviation & Maritime)

In this mixed scenario, the electrification of passenger cars is accelerated as in the 1.5TECH scenario, reaching a point where there is no further demand for liquid fuels in the passenger car segment in 2050. For heavy-duty, the assumptions remains as in Scenario 1 (based on DG CLIMA's *2050 Baseline*) considering a mixed composition of the fleet in conjunction with the role of LCLF (Total demand of liquid fuels in 2050 being half of the 2030 one with LCLF completely replacing the remaining fossil liquids by 2050).

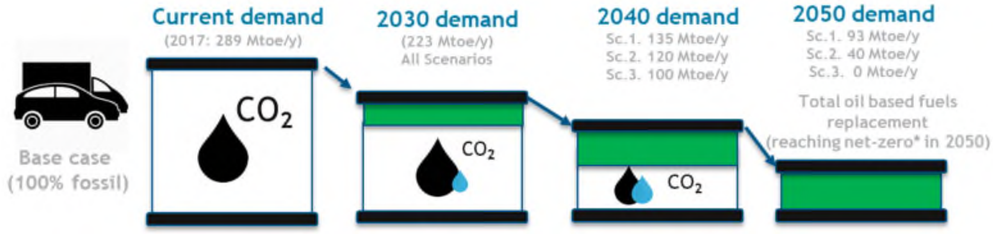
b.3) Scenario 3 (Low end – Aviation & Maritime)

This end-corner scenario considers an accelerated penetration of alternative powertrains in all road sector up to a point where there is no demand for liquid fuels (fossil or low carbon ones) by 2050.

2.1.3. Summary Road Transport

Based on the assumptions described, three 'alternative 1.5°C' scenarios have been explored, approaching net zero GHG emissions in 2050 by replacing the bulk of fuels consumed in road transport (as given by the demand scenario) by low carbon liquid fuels. The evolution of fuel and Low Carbon Fuel consumption is summarized in **Figure 8** and **Table 4**.

Figure 8 Summary – Basis for the Concawe assessment ('Alternative 1.5°C' scenario)



(*) GHG reduction compared to "Well-To-Wheels" GHG intensity of 100% fossil fuel in Road transport (light-duty (LDV) and heavy-duty vehicles (HDV))

Note. Black drops reflect fossil-based fuels; blue drops represent CO_2 reduction technologies within refining sites (initially fossil-based related) and green area illustrates the progressive penetration of low carbon liquid fuels.

Table 4 Summary – Low carbon liquid fuel demand trajectory [Concawe Scenarios].

Demand – Road transport **Liquid fuels** (Mtoe/y)	Scenario	2017	2030	2035 (*)	2040 (*)	2050 [ACP4A]
Total demand (Liquid fuels)	#1	289	223	174	135	93
	#2				130	40
	#3				100	0
Low Carbon fuels	#1	19	31	34	62	93
	#2					40
	#3		19	12	7	0
% LCF vs total demand (liquid fuels)	#1	7%	14%	20%	46%	~100%
	#2				~50%(***)	
	#3		9%	7%	7%	N/A
% reduction in total demand for liquid fuels vs 2017(**)	#1	-	23%	40%	53%	68%
	#2				56%	86%
	#3				66%	100%

Source : Concawe's internal modelling assessment (Fleet composition & Fuel availability), [EU COM, 2018]

Notes.

(*) As a simplification, an estimate of the 2035/2040 midpoints have been conducted for Scenario 1 & 2(showing a slightly sharper decrease in the 2035+ timeframe when compared against a linear interpolation).

(**) As mentioned earlier in the report, this reduction is due to the combined effect of measures such as: fuel efficiency improvement in powertrains, implementation of different levels of electrification (hybridisation) in existing internal combustion engines (ICES) and penetration of alternative vehicles (e.g. BEVs) or gaseous fuels (e.g. Hydrogen).

(***) LCLF diverted into heavy-duty segment due to the accelerated penetration of xEVs in Passenger Car segment (reducing demand for liquid fuels in this segment).

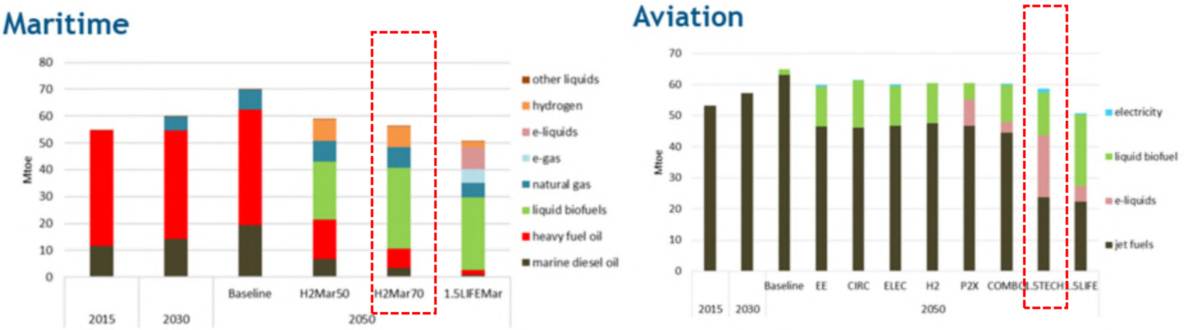
Besides the progressive penetration of low carbon liquid fuels, the Concawe alternative scenarios consider the implementation of **CO_2 reduction technologies** within the EU refining system as a way to reduce the CO_2 emissions within the sites, initially linked to the production of fossil-based fuels. Based on the Concawe Report 7/19 published within the series of the Low Carbon Pathways programme [CO_2 technologies, Concawe 8/19], the impact of the deployment of technologies such as Clean hydrogen (e.g. Hydrogen produced by water electrolysis (Renewable hydrogen) or based on natural gas steam methane reforming coupled with CCS *(Low Carbon Hydrogen)*) and Carbon Capture and Storage (CCS) are also explored within the context of this study.

The potential opportunities and the relevant implications are described in the following sections.

2.2. AVIATION & MARITIME

Compatible with the 1.5° C goal, the 2050 **demand** scenarios for both EU aviation and maritime sectors are based on the demand and fuel mix scenarios as reported in the ACP4A document [EU COM 2018] and the new mandates/sub-mandates from the recently published ReFuel EU initiative regulating the penetration of Sustainable Aviation Fuels in the aviation sector (compatible with the 1.5TECH vision):

Figure 9 ***A Clean Planet for All*. Maritime: EU international maritime fuel mix (left). Aviation: Aviation fuel mix (right)** [EU COM, 2018]



Note.
(*) The scope of the demand scenarios projected in the ACP4A includes inland waterways and national maritime freight transport activity, including EU international shipping (from/to EU) (left), as well as both domestic and extra-EU international (from/to EU) flights (right).

(**) For the maritime sector (left), the 2050 scenarios for EU international shipping do not include a 1.5TECH scenario reaching net-zero GHG emissions. As a variant explored, the 1.5LIFE scenario, reported in **Figure 9**, seems to go beyond the current IMO ambition (50% emission reduction by 2050 compared to 2005) and assumes that international maritime is ' […] *part of an economy wide net zero GHG target and reduces its emissions by about 88% by 2050 compared to 2008* […]'. Therefore, this scenario assumes more stringent measures associated with energy efficiency, penetration of alternative fuels in the fuel mix and a slower growth on activity relative to baseline due to lower imports and thus transport demand for fossil fuels. Therefore, in the absence of a 1.5TECH scenario, the total LCF liquids, diesel-like, are derived from the H2Mar70 scenario (contributing to achieve, among other technologies/energy carriers, an also ambitious 70% GHG reduction in the maritime sector by 2050 compared to 2008, higher than 2050 IMO's current ambition levels). This shows that the maritime sector could be based on drop-in fuels diesel-like but potentially other liquid e-fuels, such as e-methanol or e-ammonia, could be envisaged in 2050 (this level of fuel differentiation not included in the scope of this assessment[14]).

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[14] An on-going report commissioned by Concawe will deep dive into potential routes to reduce GHG emissions in the maritime sector, analysing different type of fuels.

Table 5 EU ReFuel Aviation – Targets and volumes of Sustainable Aviation Fuel (SAF)

SAF, %vol	2025	2030	2035	2040	2045	2050
Overall	2	5	20	32	38	63
SAF – Synthetic fuels	-	0.7	5	8	11	28

Note. Targets in % volume versus total demand for aviation, applicable to the same scope as the ACP4A (EU-flights).

This alignment with the ACP4A scenarios and ReFuel EU for aviation will ensure that the Concawe's 2050 endpoint scenario explored in this report ('1.5 alternative' scenario) is compatible with the EU Commission's goal of reaching net zero emissions by 2050 (whole EU economy level).

Table 6 Summary – Low carbon liquid fuel demand timeline (Aviation & Maritime).

	Scenario	2030	2040(*)	2050
Total demand Low Carbon liquid fuels (Mtoe/y) (*)	#1 / #2	3	35	67
	#3		31	
Maritime	#1 / #2	-	15	30
	#3		11	30
Aviation	#1 / #2 / #3	3	20	37
Total remaining fossil liquid demand (Mtoe/y)	#1 / #2	110	73	32
	#3		77	
% LCF vs total Liquid demand (Aviation & Maritime)	#1 / #2	3%	~32%	68%
	#3		30%	
% LCF vs total Energy demand (Aviation & Maritime)	#1 / #2	~3%	~30%	~57%
	#3		26%	

Source: Concawe based on [EU COM, 2018] and EU RefuelEU.

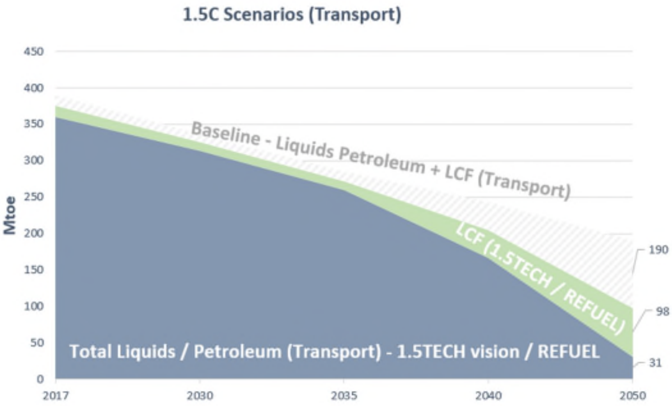
Notes: (*) The volumes are derived from the SAF mandates for aviation (consistent with 1.5TECH scenario) and the H2Mar70 for maritime. Without entering into the specific low carbon liquid fuel (LCF) technologies (and quality / type of specific fuels) which could be used in 2050, the current Concawe estimate 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 – See **Table 9**). For the aviation sector, the sub-mandate on synthetic fuels are deemed to be met by e-fuels (See **Table 5**).

The middle-points for maritime (2035-2040) presented in the subsequent figures are defined based on a linear interpolation from the data presented in **Table 6** (as an initial estimate). The wide deployment of biofuels and e-fuels is envisaged to happen in the aviation and maritime sectors from 2035 onwards, when those sectors which are heavily impacted by the price of fuels will be able to take advantage of the technological cost reduction.

2.3. CONCAWE’S ‘ALTERNATIVE 1.5°C’ SCENARIO. DEMAND EVOLUTION ACROSS EU TRANSPORT SECTOR - SUMMARY

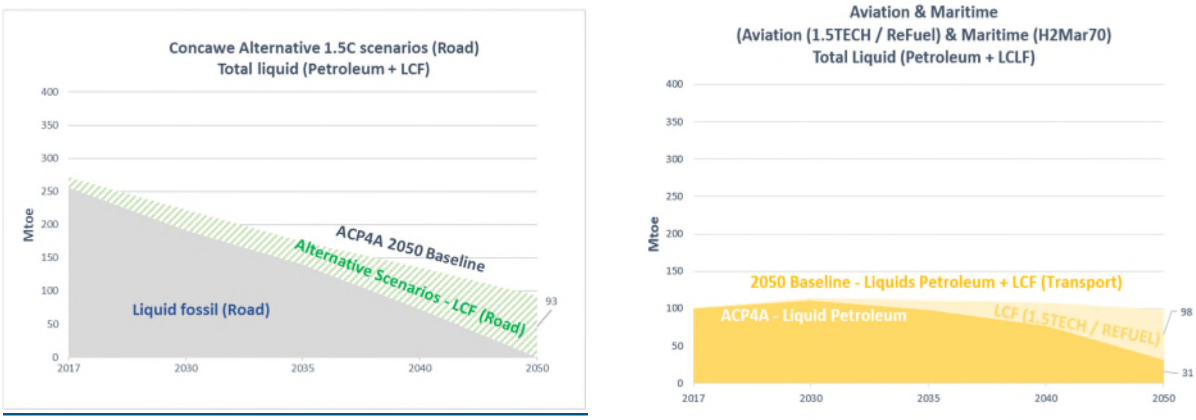
The following figure summarises the concept behind the Concawe’s alternative scenarios introduced in the previous sub-sections for the whole EU transport sector:

Figure 10 Liquid products in total transport in (a) 1.5TECH from ACP4A vs baseline and (b) Concawe’s ‘Alternative 1.5°C’ scenario for Road, Aviation & Maritime



(a) The 1.5TECH scenario defined by ACP4A presents a reduction in total demand for liquid fuels versus the 2050 baseline, with limited contribution of low carbon fuels (biofuels and e-fuels) mainly in the aviation and maritime sector[15].

(b) Road (left) and Aviation & Maritime (right)



Source: Concawe estimate derived from *A Clean Planet for all* / ReFuel data

Road (left): In this Concawe’s *‘alternative **1.5°C’** scenario 1,* the objective is to assess the impact and feasibility of a higher penetration of LCLF. The starting point is the definition of the demand for liquid fuels for road transport in a balanced powertrain mix scenario (2050 baseline in line with ACP4A) where the fossil fuels are progressively and fully replaced by low carbon liquid ones in 2050. Whereas Scenario 2 considers an intermediate step where only demand for LCLF remains in the heavy-duty segment, the lowest case (Scenario 3) considers no further demand in road. For ***aviation and maritime*** (right) transport sectors, the same hypothesis as the ones included in the A Clean Planet for all [EU COM, 2018] report and ReFuel for aviation have been used Concawe’s *‘alternative **1.5°C’** scenario* assumes the same penetration of low carbon fuels as defined in the ReFuel/1.5TECH (aviation) and H2Mar70 (maritime) 2050 scenarios[16].

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[15] The 2050 baseline demand scenario in ACP4A defines a balanced fleet mix in 2050 for Road transport which is assumed as the basis for our Scenario 1 & 2, accelerating the penetration of LCF in the aforementioned segments, fully replacing fossil fuels in road. The ACP4A also defines the Concawe - Scenario 3 (Low), with some remaining fossil demand in Aviation & Maritime. Refer to sections 2.1.2, 2.2 and 4).

[16] In the absence of a 1.5TECH scenario for the maritime sector in the ACP4A report, the *H2Mar70* one has been chosen for the purpose of this assessment (More details in Section 4.1).

3. LOW-CARBON TECHNOLOGIES

3.1. THE WELL-TO-WHEELS APPROACH

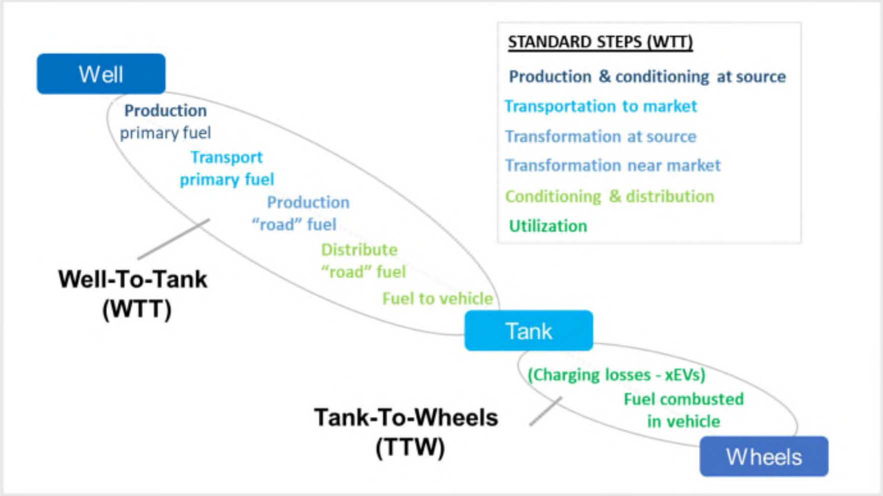
As introduced in previous sections, the Concawe's 'alternative 1.5°*C*' scenario explores the development and deployment, at large-scale, of critical technologies to reduce the carbon emissions of the final fuels linked to the European refining system.

In order to investigate the impact on the transport GHG emissions, the full **life-cycle analysis** (LCA) of the different alternatives have been considered. As a simplification, the present Concawe report limits the scope of the GHG assessment to the Well-To-Wheels (general term used in this report to refer equally to road, maritime (*Well-to-Wake) or aviation (Well-to-Propeller)* analysis as defined in the JEC[17] WTW v5 reports.

Using road transport as an illustrative example, this WTW approach:

- Does include the energy and CO_{2eq} impact due to the fuel production and vehicle use stages (**Figure 11**).
- Does not consider energy or the emissions involved in building the facilities, the production of the vehicles, or other end of life aspects.

Figure 11 Scope of the JEC WTW analysis (Energy expended and CO_{2eq})



As a reference for this study, a 100% fossil diesel fuel is considered with the breakdown of its associated WTW GHG emissions as summarized in **Figure 12** (C-segment passenger car).

Due to the main contribution of the usage phase to the overall WTW GHG emissions (~80%), besides the implementation of WTT CO_{2eq} reduction measures within the production sites (e.g. refineries representing ~8% of the total CO_{2eq} emissions), the route towards major GHG mitigation options for transport will necessarily be based on reducing the fossil-derived CO_2 emitted during its combustion in the engine (TTW).

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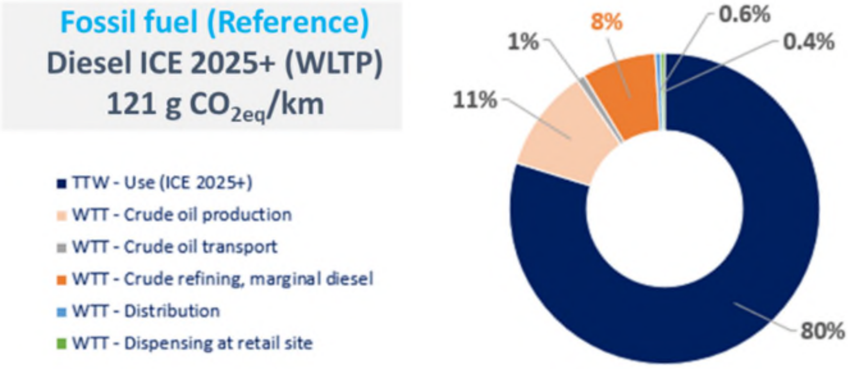
[17] The JEC consortium is a long-standing collaboration among the European Commission's **J**oint Research Centre, **E**UCAR (the European council for Automotive Research and development) and **C**oncawe.

Figure 12 Fossil fuel reference (Diesel – Passenger cars) – Well-To-Wheels breakdown [JEC WTW v5, 2020].



In order to achieve a significant and direct impact on the CO_2 emissions due to the combustion of the fuel, different measures can be envisaged:

a) <u>Reduction of total CO_2 emissions emitted at tailpipe (TTW)</u>

- Through the implementation of fuel efficiency measures as well as the replacement of the internal combustion engine (ICE) by non-combustion technologies (such as BEVs).

  The impact due to both elements (fuel efficiency and penetration of xEVs) has been indirectly included in the present assessment leading to a reduction in total fuel demand already considered in the baseline and as described in section 2.1.2.

- Capture of the emitted CO_2 at the tailpipe instead of releasing it to the atmosphere and later conversion/storage (some novel technologies, currently at R&D level are exploring this possibility for on-board CO_2 capture).

  Due to its low Technology Readiness Level (TRL), this technology has not been considered in the scope of this assessment.

b) <u>Technologies with no/minor CO_2 impact on the atmosphere (WTW)</u>

Beyond TTW, the integration of additional low GHG technologies in the production/conversion processes through, among others, energy efficiency measures, process/furnace electrification or the progressive integration of clean hydrogen or Carbon Capture and storage could also contribute to improve the Well-To-Tank intensity of the fuels with a positive impact on reducing WTW emissions.

Beyond this, the substitution of fossil-derived fuels by synthetic fuels will have a significant impact on the overall WTW picture, as recognized in RED II even if not resulting in CO_2 emission reductions at the tail pipe:

- **Biofuels**: the CO_2 released during their combustion in the engine would be equal to the CO_2 captured during the plant growth, and the net emission associated to this combustion would result to zero.
- **E-fuels**: the CO_2 is artificially captured and converted into a synthetic fuel through the reaction with hydrogen resulting from water electrolysis. Similarly, as above, the net emission associated to this combustion would be compensated WTW as the same amount of CO_2 is released to the atmosphere as the one initially captured in the production phase.

These technologies could achieve significant WTW savings compared to a fossil reference (>60%) and their remaining GHG emissions will be associated with their production phase.

3.2. KEY TECHNOLOGIES

Based on the Well-To-Wheels assessment described in the previous section, the key technologies considered in this analysis are some of the most relevant ones identified both in the Commission's *A Clean Planet for All document* [EU COM 2018] and Concawe's Low carbon pathways programme ([CO_2 technologies, Concawe 8/19]; [Refinery 2050, Concawe 9/19].

They can be divided in two main blocks:

a) Low Carbon Liquid fuels

This block includes different technologies and feedstocks to produce alternative liquid fuels compatible with existing powertrains, with the potential to **achieve significant** *Well-To-Wheels* **GHG reductions** (~60-95%) when compared with equivalent fossil-derived ones.

As illustrative selected examples of these technologies, four big families have been considered for the purpose of this analysis:

- **Food-crop** based biofuels (existing technologies, with a cap based on the renewable energy directive - RED II)
- **Hydrotreated vegetable oil** (HVO) produced either from sustainable vegetable oils or waste residues (e.g. waste cooking oil)
- **Biomass-to-Liquid** (BTL) as example of conversion routes to transform lignocellulosic and other waste materials (e.g. municipal waste) into fuels.
- Power-to-X synthetic fuels (**e-fuels**).

b) CO_2 reduction technologies

As examples of these mitigation technologies within the production sites, two technologies have been included in this assessment:

- Production of **Clean Hydrogen** within the refineries by means of low-GHG emission technologies[18].

  This includes either renewable Hydrogen, produced with water electrolysis or from biomass/biogas ('Renewable H_2') or Hydrogen produced by Steam Methane Reforming (SMR) of natural gas coupled with CCS schemes ('Low Carbon H_2').

  During the transition, these new technologies will reduce the GHG intensity of the fossil fuels produced within the refineries. Once installed and with refineries progressively replacing oil as feedstock by alternative feedstocks, the clean H_2 will enhance biofuel and e-fuel production routes.

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[18] As a simplification, this study assumes the production of the clean hydrogen to be produced within or close to the production sites (as part of direct emissions). Different business models could be envisaged though, importing this hydrogen from third parties. In any case, this decision is not deemed to impact the results as both direct and indirect emissions are considered within the scope and any potential cost/price implications are out of the scope of this assessment.

- **Carbon Capture and Storage**

  Following the same rationale as with the Clean H_2, new CCS plants linked to oil-based refineries will reduce the WTW GHG intensity of conventional fuels and products. As refineries integrate other feedstocks, such as biomass, these already installed CCS plants will be well suited to enable negative emissions (BECCS schemes) as they could capture and store the biogenic CO_2 produced during the combustion process of the biomass in the new BTL schemes integrated / co-located within the same refinery sites (see Sections 3.3 and 3.4 for more details on the technology).

The relevance of these technologies goes beyond the refining system as they are deemed necessary for transport and other energy-intensive industries in the long term[19].

It is worth noting that that the selected examples of the technologies considered in this report are **not intending to represent a roadmap** for the EU refining industry but an **example** of a potential accelerated trajectory that could contribute to reach climate neutrality in transport by 2050.

3.3. LOW CARBON LIQUID FUELS – PRODUCTION ROUTES

In this section, the technologies considered within this Concawe's assessment are explained in more detail together with their potential to reduce GHG emissions and some initial estimate on the sizes/level of investment required when looking into the 2050. More details on the specific technologies and the potential integration within the refineries has been explored in a previous Concawe report [Refinery 2050, Concawe 9/19].

3.3.1. Description of technologies

3.3.1.1. Food-crop based biofuels

Feedstocks: Food- and feed-crop (e.g. feedstocks such as sugar crops, starch crops and vegetable oils).

TRL: 9 (Commercially available)

Technology: Transesterification, fermentation, hydrogenation. e.g. Ethanol, FAME (Fatty acid methyl ester).

This section covers the use of food-crop feedstocks to produce different types of biofuels such as ethanol or biodiesel through a variety of pathways including transesterification, fermentation or hydrogenation, among others.

In this section, we are referring to ethanol and FAME which are currently produced and available in the European market, being blended with respectively fossil gasoline and diesel up to the limits of the EU Fuel standards: up to 10% ethanol in gasoline (EN 228) and 7% in diesel (EN 590[20]).

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[19] https://www.ies.be/files/Industrial_Value_Chain_25sept.pdf *A bridge towards a Carbon Neutral Europe, 2018* (EU's Energy Intensive Industries' contribution to the EU Commission's Strategy for long-term EU greenhouse gas emissions reductions).

[20] Due to the blending wall, the following grades are currently certified: B7 (EN 590) can be used without any modification to the engine. B10 (EN16734) can be used on certified engines. B30 (EN16709) and B100 (EN14214) can be used on some specific certified engines (mainly trucks engines), requiring specific monitoring (e.g. reduced oil drain interval).

In December 2018, the recast of the Renewable Energy Directive (RED II) was adopted. In RED II, the overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32%, with a specific minimum sub target of 14% for the energy consumed in road and rail transport by 2030 as renewable energy. RED II includes also a set of sustainability and GHG emission saving criteria that biofuels used in transport must comply with to be counted towards the overall 14% target.

Sustainability criteria include criteria protecting land with high biodiversity value and land with high-carbon stock resulting from direct land use change, but do not cover the issue of indirect land-use change (ILUC). Therefore, in order to address the ILUC issue, RED II sets limits for the share of biofuels produced from food and feed crops: maximum 7% of final consumption in the road and rail transport sector in a Member State.

This cap on the use of this type of biofuels is considered within the current assessment and, in the absence of any further looking legislation in this regard beyond 2030 (at the moment of drafting the present report), the 7% maximum has been kept constant over the whole period (up to 2050). The effect is that, as demand for road transport is reduced, the volume of these 'food-feed' crop based biofuels will be also reduced in the future.

We have used the following assumptions in this study:

- Existing production facilities will increase their utilization rate towards 2030 (currently below their full installed capacity) to maximize their contribution to RED II up to the cap/blending limits defined.
- No additional production capacity will be installed in Europe during the 2020-2050 timeframe.

As a reference, [JEC Alternative fuels, 2020] study has estimated the utilization rates (ratio between installed and utilised capacity) as follows:

Table 7 Assumed utilization rates for different biofuel types

Biofuel	**2018**
Ethanol – Food/feed crops	79 %
FAME	52 %

Source: JEC based on USDA report (Flach et al, 2018[21])

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[21] Flach et al (2018) *GAIN Report - EU Biofuels Annual 2018* *https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-3-2018.pdf* .

3.3.1.2. Advanced / non feed-crop based biofuels

Advanced biofuels can be produced through a wide number of different combinations of feedstocks and conversion pathways:

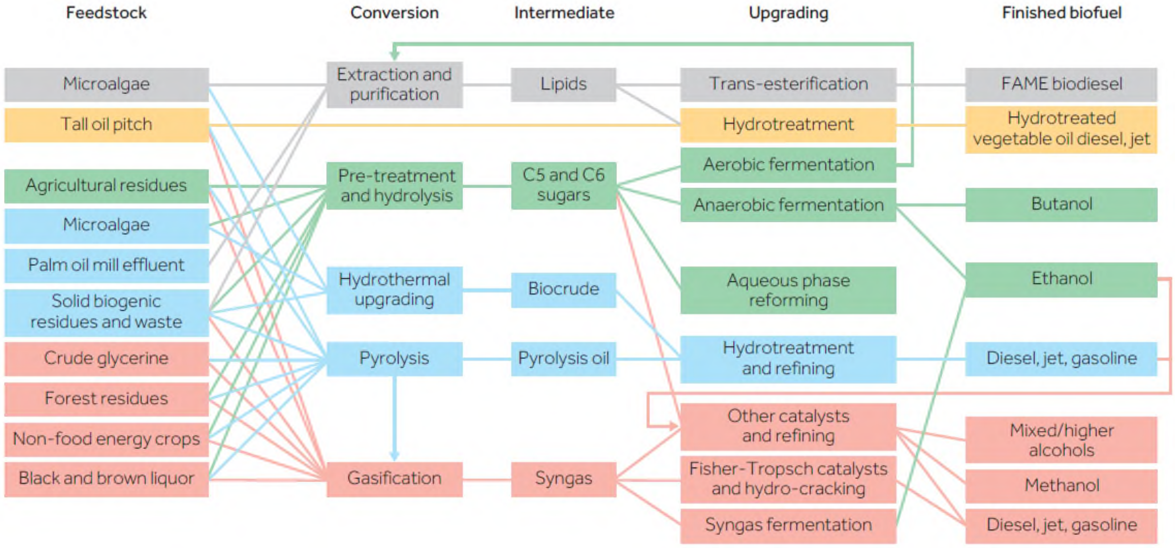

Figure 13 Example of advance biofuels pathways (Source [IRENA 2016[22]])

Due to the multiple routes available, as a simplification, this Concawe assessment focusses on two main ones based on their current technology/commercial readiness level as well as their potential to reach significant GHG reduction levels as drop-in fuels: *Hydrotreated vegetable oil* (HVO) and the Biomass-To-Liquid (BTL) including gasification, syngas and Fischer-Tropsch upgrading to produce low carbon liquid fuels.

3.3.1.2.1. Hydrotreated vegetable oil (HVO)

Feedstocks: Sustainable non-food-crop based vegetable oils/waste oils/fats (e.g. waste cooking oil)

TRL: 9 (Commercially available). Co-processing or stand-alone plants.

Technology: Hydrogenation. E.g. licensed technologies: NExBTL®, UOP.

As an alternative to trans-esterification of vegetable oil or animal fat (as potential routes also for *FAME* production), these feedstocks can also be hydrotreated allowing the final fuels to be drop-in fuels allowing higher blends with fossil diesel beyond the current FAME-related blending walls. This removes double bonds and oxygen from the unsaturated compounds such as alkenes and aromatics present in those fats and oils, yielding a paraffinic fuel which is more stable and less reactive. Depending upon the catalyst used, isomerization can be added to improve cold flow properties. The product is a sulfur-, oxygen-, nitrogen- and aromatics-free diesel which can be used up to higher levels without modifications in diesel engines[23]. The

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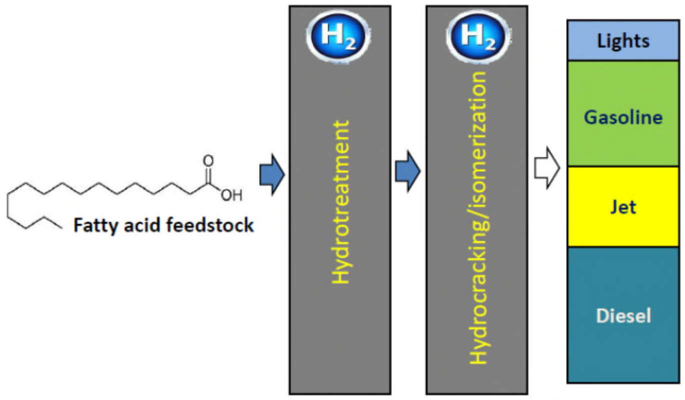
[22] Innovation Outlook - Advanced Liquid Biofuels, IRENA 2016. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf

[23] In EN590, HVO can be blended to upper levels (~80%) with fossil diesel. HVO100 (EN15940) can be used on certified engines. For instance, available to all passenger cars in Finland, whereas limited to captive fleets (hence certified trucks) in countries such as France.

final fuel properties are virtually independent on the original feedstock, so a wider range of feedstocks can be either co-processed in existing refining units (up to 30% in revamped hydrotreaters) or in dedicated units [Concawe 19.9-1].For the purpose of this analysis, we refer to non-food crop based sustainable feedstocks for HVO production.

The Neste process (NExBTL®) [Neste 2015] was the first to be used in commercial production although similar processes are/have been developed by other companies (e.g. UOP Ecofining, Axens Vegan) and they are currently used and commercially available at industrial scale.

Figure 14 Example of a simplified process scheme for the two stages of hydroprocessing.



Source: ETIP bioenergy (European Technology and Innovation Platform).

Note. The co-processing of vegetable oils/fats into the refinery is widely explored in [Refinery 2050, Concawe 9/19] report.

HVO is a well-stablished technology and recently new stand-alone units have been even built or announced, some of them converting traditional oil-based refineries into HVO-based biorefineries (E.g. La Mède in France[24] started up with a 500 kt capacity, Venice and Gela in Italy started up with 1.1 Mt capacity[25], a new unit to be built in Cartagena refinery in Spain of 250 kt/y[26] or recent announcements of additional capacity being studied in Porvoo, Finland and Rotterdam refineries[27]).

3.3.1.2.2. Biomass-to-Liquid (BTL)

Feedstocks: Lignocellulosic biomass including wood and residues from forestry, waste-wood from industry, agricultural residues (straw and stover) and energy-crops. Option to use other feeds e.g. municipal solid waste.

TRL: 4 - 8

Technology: Multiple routes. Selected example: Thermochemical conversion routes such as BTL (gasification and Fischer-Tropsh synthesis) or pyrolysis/hydrothermal liquefaction (HTL).

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[24] https://totalenergies.com/media/news/press-releases/total-starts-la-mede-biorefinery

[25] https://www.eni.com/en-IT/media/press-release/2021/04/eni-new-systems-installed-venice-biorefinery-eliminate-palm-oil-entirely.html; https://www.eni.com/en-IT/media/press-release/2019/09/eni-opens-its-bio-refinery-in-gela.html

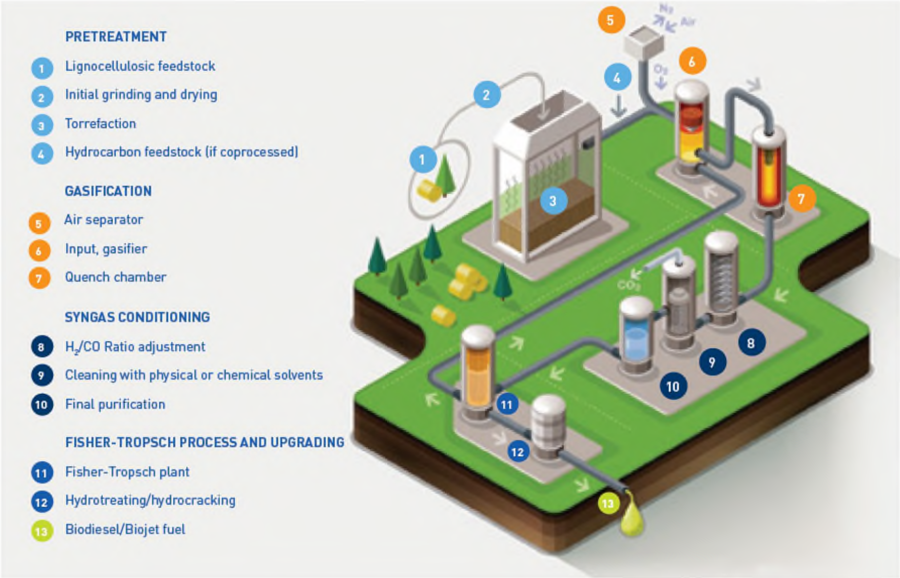
[26] https://www.repsol.com/en/press-room/press-releases/2020/repsol-to-build-spains-first-advanced-biofuels-plant-in-cartagena/index.cshtml

[27] https://www.neste.com/releases-and-news/renewable-solutions/neste-selects-rotterdam-location-its-possible-next-world-scale-renewable-products-refinery

As one example of the thermochemical conversion routes to transform lignocellulosic biomass into fuels (**Figure 13**), the *Biomass-To-Liquid* technology, through gasification and Fischer-Tropsch (FT) synthesis, has been selected among the routes with higher TRL (TRL 8) closer to commercialization.

The figure below illustrates a BTL process where, after pre-treatment, gasification converts dry biomass to syngas (a mixture of H_2 and CO) under high pressure and temperature conditions. After the syngas conditioning step, typically including a water-gas shift reaction or clean hydrogen import, the Fischer-Tropsch process converts this conditioned syngas into a mix of hydrocarbons (FT-wax) which will be upgraded via typical refinery processes into final high-quality products suitable for transport: mainly paraffinic diesel and kerosene, the latter requiring further adjustment via either a modified catalyst / isomerisation units to meet cold-property related specifications.

Figure 15 Example of a BTL technology: BioTofuel project.



Source: https://www.total.com/en/energy-expertise/projects/bioenergies/biotfuel-converting-plant-wastes-into-fuel

It is worth highlighting that:

a) In principle, the individual steps of the conversion pathways have been well proved at commercial scale for fossil feedstocks. However, the heterogeneity of the lignocellulosic feedstocks which could be treated in BTL plants adds additional layers of complexity in terms of pre-treatment and syngas conditioning (as Fischer-Tropsch requires quite strict and stable syngas quality). No commercial BTL plant has been built yet.

b) As described in **Figure 13**, alternative routes to the synthetic BTL pathway based on gasification and FT technologies include other thermochemical conversion pathways such as fast pyrolysis (Pyrolysis of e.g. chips followed by hydrogenation) or hydrothermal liquefaction (Synthesis at supercritical water conditions and hydroprocessing, currently in R&D with **TRL 4**[28] for the whole integrated process) can also be envisaged.

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[28] The HTL process has been under bench-scale development for some time. It converts the feedstock to a mix of solid and liquid products in superheated water. The liquid fraction has to be upgraded to hydrocarbon fuel by hydrogenation (Hydro-De-Oxygenation - HDO). [Steeper Energy 2008]. Other studies [IC 2021] indicates higher TRLs (5-6 for the production of synthetic crude oil (slurry) but lower TRL of 4 for the overall process including upgrading to the final fuel (not proved yet).

c) Besides the technology challenges to scale-up these technologies at industrial scale and their potential integration within the refineries, the full development of a sustainable supply chain is required. This will include additional R&D efforts and framework conditions to ensure that the resources are mobilised, pre-treated and distributed to the industrial sites for their final conversion. Given the high volume of biomass needed, it is indeed probable, if this conversion route is successful, that a delocalized pre-treatment step (e.g. pyrolysis, torrefaction) will be developed to increase the energetic content of the biomass supplied to central conversion units. A numerous challenges and opportunities to maximize this availability towards 2050 are widely covered in several relevant reports (e.g. EU Commission related reports Ecorys, 2017 and ENSPRESO 2019 as well as the recent Imperial College London Consultants one, summarized in Section 5).

d) BTL coupled with CCS: An example of negative emissions (BECCS)

The advanced biofuel production routes based on the gasification of lignocellulose biomass could offer an interesting opportunity for the industry to explore the concept of BECCS. In these BTL plants, CO_2 is emitted by the syngas production process and the Fischer-Tropsch process which could be potentially captured and stored in CCS permanent reservoirs.

The net effect of this BTL site coupled with CCS is that some biogenic CO_2 (initially absorbed by the plant) is effectively captured and removed from the cycle allowing net negative GHG emissions associated to the production process which could compensate some remaining emissions from fossil-fuels (e.g. fossil jet fuel in aviation).

3.3.1.3. Power-to-X synthetic liquid fuels (e-fuels)

Feedstocks: CO_2 (and renewable electricity)

TRL: 6 - 9[29]

Technology: Water electrolysis + fuel synthesis (e.g. Fischer-Tropsch; methanol route). More details on the [*e-fuels*, Concawe 14/19] report

E-fuels are synthetic fuels, resulting from the synthesis of green hydrogen produced by the electrolysis of water, using green electricity and carbon dioxide (CO_2) captured either from a concentrated source (flue gases from an industrial site) or from the air (Direct Air Capture).

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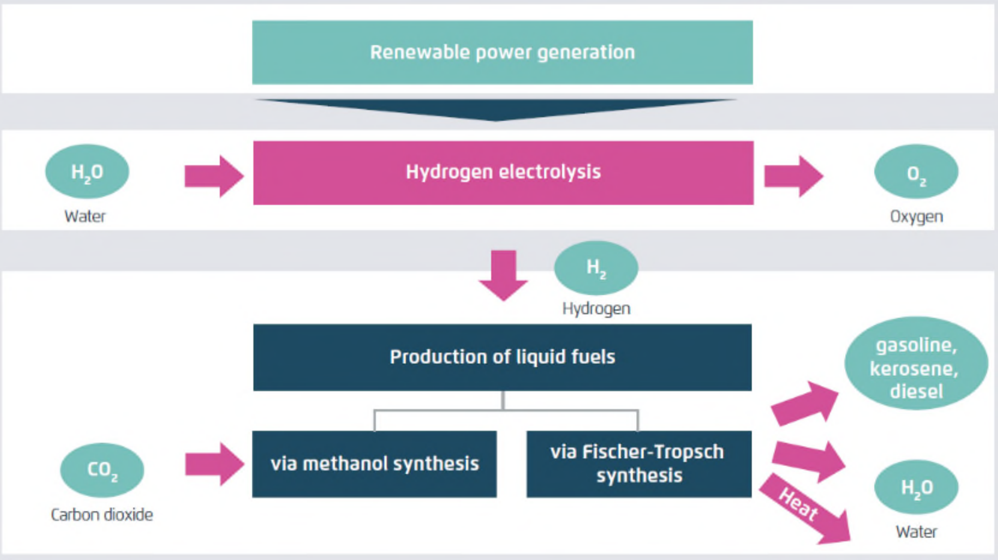
[29] The TRL level depends on the e-fuel technology. There are commercial power-to-methanol plants in Island and Switzerland (TRL 9) whereas some parts of the FT related technology are still at TRL 6 (with examples of semi-industrial plants announced in the coming years).

Figure 16 Summary of main processes to synthetize e-liquid fuel



Source: [Frontier Economics/Agora 2018]

Note:

- As with the BTL technology described in previous section, the Fischer-Tropsch process resembles the one applied in coal and gas production facilities[30]. When applied to e-fuels, this technology has already been successfully demonstrated at pilot plant scale although future challenges lie in the scalability and accessibility to low cost renewable electricity.
  - New pre-industrial scale projects (8 kt/y capacity) have been announced recently and planned to be initiated in 2021 in Heroya (Norway)[31], based on one-step co-electrolysing carbon dioxide and water in solid oxide electrolysers to deliver syngas without the Reverse-Water-Gas-Shift (RWGS) reaction, allowing an increase in efficiency of 15% points compared to the conventional two steps process (electrolyser + RWGS) [Sunfire 2018].
  - Alternative concepts to produce conventional CO/H_2-syngas are in an early development phase and include direct electrochemical reduction of CO_2 and electrocatalytic co-reduction of CO_2 to CO and water to hydrogen. These concepts are investigated in a number of research institutes on lab-scale, their TRLs are therefore low (TRL 1-3).
  - Other projects have been recently announced to produce e-kerosene (ReWest100 project[32]). Lufthansa has announced a project to source 5% of the kerosene it uses at Hamburg airport (Germany) with e-kerosene within 5 years (by 2025) (17.5 kt/y e-kerosene) supplied by the nearby Heide refinery (*Klesch Group*).

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[30]. This part of the e-fuels route has been commercialised producing fuels at a scale comparable to conventional refining processes. As example, Pearl GTL facility in Qatar is the largest synthetic liquids (GtL) plant in operation in the world.

[31] First commercial plant aiming to produce 10 million litres or 8,000 tons/year of the synthetic crude oil each, substitute e-crude annually on the basis of 20 megawatts of input power. http://www.co2value.eu/wp-content/uploads/2019/09/8.-SUNFIRE.pdf

[32] https://www.westkueste100.de/

- The methanol-to-synfuel can be considered as a mature technology as examples of power-to-methanol (e-methanol) plants are installed in Iceland[33] and Switzerland. More recently, *Sunfire* and *TotalEnergies* have teamed up on a pilot project to produce e-methanol in one refinery in Germany[34].
- Factors such as accessibility to affordable and continuous renewable electricity sources as well as further development (R&D) on big-scale electrolysers, improved carbon capture schemes and syngas/e-fuel conversion facilities are some of the key elements to enable the scaling up of this technology in the mid-term future.

This is a rich area for development as drop-in fuels can achieve low (approaching zero) WTW CO_2 intensities in a conventional diesel engine[35]. Their higher energy density compared to batteries offers an interesting solution in usages for which no electricity-based alternatives can be found (e.g. aviation and shipping).

3.3.2. GHG potential reduction and plant's size/investment estimate. Basis

3.3.2.1. GHG reduction savings

As introduced in previous section, in November 2016, the European Commission published its ‘Clean Energy for all Europeans’ initiative. As part of this package, the Commission adopted a legislative proposal for a recast of the Renewable Energy Directive and in December 2018, the revised Renewable Energy Directive 2018/2001/EU (RED II) entered into force.

As part of the RED II, the directive includes a number of GHG emission saving criteria (*minimum threshold*) that biofuels used in transport must comply with to be counted towards the overall 14% target in 2030. In particular, RED II introduces sustainability for forestry feedstocks as well as GHG emission saving criteria for solid and gaseous biomass fuels as reported below:

Table 8 Greenhouse gas savings thresholds (minimum) in RED II

Greenhouse gas savings thresholds in RED II			
Plant operation start date	Transport biofuels	Transport renewable fuels of non-biological origin	Electricity, heating and cooling
After October 2015	60%	-	-
After January 2021	65%	70%	70%
After January 2026	65%	70%	80%

In this Concawe's assessment, the default GHG intensity values used as references are derived from both RED II, JEC WTW v5 and SGAB[36] for the 2020-2030 timeframe while providing a longer-term perspective showing potential improvement in the production pathways towards 2050 (e.g. energy efficiency improvement, process electrification with low-carbon intensity electricity and an increasingly use of feedstocks with lower WTW emission factors, leading to some additional GHG savings in the 2030-2050 period).

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[33] Carbon Recycling International (Svartsengi, Iceland). Capacity: 4,000 t/y e-methanol (6 MW electrolysis).

[34] https://www.reuters.com/article/total-sunfire-hydrogen-idUSL5N26N4BY (500t/y of e-methanol in the first three years) in Leuna refinery in Germany, starting in 2021).

[35] JEC WTT, WTW v5 reports (https://ec.europa.eu/jrc/en/jec/activities/wtw). ILUC not included.

[36] "Building up the Future - Cost of Biofuel", SGAB https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33288&no=1

The following GHG savings have been considered in this assessment for the different type of technologies selected as examples:

Table 9 Assumed WTW GHG reduction (end-points) versus reference fossil fuel (diesel)

WTW GHG reduction vs fossil	**2030**	**2050**
Source	**RED II / SGAB / JEC WTW v5**	**Concawe[37]**
Food-feed crop biofuels ('Conventional / 1G') (*)	65%	70%
Advanced biofuels / Non food-crop	75%	85%
e-fuels (**)	~95%	

Notes.

(*) In the absence of a 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 low carbon liquid fuels towards 2050 as the energy demand in transport is reduced.

(**) Renewable electricity

3.3.2.2. Plant size/investment estimate

The size and investment requirement for future low carbon liquid plants is quite uncertain at this stage depending on the level of development/deployment of the technology:

- For HVO, which exists at industrial scale there is a number of examples of commercial plants where the reported CAPEX and size can be used as a reference (e.g. HVO La Mède in a Total refinery in France with 500 kt/y capacity).
- For some of the other technologies, at earlier stages of development/scale-up as described in section 3.3.2, the numbers below should be taken as Concawe's best estimate. In this regard, a low and high range is reported which is also aligned with other references [IEA 2019][38] [Hannula and Reiner 2019] [39] and previous Concawe's estimate [Concawe 9/19].

Table 10 New built-plants(*): capacity and CAPEX

Basis (per plant)	Capacity - Industrial scale (**) (Mtoe/y)	CAPEX(*****) (M€)	CAPEX intensity (M€/ktoe/y)
New-built HVO plant	0.5	275	0.55
BTL plants (***) (Lignocellulosic)	0.15	610 -900	4.0 - 6.0
e-fuels	0.2 (****)	400 - 650(*****)	2.0 - 3.3

Notes.

(*) Due to the cap on food-crop based biofuels as well as used cooking oil and animal fat, no investment on additional capacity is envisaged towards 2050, increasing the utilization rate of existing plants when required.

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[37] Concawe's estimate in line with [Ricardo 2018]. Potential reduction in production processes due to additional energy efficiency measures and electrification of processes (e.g. Replacement of H_2 production by Clean H_2), reduction in emissions in the transport step, etc.

[38] https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf.

[39] *Near-Term Potential of Biofuels, Electrofuels, and Battery Electric Vehicles in Decarbonizing Road Transport*, I. Hannula, D. Reiner. 20019. https://www.cell.com/joule/fulltext/S2542-4351(19)30416-7

(**) In the absence of commercial plants, the capacity of the future industrial units is quite uncertain. Factors such as availability and accessibility to local resources in a sustainable way as well as decentralised versus centralised models (with or without integration/co-locations within the refinery site) may impact severely the economy of scale.

(***) As an example of the potential technologies to process lignocellulosic/waste-like feedstocks, the *Biomass-to-Liquid* technology has been chosen based on the 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 the thermal liquefaction processes, are deemed to offer less CAPEX intense routes (up to ~50% [Concawe 9/19]) and could be also deployed in parallel to this BTL route (as a simplification, not included in this analysis because of their lower TRL. Higher capacity plants could also be foreseen, benefitting from some CAPEX optimisation. 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) has been preferred with an impact on a higher number of plants / investment requirement by 2050. Besides this, it is relevant to note that H_2 consumption is considered as an OPEX and, therefore, new potential H_2 production units that may need to be built are not included in the estimated investment. The synergies with the existing H_2 production units as fossil fuel is progressively replaced have been investigated in the Concawe *Refinery 2050* report [Concawe 9/19] and potential synergies between existing sites and new plants during the transition would need to be investigated in more detail.

(****) 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 reduction (see Figure 5.4.2-1 in Concawe 9/19 report). 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). Regarding the origin of the CO_2, this assessment does not differentiate between direct air capture (DAC) technologies or CO_2 captured from concentrated sources recognizing that different energy consumptions and CAPEX (higher in the case of the DAC) would be required.

(*****) As a simplification, as those plants are not existing today and due to the uncertainty around the CAPEX figures, we have not attempted to estimate any learning rates and the estimated CAPEX has been used throughout the whole timeframe until 2050 (As a reference, some details on potential cost reduction for some key low carbon fuel technologies are included as an **Appendix 2** [IEA 2019]. Besides this, feedstock costs are considered as OPEX for the purpose of this initial assessment and therefore, additional potential and non-negligible investment to source and procure raw materials may be required depending on the selected business model, company and regional specific.

3.4. CO_2 REDUCTION TECHNOLOGIES - CLEAN H_2 AND CCS AS KEY ENABLERS

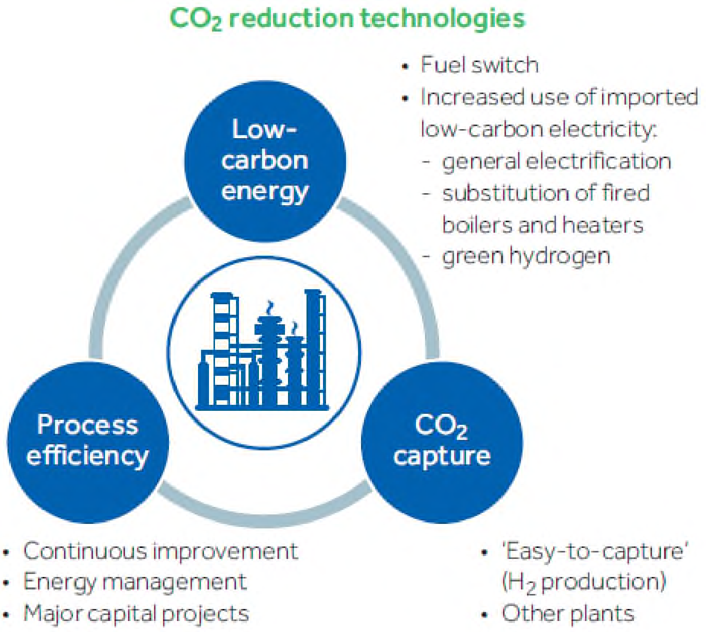
Technologies: CO_2 reduction technologies integrated within the EU refining system such as energy efficiency measures, use of low carbon energy sources (e.g. Clean H_2) and Carbon Capture and Storage (CCS).

TRL: 7-9 (Novel technologies in development)

Details: For the purpose of this assessment, the selected *Clean H_2* routes include H_2 through water electrolysis and H_2 produced by Steam methane reforming (of biomass or natural gas) coupled with Carbon Capture and Storage schemes.

As mentioned in Section 3.2, there is a number of CO_2 reduction technologies which offer potential ways to mitigate the CO_2 emissions at refining site with a positive impact on reducing the WTT carbon intensity of the final fuels. These technologies, their potential savings and estimate investment requirements are widely described in the Concawe report [CO_2 technologies, Concawe 8/19].

Figure 17 CO_2 reduction technologies covered in the Concawe CO_2 technology report [Concawe 8/19]



For this assessment, we are referring to the potential CO_2 emissions which could be potentially reduced by the progressive implementation of two selected examples: *Clean H_2* and Carbon Capture and Storage (CCS) technologies within the European refining system.

It is worth noting that these technologies, with the potential to be integrated within the refining scheme in the short-term, are deemed to be key enablers and accelerators of other future low carbon technologies as:

- H_2 is a key feedstock in both biofuel (enhancing carbon efficiency) and e-fuel production (as key feedstock)

  Besides this, H_2 has also been identified as a critical element in other sector's low-CO_2 routes towards 2050 - including chemicals, iron and steel.

  Therefore, investing in *Clean H_2* technologies at an early stage, replacing H_2 production routes within the current refineries, will contribute to accelerate the path towards industrial scale-up and wide deployment of technologies such as electrolysers.

- Carbon capture is also a key element when reaching the EU climate change objectives. Enhancing and deployment of CO_2 capture technologies within the refineries will pave the way not only for Carbon Capture and Usage (CCU) schemes (e.g. e-fuels production routes where CO_2 is the main feedstock) but also for routes to achieve negative emissions (through the BECCS schemes integrated / co-located within the same refinery sites (see section 3.3.1.2.2).

The summary of these selected technologies and their potential to abate CO_2 emissions is described hereafter.

3.4.1. Clean Hydrogen

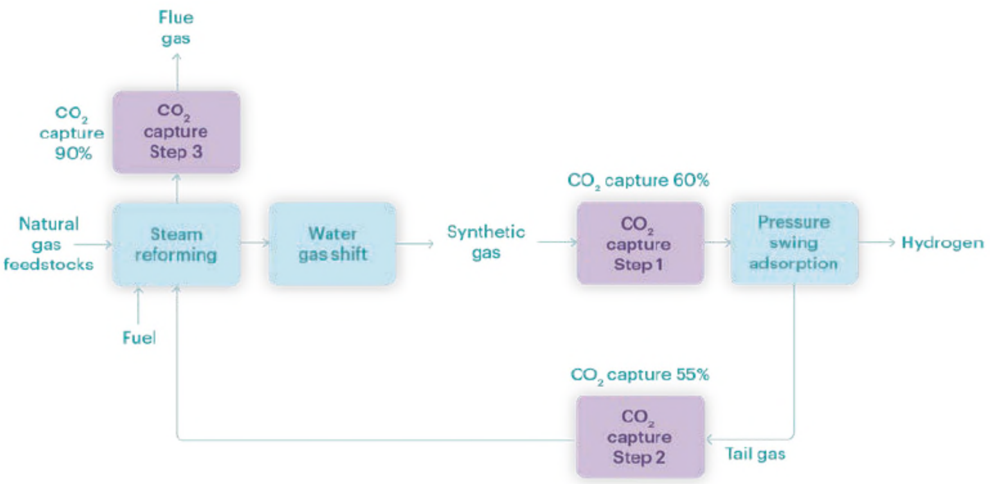
As described, the routes towards the integration of 'Clean H_2' in refineries include the replacement of conventional H_2 production routes in the EU refining system today by alternative low CO_2 intensive pathways initially as a way to reduce the carbon intensity of fossil-based fuels, potentially and progressively using the already installed capacity afterwards for biofuel and/or e-fuel production as a certain refining site transitions towards the deployment of new conversion units (Section 3.3). A brief description of these pathways is included below:

a) *Low-carbon hydrogen ('Blue' H_2)*

This route includes hydrogen production through mainly natural gas steam reforming (SMRs) as the most widespread technology at larger scale, coupled with CCUS schemes.

In this case, natural gas is used both as a fuel and as a feedstock and different CO_2 streams are produced as a result of the combustion as well as 'process' related CO_2. In this scheme, the diluted CO_2 emitted is captured and either used (e.g. for e-fuel production) or sent to a storage facility.

Figure 18 Production process of H_2 from natural gas steam reforming (SMR) coupled with Carbon Capture schemes



Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

This scheme is well known with several industrial plants in operation nowadays. When applied to refineries, different studies are reporting a CO_2 capture rate > 70% (e.g. [SINTEF 2017]).

b) *Renewable hydrogen ('Green' H_2). E.g. Water electrolysis*

An additional route to reduce GHG emissions during the H_2 production process is through the electrolysis of water using renewable electricity.

This is a pathway still not widely available at industrial scale (IEA reports ~0.1% of dedicated production globally[40]) and as a critical parameter for cost reduction, larger electrolyser projects are needed to demonstrate accelerated

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[40] https://www.iea.org/hydrogen2019/

scale-up. In this sense, there is a number of EU funded R&D projects where O&G companies are actively working on the development of water electrolysers within existing refineries. As some examples:

- REFHYNE[41] project, installing a 10 MW electrolyser in one refinery from Shell in Germany started up in July 2021[42], with the aim of expanding it to 100 MW electrolyser capacity under the new REFHYNE II project.
- More recently, REPSOL has announced the installation of a 10 MW electrolyser, signing a memorandum of understanding with Aramco to carry out the technological development of the project of an e-fuel plant in a refinery located in Spain by 2024[43].
- The project *H_2-Fifty* targeting the construction of a 250 MW electrolyser, operated by BP and Nouryon and expected to become operational in 2025 in the Port of Rotterdam[44].
- Several Danish companies (Copenhagen Airports, A.P. Moller - Maersk, DSV Panalpina, DFDS, SAS and Ørsted) have also announced the first partnership of its kind to develop an industrial-scale production facility to produce sustainable fuels in the Copenhagen area, deploying one of the world's largest electrolysers (250MW electrolyser facility which could be operational by 2027 and produce 1.3 GW by 2030)[45].

Besides the challenges on the technology scale-up and the intermittency issue of renewables, the hydrogen infrastructure is still not in place for the massive use of this product and O&G companies are also actively involved in developing *Green H_2* hubs[46] in industrial areas to accelerate this deployment. In this regard, Low- carbon H_2 , '*blue*' H_2, is also seen as a potential accelerator for the further deployment of Clean H_2 (*H-vision* project)[47].

3.4.2. Carbon Capture and Storage

The concept of capturing the CO_2 produced by combustion or other conversion processes and storing by injecting it into suitable geological formations has been gaining credibility in the last few years, especially after the *Conference of Parties* (COP 21) in December 2015, where the need of deep-cut CO_2 technologies such as *Carbon Capture and Storage* (CCS) has been emphasized. Besides this, in *A Clean Planet for all*, CCS and CCU have been identified as key technologies in all 2050 scenarios.

- Technology (CCUS):

  The carbon capture CO_2 technology is a process that involves the separation of CO_2 from other gases, compression and liquefaction, transport (by pipeline or ships) to the point of injection and injection under pressure.

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[41] https://refhyne.eu/ (10 MW equivalent to ¬ 1.3 kt Hydrogen/y)

[42] https://www.shell.com/media/news-and-media-releases/2021/shell-starts-up-europes-largest-pem-green-hydrogen-electrolyser.html

[43] https://www.spglobal.com/platts/en/market-insights/latest-news/coal/061520-spains-repsol-to-develop-hydrogen-fed-synthetic-fuel-plant-at-bilbao

[44] https://www.portofrotterdam.com/en/news-and-press-releases/rotterdam-boosts-hydrogen-economy-with-new-infrastructure

[45] https://orsted.com/en/media/newsroom/news/2020/05/485023045545315

[46] https://www.h2-view.com/story/shell-wants-to-create-a-green-hydrogen-hub-in-the-port-of-rotterdam/

[47] https://www.deltalinqs.nl/stream/h-vision-final-report-blue-hydrogen-as-accelerator

Separation of CO_2 from other gases can be made by various technologies, and among them some, like amine-based processes, are based on already well-established ones (TRL >7). Other emerging technologies[48], described in a recent Concawe report [CCS, Concawe 18/20] are also in different stages of development.

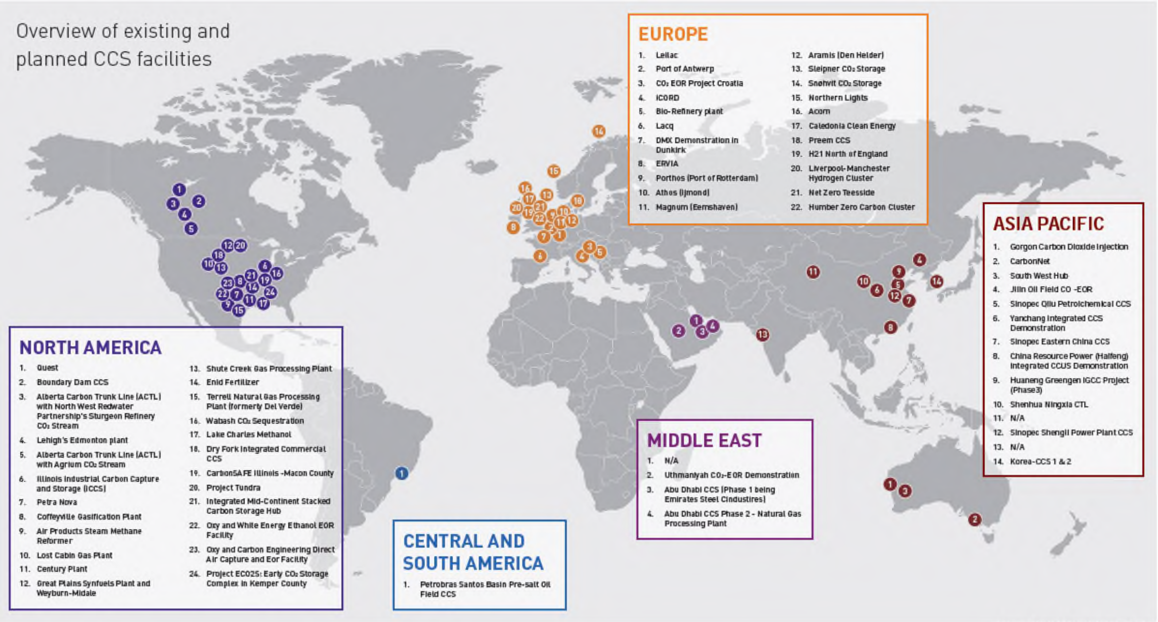
Regarding the accessibility to storage locations, there are many such structures available in most areas of the globe from depleted gas and oil fields to salt domes and aquifers where CO_2 could be stored in the long-term. CCS storage capacity potential for Europe varies between sources. From 300 $GtCO_2$ estimated by GCCSI [GCCSI 2019[49]] to a more conservative estimate [GeoCapacity 2009] of about 117 Gt CO_2.

Alternatively, to this storage route, once CO_2 is captured either from a concentrated source or directly from air (Direct Air Capture, DAC), it can be used as a feedstock for the production of fuels, carbonates, or other chemicals; this possibility is referred as Carbon Capture and Utilisation (CCU).

- Examples:

As examples of commercial scale, CCS is being undertaken in industries such as natural gas processing, fertilizer production, hydrogen production, coal gasification and iron and steel production worldwide. Globally, 43 large-scale CCS facilities (18 in commercial operation, 5 under construction and 20 in various stages of development) are reported around the world [GCCSI 2019].

Figure 19 Global CCS projects (IOGP 2020)



Source: Global CCS Institute and IOGP data

Several of those are pilot projects already in operation in the oil and gas industry. More specifically, in Europe, there are currently two operating CCS large-scale sites both in Norway [*Sleipner* and *Snovhit*] and some other projects are in development. Some relevant examples for the EU refining industry are mentioned below:

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[48] In Nov 2019, ExxonMobil and FuelCell Energy, Inc., signed a new two-year expanded joint-development agreement to develop carbonate fuel cell technology to capture carbon dioxide from industrial facilities.

[49] GCCSI 2019, Global CCS Institute (GCCSI): The Global Status of CCS 2018; February 2019

- ***Norway Full Chain CCS project***: Oil & gas majors such as Shell, Statoil, and Total are collaborating on the transport and storage elements of CCS demonstration *('Northern Lights' project)*, of which, the Norwegian government has progressed to the FEED stage. CO_2 will be captured at Norcem's cement plant in Brevik and at Fortum waste-to-energy plant in Oslo (400 kt CO_2/y from each plant) and stored in the North Sea. The Norwegian government, Shell, Equinor and Total have recently announced their investment decision on its demonstration project, which is expected to be operational by 2024[50].
- A joint project in the Port of Rotterdam aims to establish a common infrastructure to collect CO_2 captured from a variety of refineries in the area (2-5 Mt CO_2/y) and store it in empty gas fields in the North Sea by end 2023. The signed agreement includes companies such as ExxonMobil, Shell, Air Liquide and Air Products, for the capture step, while the transport and storage step is being prepared by *Porthos*, a project organisation from EBN, Gasunie and the Port of Rotterdam Authority[51].
- Similarly, another CO_2 reduction project in the Port of Antwerp (*Antwerp@C*[52]) is an example of consortiums being built and funded by EU COM to support CCUS schemes. In this case, the consortium consists of Air Liquide, BASF, Borealis, ExxonMobil, INEOS, Fluxys, Port of Antwerp and Total and its ambition is to reduce ~19 M t GHG within the port by 2030.

Following the same rationale as with the Clean H_2, new CCS plants linked to oil-based refineries will reduce the WTW GHG intensity of conventional diesel in the very short-medium timeframe. Towards 2050, as refineries integrate other alternative feedstocks replacing oil, these already installed CCS plants will be well suited to enable negative emissions (BECCS schemes) as they could capture and store the biogenic CO_2 produced during the combustion process of the biomass in the new BTL schemes. These negative emissions could compensate the GHG derived from the remaining use of fossil fuels in the hard-to-abate sectors such as aviation (Additional details in **Section 4.2.1** / **Figure** 27 [EU COM 2018]).

3.4.3. GHG potential reduction & plant size/investment estimate. Basis

As the basis for this assessment, the information and estimate from a previous Low Carbon Pathways' Concawe report [CO_2 technologies, Concawe 8/19] is directly used. This report assesses the potential role of the CO_2 reduction technologies within the EU refining system (not linked to any alternative feedstock related modifications) exploring both 2030 and 2050 scenario, assessing the required capacity based on the fossil fuel production as a way to reduce the remaining WTT emissions. It is worth noting that the installed capacity can potentially utilised later for / linked to biofuel and/or e-fuel production, as the refining system transition towards alternative feedstock with clear synergies in terms of CAPEX reduction, not considered in detailed within the scope of this analysis:

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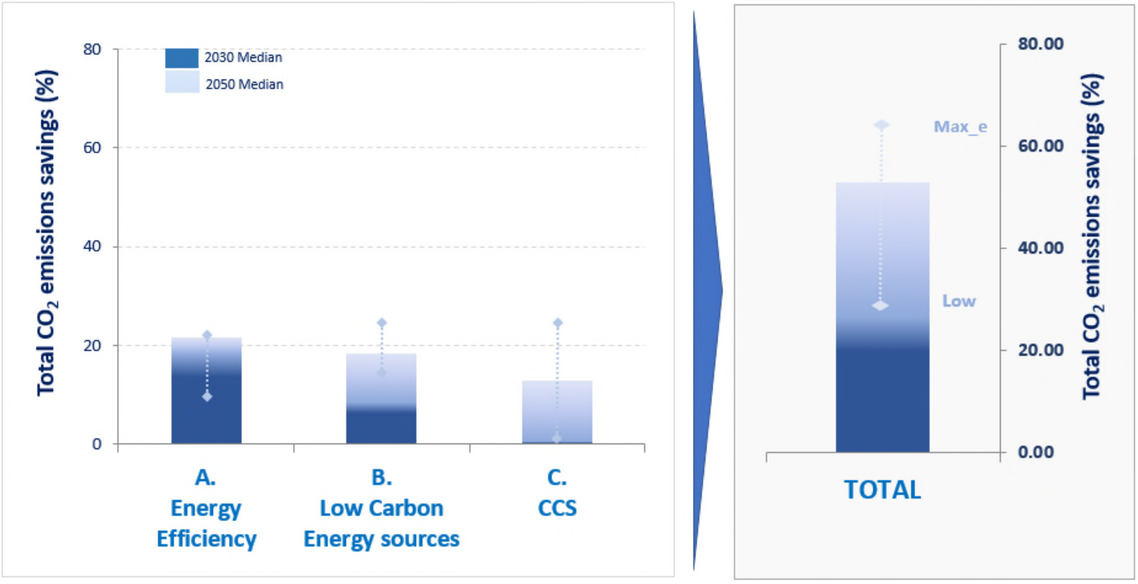
[50] https://www.nsenergybusiness.com/news/company-news/northern-lights-ccs-norway-investment/

[51] https://www.portofrotterdam.com/en/news-and-press-releases/ccs-project-porthos-a-step-closer

[52] https://newsroom.portofantwerp.com/eu-supports-antwerpc-innovative-co2-reduction-project-by-granting-cef-funding

Figure 20 Cumulative total emission savings. Source: Concawe [CO_2 technologies, Concawe 8/19]



Note: Electrification may account for up to ~23% of the CO_2 reduction in the 2050 High electrification sensitivity case. This incurs significant additional capex outside the refinery not included in the scope of this assessment.

Based on the Concawe report, this analysis assumes a WTT GHG reduction based on CO_{2eq} reduction technologies such as energy efficiency, Clean H_2 and CCS plants of **25% by 2030 and up to 60% by 2050**[53] with the following CAPEX per site:

Table 11 Basis for Clean H_2 and CCS: CO_2 avoided and CAPEX per site.

Basis	CO_2 avoided (per site) Mt CO_2/y	CAPEX (M€) (***) per site
Clean H_2 (E.g.Electrolyser) (*)	0.3	~150
CCS (**)	1.0	~500

Notes. Summary of calculations based on [CO_2 technologies, Concawe 8/19]:

(*) Clean H_2 (Water electrolysis as selected example of the technology):

- GHG emissions in a 'notional/average' EU refinery: ~1.6 Mt CO_2 (~20% of the emissions per site due to SMR) → 0.3 Mt CO_2/y max potential reduction due to SMR replacement by Clean H_2 schemes / per site.
- Total CO_2 reduction emission within refining EU system due to H_2: ~4 Mt CO_2/saved with associated CAPEX of ~1900 M€ at EU level (*Reference 2050 - Max H_2 case*) → 12 installations required / ~150 M€ per site.

(**) Carbon Capture and Storage

- Potential reduction savings: in the previous Concawe report, ~25% of the emissions of the total EU system (once electrolytic H_2 and other electrification measures have been implemented) could be captured and stored (*max case* in **Figure 21** / category C: CCS). Based on an estimated capacity of 1 Mt CO_2/y[54] per CCS plant for an average refinery.

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[53] As a simplification, only Clean H_2 and CCS technologies will be used to estimate the timeframe / required CAPEX in this assessment. Therefore, the additional CO_2 reduction technologies identified in this study such as energy efficiency or electrification) have been included in this analysis as additional $CCS_{equivalent}$ plants (to achieve the 60% GHG reduction estimated in the Concawe 8/19 report).

[54] Note that, as mentioned earlier, CCS technology has been chosen, as a simplified approach, to quantify the whole potential for CO_2 reduction in the EU system due to additional CO_2 reduction technologies (Clean H_2 excluded). Therefore, the number of total $CCS_{equivalent}$ plants are reported in Section 4.1 *New plants*).

- CAPEX: In the Concawe report, the CAPEX estimate is ~400 M€/t/y for CCS schemes when applied to overall refinery emissions. As a simplification, it has been assumed that CO_2 captured from SMR are less CAPEX intensive and will be progressively reduced towards 2050 (in line with the assumption on replacement with electrolytic H_2). As a result, the CAPEX estimate has been estimated at ~500 M€/site for diluted sources (including 15% of additional CAPEX due to transport and storage), assumed constant through the whole time period.

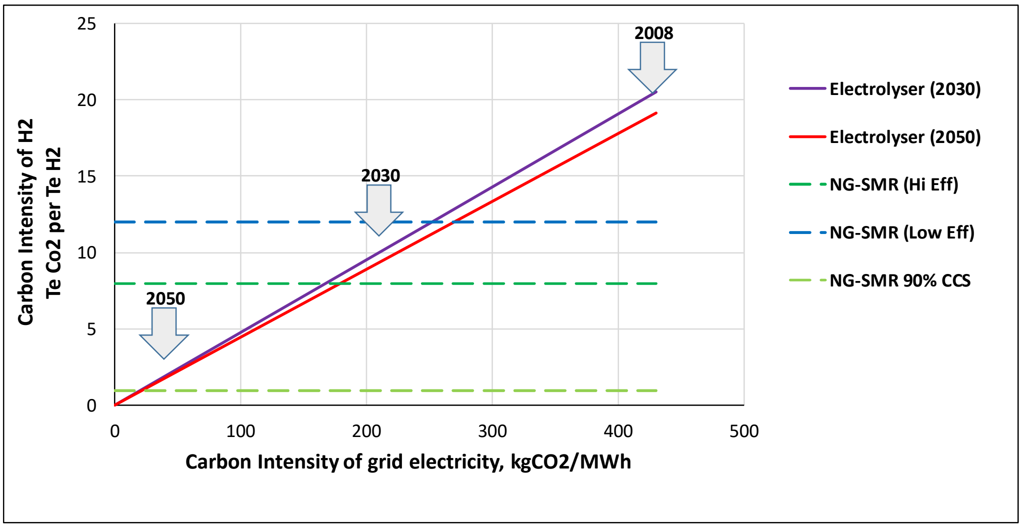
(***) As a simplification, in both cases, the potential CAPEX reduction due to the development and scale-up of the technologies has not been considered.

Additional details on the specific assumptions, technologies on GHG reduction potential, size and investment of the Clean H_2 and CCS in the EU refining system (as a whole) are summarized below:

a) **Clean Hydrogen:**

The **Figure 21** compares the carbon intensities (tons CO_2 per ton hydrogen) of the various options at different CO_2 emission-factors for the electricity grid. It suggests that electrolysis using grid-mix electricity would not be carbon efficient compared to standard SMR until about 2030 and compete with SMR + CO_2 capture options when the grid reaches higher levels of decarbonisation (2050 horizon).

Figure 21 CO_2 intensity of hydrogen production routes via SMR or electrolysis [CO_2 technologies, Concawe 8/19]



Note that, in 2030, emissions from SMR (no CCS) and electrolysis are virtually the same.

As a representative example of Clean H_2, the water electrolysis route has been used for this assessment based on the following assumptions [CO_2 technology, Concawe 8/19]:

- Electrolysis is being developed for both small-scale (distributed) and large-scale (centralised) hydrogen production. Low-temperature electrolysis (e.g. PEM electrolysers) may suit both applications; high-temperature electrolysis (e.g. solid-oxide electrolysers) are thought to offer better efficiency but might be limited to centralised applications. Estimates from literature for CAPEX, OPEX and efficiency vary within a wide range and most sources assume that the specific capital cost will fall significantly over this period due to improved efficiency and operation at higher current densities. The figures reported in [CO_2 technology, Concawe 8/19] are used:

Table 12 Efficiency and cost of electrolysers

Case	2030	2050
Efficiency %	70%	75%
Capacity Factor	85%	85%
Initial capex, \$/kW-H_2	1000	650
Fixed opex, % of capex	5%	5%

Note: based on lower heating values

- **Quantification**

Supply of low-cost carbon-free electricity (in times of surplus) is considered to be available 10% of the time. Not all refineries would invest in electrolysers so that only a fraction of the refinery hydrogen production capacity would be concerned (up to 25% by 2030 and up to 50% by 2050).

Continuous production would only be in place by 2050 when the standard grid electricity is substantially decarbonized (2050). We have assumed that it would concern up to an additional 35% of the demand, this figure being also limited by the availability of internal fuels. It could be increased to 50% of the demand if CO_2 capture was introduced at scale (because this would create an additional energy demand).

Electrolyser CAPEX, equivalent to 4.2 and 2.6 €/kg H_2 annual production capacity in 2030 and 2050 respectively. This was considered as refinery investment and as such accounted for in the total CAPEX and OPEX figures.

b) Carbon Capture and Storage (CCS):

Individual refineries are relatively large CO_2 emitters (typically several Mt/a) as a combination of a number of separate sources. The larger refinery sources of CO_2 are fired heaters, FCC units and hydrogen plants. CO_2 concentration also varies a great deal from concentrated streams from hydrogen plants (actual concentration depends on the technology) to low concentration combustion flue gases.

CO_2 capture in refineries has been reviewed extensively by Concawe [Concawe 7/11] indicating costs of 80-180 €/t CO_2 mitigated depending on source, scale and technology. A recent update by SINTEF [SINTEF 2017] focussing on retrofitting CO_2 capture to refineries suggests costs of 160-200 €/t CO_2 (costs are likely to be lower for emissions from hydrogen plants).

Quantification

For participating sites, we have assumed that 90% of hydrogen-related emissions - when no electrolysers are installed - would be captured. The balance would bring the total proportion of emissions captured at a given site to 70% (in line with [SINTEF 2017[55]]).

Energy consumption, CAPEX and OPEX were taken from DNV GL, 2018 for hydrogen-related emissions and SINTEF, 2017 for the balance. The cost figure for transport and storage is highly uncertain (as an estimate, we have included a notional cost of 15 €/t CO_2 avoided [Concawe 7/11]).

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[55] https://www.sintef.no/en/projects/recap/

Table 13 CO$_2$ Capture parameters

		Hydrogen-related	Generic
Capex	€/(t/a CO2 avoidance capacity	300	419
Capital charge @15%	€/t CO2 avoided	45	63
Opex	€/t CO2 avoided	12	30
Energy	GJ/t CO2 avoided	1.1	8.1

Note. Capex Capital charge@15% refers to the annualized CAPEX assuming 15% capital charge divided by annual CO$_2$ savings (t CO$_2$/a). This does not include OPEX. OPEX included in the table are non-energy related ones.

4. RESULTS

4.1. LOW CARBON LIQUID PROJECTIONS TOWARDS 2050. SUMMARY

Based on the assumptions described in previous sections and considering the technology readiness levels (TRL) of the different technologies and feedstocks analyses as well as the time to develop, construct and start-up new plants, different theoretical scenarios with an associated timeline have been explored based on the following key educated assumptions:

- *Food-crop based biofuels ('1G')*

  As described in section 3.3.1.1, we have assumed that no additional capacity is installed from 2020 onwards, maximising its utilization towards the maximum 7% cap as defined by RED II. In the absence of another framework beyond 2030, the % cap is kept constant until 2050) and capacity is reduced in line with the Fuels demand.

- *Hydrotreated Vegetable Oils ('HVO')*

  Based on the current installed capacity, we have assumed that another full-industrial scale site starts to be built in the early 20s, in full operation in 2024 and followed by a number of additional plants being built in the 2020-2030 timeframe. We have assumed double capacity in 2030 versus 2020 and, as an assumption, no additional plants beyond 2030 due to potential limitations in feedstock availability in Europe.

  It is important to note that:

  - Additional routes to alternative sustainable feedstocks, recognized as advanced biofuels, could potentially leverage additional installed capacity in the 2030/2050 timeframe.
  - HVO is also being co-processed in several refinery sites nowadays. As a simplification and as an estimate of the potential, we are focusing this assessment on new full revamps/built plants of industrial scale as defined in Section 3.3.2.2.

- *Lignocellulosic residues / wastes ('BTL')*

  In this case, BTL technology has been chosen as a representative technology of advanced biofuel processes (See section 3.3.1.2.2 / 3.3.2.2). In an accelerated R&D scenario, we have assumed an optimistic case where:

  - Additional efforts on developing/scaling-up the technology at industrial scale are pursued in the early 20s so that the first-of-a-kind industrial site could be in operation in 2023. The date for this first industrial plant is, of course, tentative and will play a major role on the timeframe for the deployment of the successive plants as tentatively defined in this theoretical assessment.
  - Immediate engineering and construction of second-of-a-kind plants will follow, integrating initial learning from the operation of the first plant during its first year of operation. Based on that, the progressive deployment of the second wave of plants has been delayed until early 2027 but with a rapid mass deployment right after.
  - This assumes an accelerated build-up of a **sustainable supply chain** being developed in parallel to the engineering / construction phase of the first industrial sites during this timeframe. This implies an unprecedented risk

(business plans) for the companies involved in the construction of the BTL technologies as the supply chain of lignocellulosic/waste materials is currently at its very early stages of development. Industrial hubs are likely to play a key role here as additional joint efforts of a number of different stakeholders across the whole value chain are deemed to be required (e.g. access to sustainable resources, mobilization and transport to industrial conversion sites).

  - It is worthy of note that, whereas we have focused this analysis on drop-in fuels (compatible with the existing vehicles, infrastructure), some additional ethanol lignocellulosic-based plants could become also available at industrial scale within this timeframe (Ethanol penetration limited by the current blending walls to E10 grade so far). As a simplification, the impact of further increase on this ethanol blend has not been explored in this analysis.

- *E-fuels*

  With similar challenges as the BTL technologies in terms of the Fischer-Tropsch technologies and assuming a big incentive based on R&D efforts in scaling up water electrolysers, and developing industrial size Reverse Water-Gas Shift, the deployment of the first-of-a-kind e-fuel industrial size is delayed until 2025+ in our assessment (a little bit more conservative than some recent announcements and subject to confirmation as the technology is developed).

  - The mass deployment has been estimated to happen four years later assuming that accessibility to renewable electricity at an affordable price is granted in Europe. The possibility to import e-fuels from other parts of the world is not integrated in this study and is currently being explored in another soon-to-be-published Concawe report.

- *CO_2 reduction technologies (E.g. Energy efficiency, CCS and Clean H_2)*

  As a simplification for this conceptual assessment:

  - Based on the projects already in well-advanced phases and considering additional R&D efforts on the electrolyser scale-up in the coming years, the first-of-a-kind industrial scale units for both CCS and industrial electrolysers in the refining industry are envisaged to happen in 2023 with a progressive deployment of additional projects/units already in the pipeline the years after (2025+).
  - It is important to mention that, as a simplification and to give an estimate on the potential role of energy efficiency measures and other technologies as described in CO_2 technology report [Concawe 8/19], additional 'CCS equivalent' plants have been included in the assessment to reflect the potential reduction on CO_2 savings within the EU refining system (described in section 3.4.3). These additional plants exclude Clean H_2 units which are assessed independently.
  - It is also worth reminding that both CCS and H_2 technologies, initially installed to reduce the WTT intensity of the remaining diesel/gasoline fuels, will continue to function when alternative feedstocks will be processed (as H_2 demand to process low carbon feedstocks will increase and CCS will play a role, for example, in achieving negative emissions when coupled with BTL technologies).

Based on the comments mentioned above, an ambitious timeframe has been defined as summarized in **Figure 22** for Scenario 1 (as an example of the potential towards 2050).

Figure 22 Summary. New plants scale-up and timeframe towards mass deployment (Scenario 1 – Selected as an illustrative example)

Source: Concawe's theoretical assessment ('Alternative 1.5°C' scenario for transport (Road, Aviation & Maritime).

Note. This analysis is to be considered as a theoretical assessment on a potential trajectory to contribute to EU climate targets and, as such, only a limited number of low carbon feedstocks and technologies with different TRLs have been chosen as a simplification. Therefore, this document is not intended to be 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 scale-up of the different technologies presented and their related value chain. This assessment provides an example of a potential accelerated trajectory that could contribute to reach climate neutrality in transport by 2050.

As a result of the simplified modelling conducted based on the assumptions described, the implications of the three scenarios (trajectories) for the development and mass-deployment of Low Carbon fuels in transport are presented hereafter. In this context, the following sections summarise the foreseen LCLF volumes and estimate on the GHG reduction levels for each of the scenarios. The investment requirements are directly inferred from the deployment of new units (Section 4.1) and their associated CAPEX (Sections 3.3.2 & 3.4.3) and are deemed to be considered as the best available estimate of order of magnitude for investment costs, as technologies are still to be developed at industrial scale.

Figure 23 Summary. Volumes of Low Carbon Liquid Fuels estimate in the three Concawe's scenarios (S1/S2/S3).

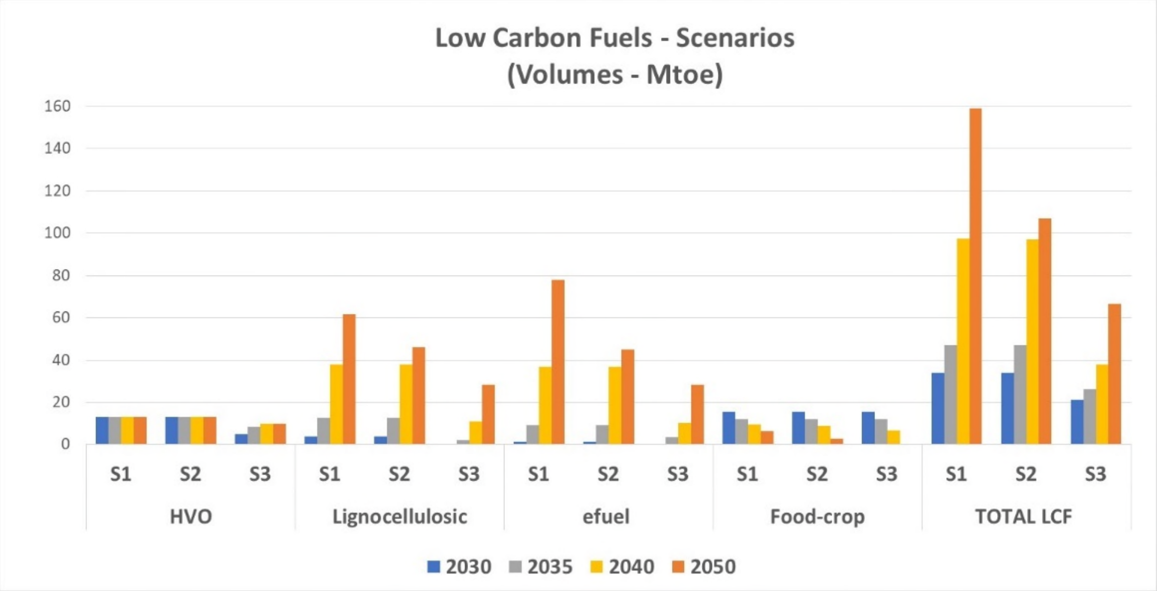


Figure 24 Summary. Investment required for the deployment of Low Carbon Liquid Fuels in the three explored Concawe scenarios.

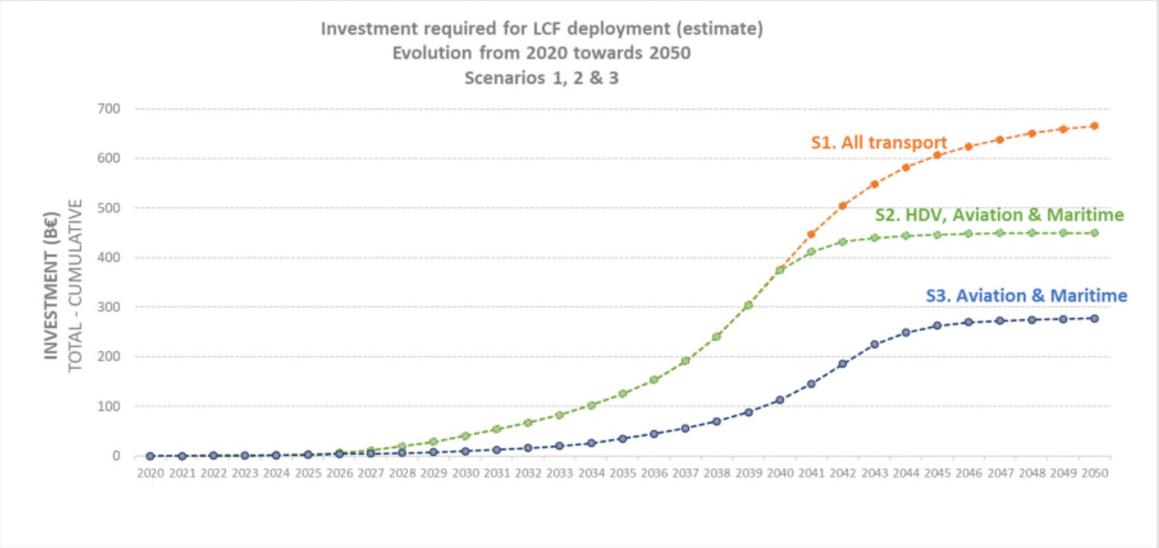
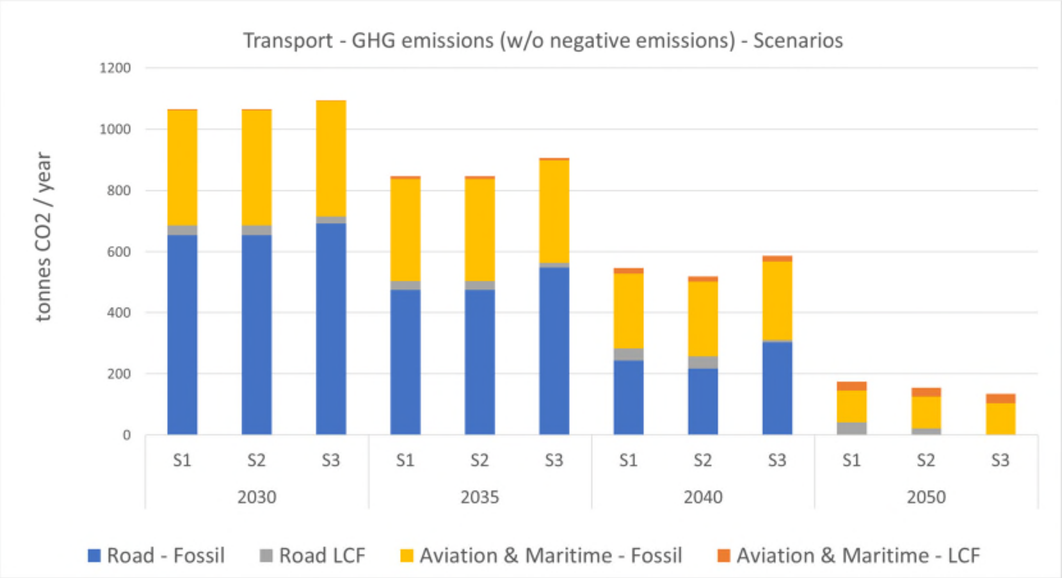


Figure 25 Summary. GHG emissions trajectory. Scenario comparison.



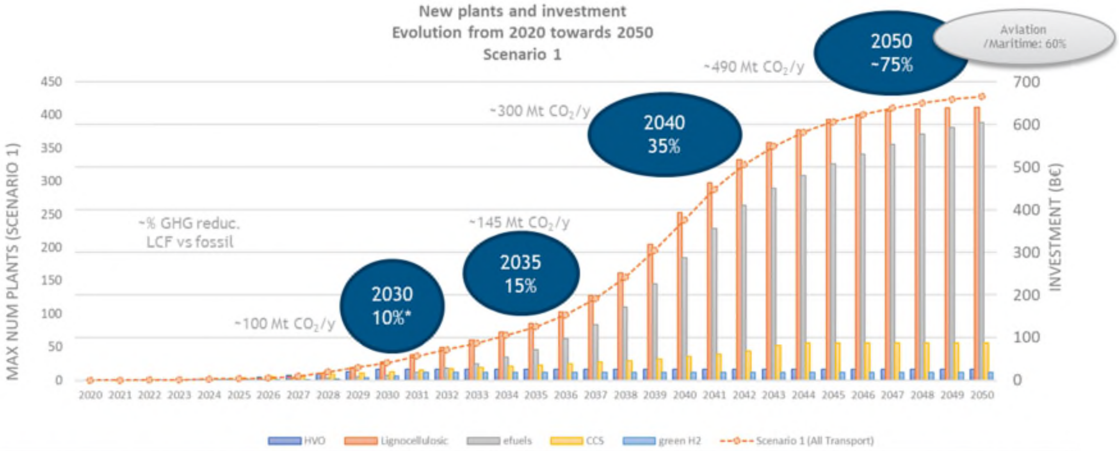
Note. The application of BECCS schemes to the biofuel production routes explored in this report are estimated to produce negative GHG emissions ranging between 20-60 Mt CO_{2eq}/y.

4.2. SCENARIO #1: ALL TRANSPORT SECTOR

4.2.1. Summary

This section summarizes the high end-case scenario in which Low Carbon Fuels are deployed across the whole transport sector. The following figure illustrates the level of low carbon fuel volumes, investment, new biofuel/e-fuel plants and additional CO_2 reduction levels which could be achieved when road, aviation and maritime sectors are integrated in a holistic picture:

Figure 26 Summary of ‘1.5 alternative’ scenario 1: Projections. Transport sector (Road, Aviation & Maritime)



Cumulative (Transport)	2020-2030	2020-2035	2020-2040	2020-2050
Total volume LCF (Mtoe)*	~30	~50	~100	~160
Total new plants (bio+efuels)	~50	~150	~450	~820
Total investment, B€*	~30-40	~90-120	~250-380	~440-670
Ratio of investment, B€/y	~5 (2020/2030)	~35 (2030-2040)		~30 (2040-2050)

** For road, GHG reduction compared to the 2030 WTW GHG intensity of 100% fossil fuel in Road transport (Light Duty (LDV) and Heavy Duty vehicles (HDV))*

** Aviation and Maritime - GHG reduction compared to a scenario where all the demand for liquid fuels is satisfied by 100% fossil fuel*

The main figures behind this scenario 1 are presented in the table below (detailed data included in **Appendix 4**):

Table 14 Summary of trajectory towards alternative 1.5°C scenario (Scenario 1)

Transport (Road, Aviation & Maritime)			2030	2035	2040	**2050 (Alt 1.5° - Concawe)**
Volumes	Total energy demand	Mtoe/y	352	316	280	209
	Total demand for liquid fuels		337	285	243	191
	Food-crop based '1G'		16	12	9	7
	Advanced / Non-food crops (HVO+BTL)		17	29	49	73
	e-fuels		1	6	38	79
	Total LCF		34	47	97	159
	Total liquid fossil fuel		303	238	146	32
	% LCF in total liquid fuels		~10%	~15%	~40%	~80%
Num. plants / units	Num total plants (Bio+e-fuel)	-	50	146	453	817
	Num plants (CCS_{eq}+Green H_2)	-	19	35	48	68
Investment	Total investment (min) - Cumulative	B€	31	88	254	445
	Total investment (max) - Cumulative		41	125	376	666
GHG savings	WTT savings	%	25%	30%	45%	60%
	WTW GHG intensity (LCF reduction vs fossil)	%	**~71%**	**~77%**	**~83%**	**~90%**
	WTW savings (Total GHG reduction vs 100% fossil)	%	9%	15%	35%	74%
	% WTW savings due to LCF in total demand for liquid fuels – Aviation/Maritime (**)	%	~4%	~11%	30%	60% (***)
	GHG Savings – LCF	Mt CO_2/y	105	145	300	490

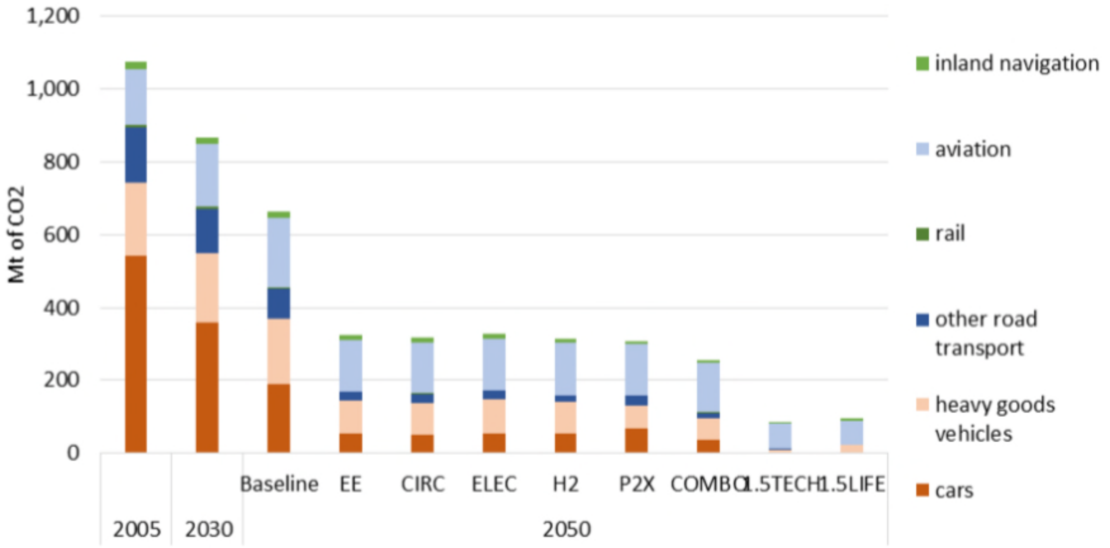
Note.

(*) GHG emission reduction versus total demand of liquid fuels in the alternative being 100% fossil.

(**) As a reference, the contribution of LCF to the total GHG reduction (%) in aviation and maritime is reported. This is the result of prorating the %GHG savings due to the penetration of LCF considering the total volume of LCF in those sectors (Section 3.3.2). Note that the reference is always the total demand for liquids being satisfied with a 100% fossil kerosene and marine fuel. The remaining % GHG savings towards 2050 (e.g. up to 70% in maritime as defined in the H2Mar70 scenario) is achieved through other technologies such as penetration of H_2, natural gas (including e-biomethane), etc.

(***) The remaining CO_2 emissions, fossil fuel related, in aviation and maritime (See Figure 27) are equivalent to ~105 Mt CO_2/y in the Concawe '1.5 alternative' scenario and they could be potentially compensated by additional negative emissions (e.g. Potentially through an increase in the deployment of BECCS schemes coupled with the new bio-fuel production plants, as explained in the section on road transport). In any case, these remaining CO_2 emissions in transport are in line with the 1.5TECH scenario (see Figure 58 from ACP4A document) and, thus, compatible with the European climate ambition.

Figure 27 CO$_2$ emissions from transport in 2050 (Mt CO$_2$). Source: [ACP4A, EU COM 2018 - Fig. 58]



Source: PRIMES.

4.2.2. Example of methodology applied: Road transport

As an illustrative example of the rationale and modelling work conducted, the results for Scenario 1 when applied to road transport are presented in detail below.

a) Volumes – Low Carbon fuels

The definition of trajectories for future low carbon fuel volumes reported below based on demand scenarios and installation of new units as defined in sections 2.1.3/4.1:

Table 15 Summary of demand in road transport (Mtoe) – Scenario 1

	2017	2030	2035	2040	2050 (CP4A - 1.5TECH)
	Mtoe/y	Mtoe/y	Mtoe/y	Mtoe/y	Mtoe/y
Food-crops based	14	16	12	9	7
HVO	5	10	10	10	10
Advanced biofuel (BTL)	-	4	6	22	30
e-fuel	-	1	6	21	46
Total Low carbon fuel (LCF)	19	31	34	62	93
Total liquid demand ROAD	290	223	174	135	93
Fossil fuel	270	192	140	73	-
% LCF in road	7%	14%	20%	46%	~100%

b) GHG reductions

b.1) Alternative feedstocks

Based on Section 3.3.2, the following trajectory for technology improvement and GHG reduction has been used:

Table 16 Summary of GHG reductions – Alternative feedstocks (WTW)[56]

	2017	**2030**	**2040**	**2050 (Alt 1.5° - Concawe)**
Food-crops based	65%	65%	68%	70%
Advanced / Non-food crops (HVO / BTL)	70%	75%	77%	85%
e-fuels	95%	95%	95%	95%

b.2) CO_2 reduction technologies (WTT)

Based on the potential GHG savings described in Section 3.4.3, the following WTT potential improvement have been derived (simple allocation of same ratio of GHG reduction at site level to liquid fuel CO_2 intensity):

Table 17 Summary of GHG reductions – CO_2 reduction technologies (WTT). E.g. Road transport

PCs - Fossil based liquid fuels	**2030**	**2035**	**2040**	**2050 (Alt 1.5°C - Concawe)**
Reduction at refining site - Refining (WTT)	25%	30%	45%	60%
WTT refining (pro-rated Gasoline + Diesel), g CO_2/km(g CO_2/km) - Fossil	7.1	6.6	5.2	3.7
WTT improved (delta), g CO_2/km	2.3	2.8	4.3	5.7
% GHG reduction vs WTW (2030 fossil) (*)	2%	2%	4%	5%

Notes.

(*) Based on **Figure 12** reporting the reference for 100% fossil fuel (WTW 121 g CO_2/km in 2030) and its relative WTT contribution. As a simplification, no additional changes in the gasoline to diesel ratio versus the 2030 reference has been considered.

(**) *Improved* refers to the lower WTT intensity value as a result of the implementation of the CO_2 reduction technologies described in Section 3.4).

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[56] Refer to footnote number 37.

b.3) GHG reduction trajectory - estimate (WTW)

Based on (b.1) and (b.2), a summary of the estimated GHG reduction saving trajectory can be found in **Table 18**:

Table 18 Summary of GHG reduction (%) – Scenario 1

	2017	**2030**	**2035**	**2040**	**2050 (Alt 1.5°C - Concawe)**
	WTW, g CO_{2eq}/km	WTW, g CO_{2eq}/km	WTW, g CO_{2eq}/km	WTW, g CO_{2eq}/km	WTW, g CO_{2eq}/km
Improved WTT - Fossil[57]	143	119	118	117	115
Food-crop based ('1G')	50	42	42	39	36
Advanced / Non-food crops (HVO / BTL)	43	30	30	28	18
e-fuels	7	6	6	6	1
Average LCF (pro-rated based on volume), g CO_{2eq}/MJ	48.1	35.6	30	22.1	10.8
% GHG reduction due to LCF (pro-rated based on volume) (**)	66%	71%	75%	82%	89%
Total mix LCF+fossil, g CO_{2eq}/km	136	107	100	73	11
% versus total fossil (2030)	4%	11%	17%	40%	~90%

Notes.

(*) No further improvement in ICE from 2030 onwards (2030 JEC WTW values for gasoline / diesel).

(**) Pro-rated based on information Table 15 (volume) and Table 16 (individual GHG savings)

c) Summary: Volume, number of plants, investment and GHG reduction levels towards 2050

The information included below summarizes the key parameters derived from the theoretical assessment conducted:

Table 19 Summary of trajectory towards alternative 1.5°C scenario 1

			2030	2035	2040	**2050 (Alt 1.5° - Concawe)**
Volumes	Total liquid demand (Road)	Mtoe/y	223	174	135	**93**
	Food-crop based '1G'		16	12	9	**7**
	Advanced / Non-food crops (HVO+BTL)		14	16	32	**40**
	e-fuels		1	6	22	**46**
	Total LCF		**31**	**34**	**62**	**93**
	Total Fossil		192	140	73	**0**
Num. plants / units	Num total plants (Bio + e-fuel)	-	42	70	252	**430**
	Num plants (CCSeq+ Clean H_2)	-	19	29	48	**68**
Investment	Total investment (min) - Cumulative	B€	29	52	155	**249**
	Total investment (max) - Cumulative		38	71	225	**366**
GHG savings	WTW savings (Total GHG reduction vs 2030)	% (**)	~10%	~20%	~40%	**~90%**
	GHG Savings – LCF (**)	Mt CO_2/y	90	100	190	**280**
	BEVs equivalents (****)	M vehicles	~50	~60	~100	~160

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[57] Estimated based on **Table 14.**

Notes:

(*) This %s is the result of pro-rating the individual % GHG reduction saving associated with each type of low carbon fuel (LCF) by their relative contribution in the total LCF volume.

(**) To estimate the reduction in total CO_2 emissions versus a 100% fossil reference and as a simplification, an emission factor of **3.16 kg CO_2/kg fossil diesel**[58] has been assumed. This % is calculated based on the remaining GHG emissions from LCLF in year "n" versus the total GHG emissions in 2030.

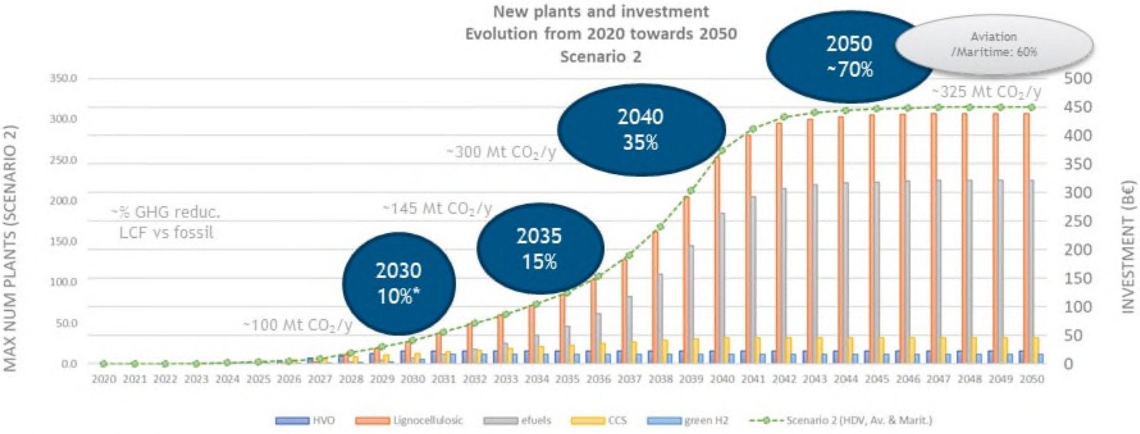
(***) Based on previously installed CCS facilities linked to refinery sites, as a simplification, we have assumed that the same facilities will be use to progressively store CO_2 from biofuel production as we approach 2050 (where oil is progressively replaced by alternative feedstocks). Due to the different scale of the BTL plants versus conventional refineries, additional investment on CO_2 capture technology will be required (Due to the uncertainty around this, the additional CAPEX has not been included in the current estimate). These negative emissions have not been included in the calculation of the 2050 GHG savings due to Low carbon fuels and could help reach a completely net-zero GHG scenario in 2050.

(****) Bases for $BEV_{equivalent}$ initial estimate (WTW): ICE / C-segment - EU Benchmark - Concawe Review, 2019) replaced by BEVs purely RES. 17 t CO_2/ 150,000 km. 10 years (Lifetime) <> 1.7 t CO_2/year emissions saved per each BEV replacing an ICE vehicle.

4.3. SCENARIO #2. HEAVY-DUTY, AVIATION & MARITIME

This scenario assumes a penetration of Low Carbon Fuels only in the heavy-duty road sector and the 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 28 Summary of '1.5 alternative' Scenario 2: Projections. Heavy-duty, Aviation & Maritime



Cumulative (Transport)	2020-2030	2020-2035	2020-2040	2020-2050
Total volume LCF (Mtoe)*	~30	~50	~100	~110
Total new plants (bio+efuels)	~50	~150	~450	~550
Total investment, B€*	~30-40	~90-120	~250-380	~300-450
Ratio of investment, B€/y	~5 (2020-2030) ~30 (2030-2040) ~10 (2040-2050)			

** For road, GHG reduction compared to the 2030 WTW GHG intensity of 100% fossil fuel in Road transport Heavy Duty vehicles (HDV)*

** Aviation and Maritime - GHG reduction compared to a scenario where all the demand for liquid fuels is satisfied by 100% fossil fuel*

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[58] Fossil diesel (B0) consistent with the CO_2 emission factor used in the JEC WTW v5 analysis.

Table 20 Summary of trajectory towards alternative 1.5°C scenario (Scenario 2)

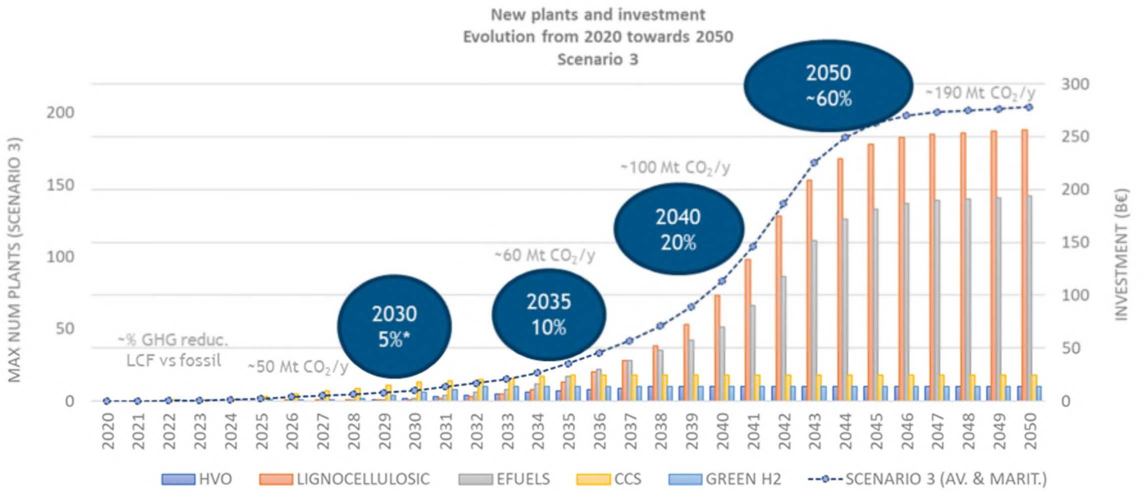
Transport (Heavy-duty, Aviation & Maritime)			2030	2035	2040	**2050 (Alt 1.5° - Concawe)**
Volumes	Total demand for liquid fuels	Mtoe/y	337	285	235	138
	Food-crop based ‘1G’		16	12	9	3
	Advanced / Non-food crops (HVO+BTL)		17	25	51	59
	e-fuels		1	9	37	45
	Total LCF		34	47	97	107
	Total liquid fossil fuel		303	238	138	31
Num. plants / units	Num total plants (Bio+e-fuel)	-	50	146	453	547
	Num plants (CCS_{eq}+Green H_2)	-	19	35	46	46
Investment	Total investment (min) - Cumulative	B€	31	88	253	302
	Total investment (max) - Cumulative		41	125	375	451
GHG savings	**WTW GHG intensity (LCF reduction vs fossil)**	%	~71%	~77%	~83%	~90%
	WTW savings (Total GHG reduction vs 100% fossil)	%	9%	15%	35%	70%
	% WTW savings due to LCF in total demand for liquid fuels – Aviation/Maritime (**)	%	~4%	~11%	30%	60% (***)
	GHG Savings – LCF	Mt CO_2/y	105	145	300	325

Note. Detailed values included in **Appendix 4**.

4.4. SCENARIO #3. AVIATION & MARITIME

This scenario assumes a penetration of Low Carbon Fuels only in the aviation and maritime sectors. Due to the smaller market volume compared to Scenario 1 and Scenario 2, the mass deployment of the related technologies is slowed down:

Figure 29 Summary of '1.5 alternative' Scenario 3: Projections. Aviation & Maritime



Cumulative (Transport)	2020-2030	2020-2035	2020-2040	2020-2050
Total volume LCF (Mtoe)*	~20	~25	~40	~70
Total new plants (bio+efuels)	~7	~35	~130	~340
Total investment, B€*	~10	~30-35	~80-110	~190-280
Ratio of investment, B€/y	~1 (2020-2030)		~10 (2030-2040)	~15 (2040-2050)

** Aviation and Maritime - GHG reduction compared to a scenario where all the demand for liquid fuels is satisfied by 100% fossil fuel*

Table 21 Summary of trajectory towards alternative 1.5°C scenario (Scenario 3)

Transport (Aviation & Maritime)			2030	2035	2040	**2050 (Alt 1.5° - Concawe)**
Volumes	Total demand for liquid fuels	Mtoe/y	337	285	205	98
	Food-crop based '1G'		16	12	7	0
	Advanced / Non-food crops (HVO+BTL)		7	9	21	38
	e-fuels		0	3	10	28
	Total LCF		23	25	38	67
	Total liquid fossil fuel		314	260	167	31
Num. plants / units	Num total plants (Bio+e-fuel)	-	7	35	133	340
	Num plants (CCS_{eq}+Green H_2)	-	19	28	28	28
Investment	Total investment (min) - Cumulative	B€	10	27	79	186
	Total investment (max) - Cumulative		11	35	113	278
GHG savings	**WTW GHG intensity (LCF reduction vs fossil)**	%	~70%	~75%	~80%	~90%
	WTW savings (Total GHG reduction vs 100% fossil)	%	5%	10%	20%	60%
	GHG Savings – LCF	Mt CO_2/y	50	60	100	180

Note. Detailed values included in **Appendix 4**.

Should the economic/market conditions be in place, there could be a potential for the EU refining industry to maximise the level of investment rate up to the levels defined in Scenario 1 (HIGH), equivalent to ~30 B€/y in the period 2040-2050, potentially replacing all the remaining fossil liquid fuels in aviation and maritime. This assumption will portray a sensitivity case around this scenario 3 in which the total level of LCF could reach ~100 Mtoe with a level of cumulative investment ranging between 280-420 B€ (~500 new plants) in the period 2020-2050, similar to the levels reached in Scenario 2[59].

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[59] In such case of total replacement of fossil fuels, other considerations beyond the fuel production need to be addressed (not covered in the scope of this study). As an example, this scenario may create a problem of availability of oil-based bitumen and lubricants, as the lighter fractions of the barrel (usually derived to fuels) would not have any demand/destination beyond potential export.

5. SUSTAINABLE FEEDSTOCK AVAILABILITY

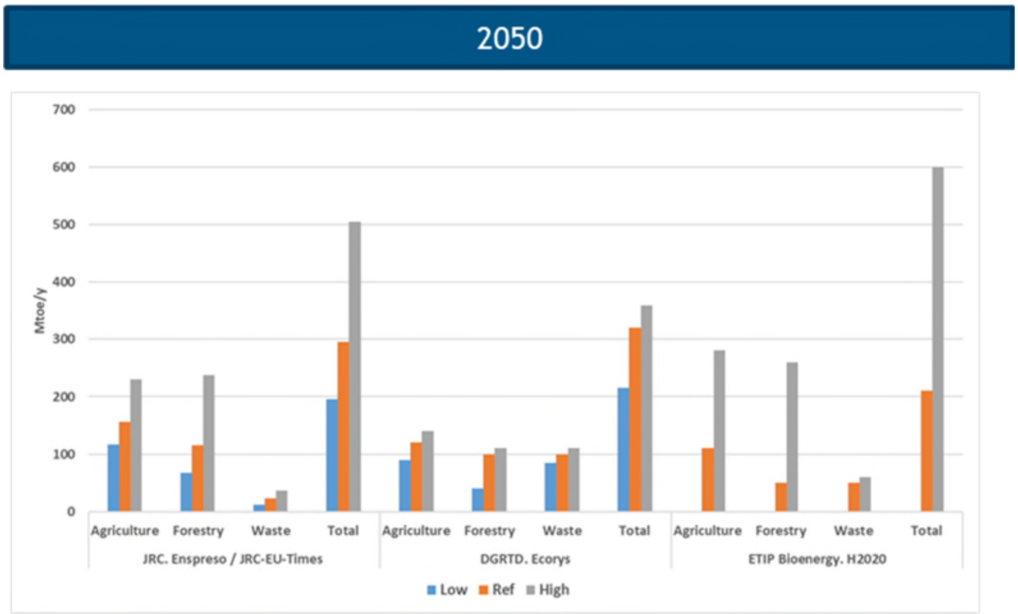
One of the key factors when assessing the technical feasibility of the Concawe's 'alternative *1.5°C*' scenarios analysed is the amount of sustainable feedstock that could become available for low carbon fuel production routes.

As described in **Table 1**, the total volume of low carbon fuels that could be required for transport sector ranges between ~70 Mtoe/y in the low scenario (#3) up to ~160 Mtoe/y when the whole transport sector is considered (Scenario #1). These values should be considered as an estimate of total capacity installed required in the demand scenario used as a reference in this analysis[60] (some volume could be potentially diverted from road to other sectors as required and/or other technologies being developed by 2050). It is also worth noting that these volumes include both biofuels and a share of e-fuels, the latter initially estimated as ~50% of the total demand, alleviating the potential pressure on bio-resource availability in the long term.

5.1. LITERATURE REVIEW

To assess feasibility in terms of sustainable biomass availability, an initial literature review comparing the potential availability forecasted by different sources has been conducted[61] (see **Appendix 1**). Several studies released under the umbrella of the European Commission ([Ecorys, EU COM 2017], [ENSPRESO, JRC 2019] and more recently [ADVANCEFUEL, ETIP 2020[62]]) are included in this review, exploring the maximum potential for bioenergy at EU level.

Figure 30 Summary of potential biomass availability for bioenergy (EU level) 2020/2050. Comparison of different external sources



Note. Algae potential not considered in DG RTD Ecorys, as they state it is uncertain due to high costs. DG RTD Ecorys consider a 2-10 Mtoe/y e-fuels production by 2050.

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[60] Part of this volume could be potentially diverted from road to other sectors (e.g. aviation) as required and/or as other technologies penetrate in a more accelerated way by 2050.

[61] https://www.concawe.eu/wp-content/uploads/Concawe-Review-27-2-web-resolution-2.pdf

[62] http://www.advancefuel.eu/en/news/final-event-how-can-europe-develop-a-market-for-advanced-renewable-fuels

From the comparison of these reports, the potential biomass available for the whole EU bioenergy system is estimated to range from 215 up to 535 Mtoe/y by 2050 (Ecorys Low /ENSPRESO High). ENSPRESO is more optimistic than Ecorys with a higher potential foreseen in agriculture & forestry. However, it is worth noting that this JRC/ENSPRESO high scenario includes 1G biofuel crops & dedicated cropping in high biodiversity lands and that it is not in full compliance with REDII sustainability criteria.

5.2. IMPERIAL COLLEGE LONDON CONSULTANTS' ASSESSMENT

Concawe has commissioned an in-depth analysis conducted by Imperial College London Consultants (IC) [IC, 2021] in assessing different scenarios in terms of the maximum potential sustainable feedstock availability for the bioenergy sector and their equivalence as advanced biofuels, with a view on transport.

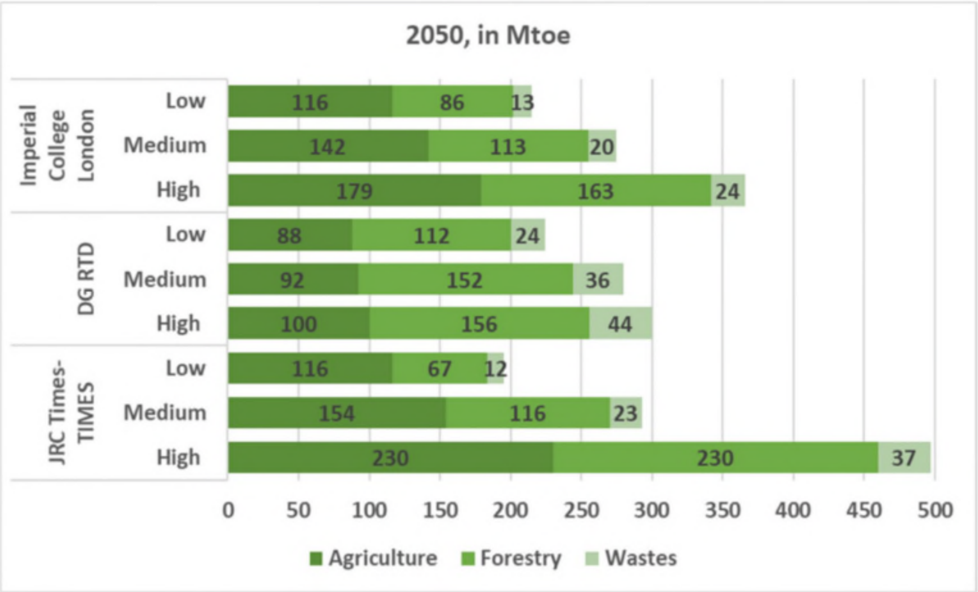
The scope of the IC study explores a low, medium and high scenario including agricultural, forestry and biowaste materials potentially used for advanced biofuels, limited to the list reported in RED II Annex IX part A/B.

The main conclusions that could be derived from this report are summarised below:

- **Sustainable feedstock availability**
  - A potential sustainable feedstock availability ranging between ~**210-370 Mtoe/y for the whole bioenergy sector is foreseen by 2050**, with no expected harmful impact on biodiversity.

    Additional sustainable feedstocks and waste materials currently not included in Annex IX of RED II, as well as algae, could potentially offer an opportunity to increase this potential.
  - The Imperial College (IC) high scenario lays in between the DG RTD and JRC ENSPRESO high cases scenarios (20% higher than DGRTD's high one and 25% lower than JRC-Times High one) with no significant differences in terms of the foreseen potential in the 2030/2050 timeframe.

Figure 31 Comparative estimates for biomass potentials (Mtoe) for bioenergy in the IC, DG RTD and JRC TIMES studies [IC, 2021]



  - It is worth noting that the bioenergy economy includes sectors such as power, industry, service, agriculture and residential sectors beyond the use of biomass for biofuel production in the transport one. In this context, different considerations such as cost and GHG reduction aspects, market mechanisms including potential competition with other low-carbon alternatives or specific policy frameworks could determine the final use of biomass in each of these bioenergy sub-sectors and, consequently, the potential availability/use for transport as a whole. As an initial look into these aspects, when the allocation of feedstock to these other non-transport bioenergy sectors is deducted from the total, following the EU COM's scenarios defined in the Impact Assessment [EU COM 2020] (130 Mtoe in 2030 and 170 Mtoe in 2050), the total **net biomass** that can be used for biofuel production, including imports[63] (49 Mtoe in 2030 and 56 Mtoe in 2050), has been estimated at ~120-260 Mtoe for 2030 and ~100 - 250 Mtoe for 2050 (ranges corresponding to the lowest and highest biomass availability scenarios presented in the IC report).

- **Advanced biofuel potential**

  Different fuel production conversion technologies could be developed to maximise the conversion of this feedstock volume into advanced biofuels by 2050. An optimistic scenario in terms of yields, routing the foreseen available feedstocks (low/high availability scenario) to the most yield efficient oriented technologies, estimates a potential biofuel availability of **80 (Low 2030) up to 250 (High 2050) Mtoe/y** of final **advanced biofuels when the total sustainable biomass that would be available for bioenergy would be converted to advanced biofuels (no biomass imports taken into account).** When the allocation of feedstock to other non-transport bioenergy sectors is applied (based on the EU COM's view as described above) and estimated sustainable biomass imports are considered based on recent statistics and projections from relevant literature[64]), the total estimated biofuel production for transport could range between **50 Mtoe/y (Low 2030) up to 180 Mtoe/y (High 2050). It is** worth noting that this is deemed a conservative estimate for transport due to the high allocation of biomass to power sector in the EU COM scenario. This potential for transport includes EU domestic production plus biomass imports.

- **Comparison with Concawe's "1.5° C alternative scenarios"**

  The comparison of the potential availability of feedstocks (and its conversion into advanced biofuels) versus the potential requirement for Low Carbon Fuel production (biofuel part) presented in **Table 22**, **Figure 32**, **Figure 33** and **Figure 34** shows that:

  - The high biomass scenarios of the Imperial College London Consultant's study estimate sufficient sustainable biomass for advanced biofuels to cover all the demand trajectories presented in 2030 and 2050, even with the EU Commission high allocation of biomass to non-transport sectors,
  - 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 total Concawe's biofuels demand in 2030 and 2050.

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[63] Note: In this study no imports of biofuels in the EU have been considered. Only imports of biomass in the EU have been considered.

[64] Imported lignocellulosic biomass (pellets from agricultural residues, wood pellets and utilised cooking oil) for bioenergy has been addressed in the IC study (Annex II).

Table 22 Biofuels demand versus potential availability

Demand				Potential availability 1 (All bioenergy)		Potential availability 2 (Allocation to transport based on PRIMES)	
2030 Concawe demand scenarios (1)	**S1**	**S2**	**S3**	**2030 Potential advanced and waste-based biofuels (EU domestic production)(2)**	**2030 Potential advanced and waste-based biofuel (EU + imports) (2)**	**2030 Potential advanced and waste-based biofuel adjusted according to PRIMES allocation to non-transport sector (EU domestic production)**	**Total 2030 Potential advanced and waste-based biofuel (EU + imports)**
LCF	34	34	22.5				
e-fuels	1	1	0.5				
Biofuels	32	32	21	76.7 - 127.5	**94.5-145.3**	**28.9 - 79.2**	**46.7 - 97.0**
2050 Concawe demand scenarios(1)	**S1**	**S2**	**S3**	**2050 Potential advanced and waste/based biofuels (this study) (2)**	**2050 Potential advanced biofuel estimated due to imports (this study)**	**2050 Potential advanced biofuel adjusted according to PRIMES allocation to non-transport sector**	**Total 2050 Potential advanced biofuel (EU + imports)**
LCF	159	107	67				
e-fuels	78	45	28				
Biofuels	81	62	39	158.5 – 252.8	**197.7-292**	**31.5 - 137.2(3)**	**70.7 - 176.4**

Notes:

(1) Biofuels demand scenarios includes both food-crop based (limited by the current RED II cap) as well as both advanced and waste based biofuels.

(2) Potential advanced biofuels taking into account that all the bioenergy estimated in the low and high scenarios of this report were allocated to advanced biofuels for transport sector. The ranges include the low and the high biomass availability scenarios, considering the maximum conversion yields for the different pathways per type of feedstock (High Technology Scenario).

(3) The potential for advanced biofuels by the estimated balance of biomass for biofuel is an approximate estimation of the estimated biomass for advanced biofuels considering the same average conversion efficiency as in this study.

Figure 32 Biofuels demand versus potential availability (2030)

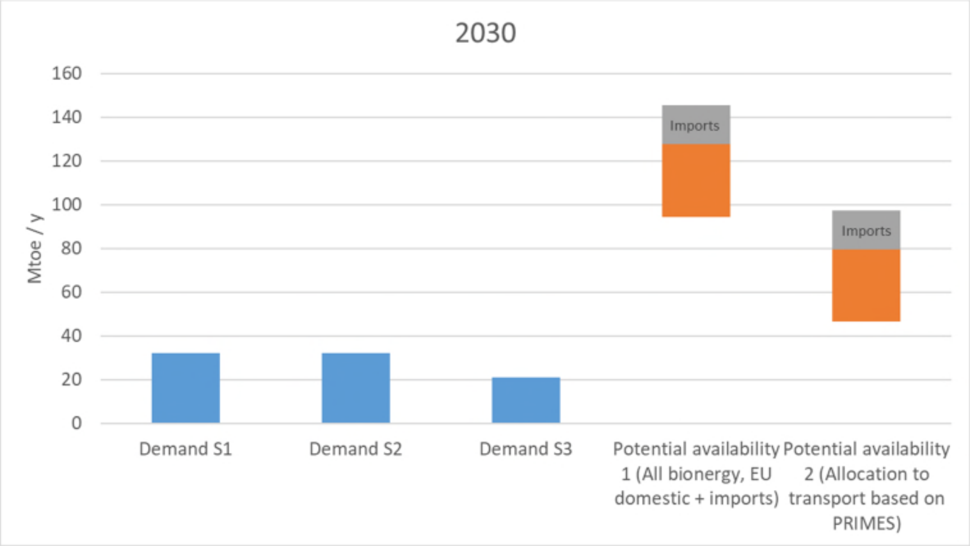
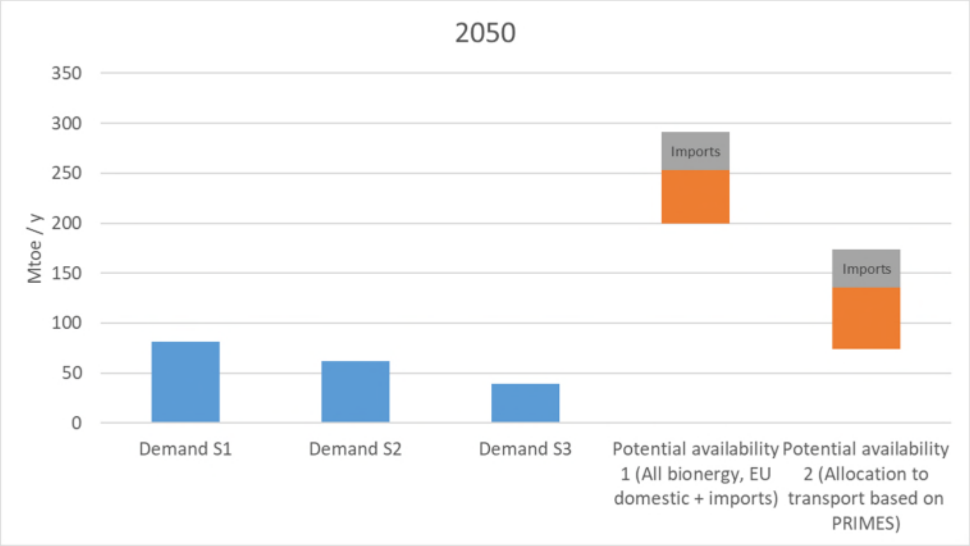


Figure 33 Biofuels demand versus potential availability (2050)



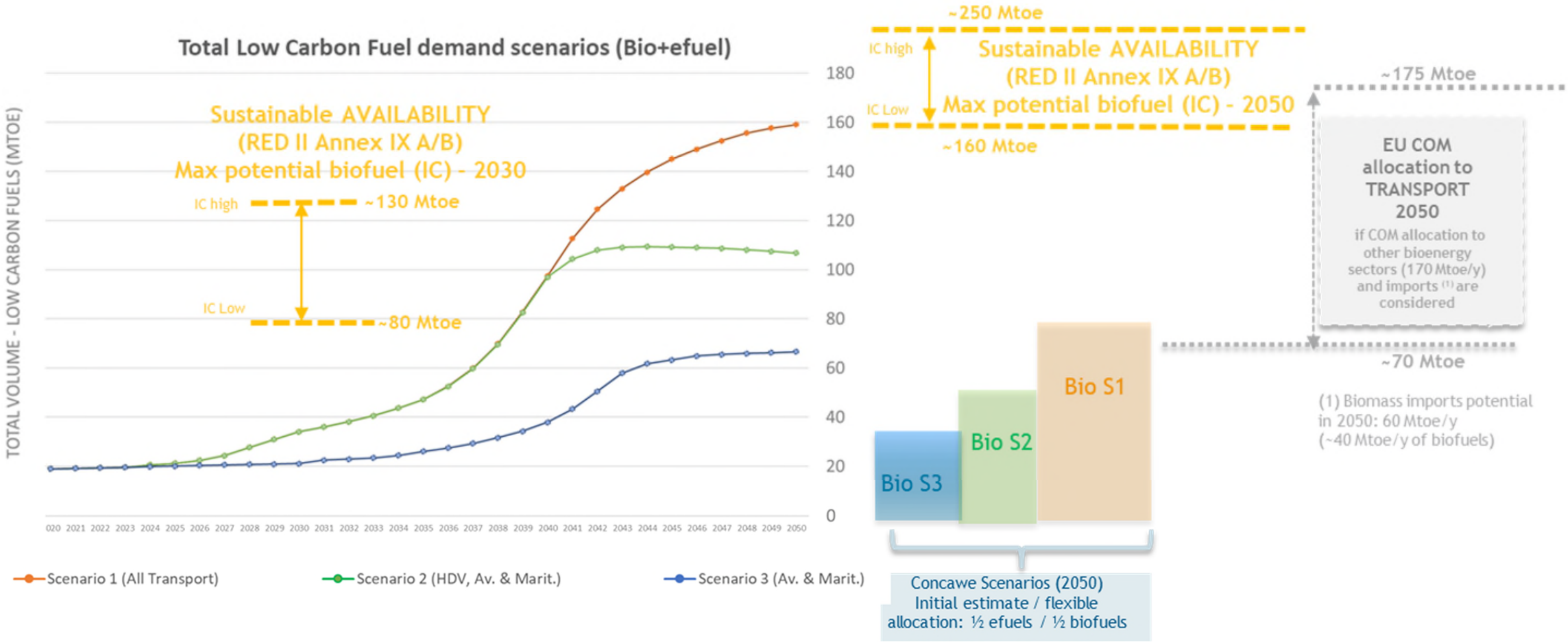
Overall it can be concluded that there is sufficient sustainable biomass to meet the three Concawe scenarios in 2030 and 2050 under considerations such as enhanced availability through Research and Innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices.There is a caveat around Scenario 1 (demand), when the 2050 timeframe and the low biomass availability scenario are considered, in which, taking imports into account, a small adjustment of the e-fuel production of ~10 Mtoe/y would be required to meet the total foreseen low-carbon fuel demand.

It is important to highlight that the biomass potentials availability estimated in this study are based on very conservative assumptions. Furthermore, the potential from algal biofuels plus other sustainable biomass feedstocks not included in RED II Annex IX has not been taken into consideration in the above calculations. Therefore, it can be concluded that the biomass potential in 2030 and 2050 could most probably be higher than those estimated by this study.

To realise this potential, additional R&D would be required as well as the implementation of improvement management strategies. Even if the potential is there, the supply chain would need to be developed to mobilise all these resources.

On top of the availability issues, other factors such as the sustainable development of the whole value chain, land availability and competition among sectors are key elements, which are currently being further investigated by Concawe to leverage the whole potential of advanced biofuels in Europe.

Figure 34 Summary of comparison between Low Carbon fuel estimate (Concawe Scenarios) and potential sustainable availability (IC Low/High)



Different considerations such as scale or CAPEX oriented decisions, production cost or decentralised vs centralised models, among others, could boost the penetration of alternative technologies depending on specific and regional conditions. Therefore, the potential presented in this study is presented for illustrative purposes as an example of the maximum potential yields and should not be considered a projection for the future.

Besides this, it is also important to highlight that the biomass potentials availability estimated in this study are based on what IC believes as a set of conservative assumptions regarding the maximum potential. Furthermore, the potentials from algal biofuels plus other sustainable biomass feedstocks not included in RED II Annex IX have not been taken into consideration at all in the above calculations providing additional flexibility and higher availability than the amounts foreseen in the IC study.

6. GLOSSARY

ACP4A	A Clean Planet for All
BECCS	Bioenergy with CO_2 Capture and Storage
BECCS	Bio-Energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BTL	Biomass-To-Liquids: denotes processes to convert biomass to synthetic liquid fuels, primarily diesel fuel
CAPEX	CAPital EXpense
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilization, and Storage
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
Concawe	the scientific body of the European Refiners' Association for environment, health and safety in refining and distribution
DAC	Direct Air Capture
EU	European Union
EUCAR	the European council for Automotive Research and development
xEVs	Electric Driven Vehicles
FAME	Fatty Acid Methyl Ester
FCC	Fluid Catalytic Cracking
FCHV	Fuel Cell Hydrogen Vehicles
FT	Fischer-Tropsch: process that converts syngas to linear hydrocarbons
GHG	Greenhouse Gas
GTL	Gas-To-Liquids
H_2	Hydrogen
HDO	Hydro-De-Oxygenation
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oils
ICE	Internal Combustion Engine
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IOGP	International Association of Oil & Gas Producers
JEC	JRC, EUCAR, and Concawe
JRC	Joint Research Centre (of the European Commission)
LCA	Life-Cycle Assessment

LCF	Low Carbon Fuel
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
NExBTL®	Neste Renewable Diesel, Proprietary technology for producing renewable diesel (Neste Oil)
NG	Natural Gas
OPEX	OPerating EXpense
PHEV	Plug In Hybrid Electric Vehicle
RED	Renewable Energy Directive
SGAB	Subgroup on Advanced Biofuels
SMR	Steam Methane Reforming
TRL	Technology Readiness Levels
TTW	Tank-to-Wheels
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
WTW	Well-To-Wheels: the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle

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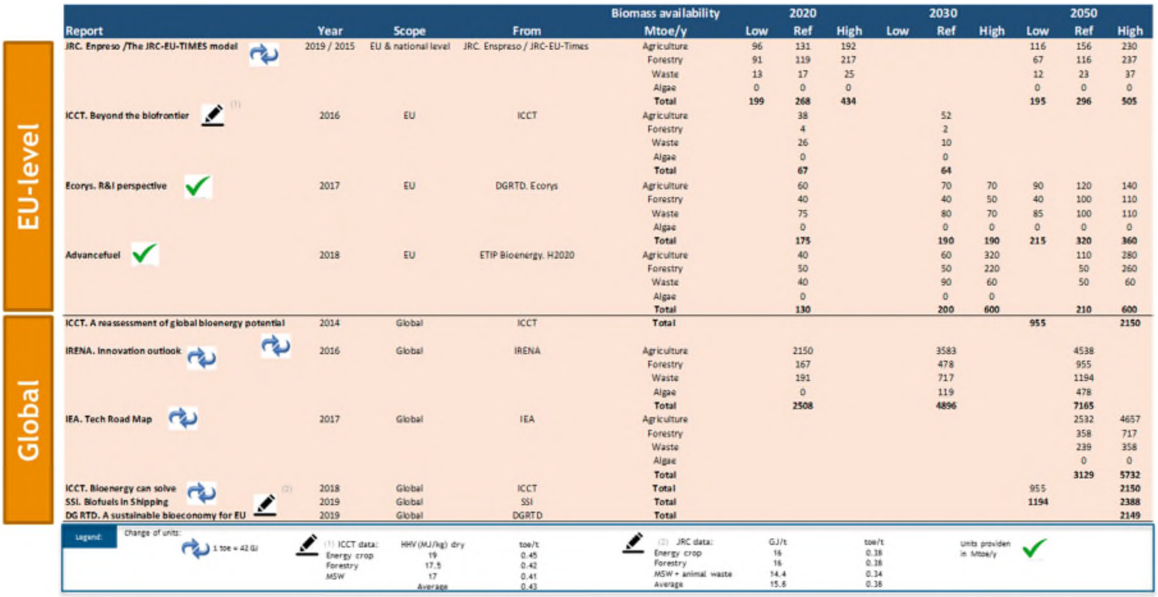
APPENDIX 1. BIO-FEEDSTOCK AVAILABILITY REVIEW (CONCAWE)

To assess feasibility in terms of sustainable biomass availability, an initial literature review comparing the potential availability forecasted by different sources has been conducted. Different relevant sources in the public domain such as [ENSPRESO, JRC 2019], [ADVANCEFUEL, ETIP 2018], [Ecorys, EU COM 2017], [ICCT 2016], [IRENA 2016] and [IEA 2017] assess the biomass availability at European and/or at a worldwide level in different low-high scenarios from 2020 to 2050. Concawe has compared them in the same basis, taking into account the heating values per type of biomass (agriculture, forestry, waste and algae) as details below:

Figure A1.1 Summary of potential biomass availability (EU and worldwide level) 2020/2050 by different sources – Concawe elaboration



					Biomass availability	2020			2030			2050		
	Report	**Year**	**Scope**	**From**	**Mtoe/y**	**Low**	**Ref**	**High**	**Low**	**Ref**	**High**	**Low**	**Ref**	**High**
EU-level	**JRC. Enpreso /The JRC-EU-TIMES model** 🔄	2019 / 2015	EU & national level	JRC. Enspreso / JRC-EU-Times	Agriculture	96	131	192				116	156	230
					Forestry	91	119	217				67	116	237
					Waste	13	17	25				12	23	37
					Algae	0	0	0				0	0	0
					Total	**199**	**268**	**434**				**195**	**296**	**505**
	ICCT. Beyond the biofrontier ✎ (1)	2016	EU	ICCT	Agriculture		38			52				
					Forestry		4			2				
					Waste		26			10				
					Algae		0			0				
					Total		**67**			**64**				
	Ecorys. R&I perspective ✓	2017	EU	DGRTD. Ecorys	Agriculture		60			70	70	90	120	140
					Forestry		40			40	50	40	100	110
					Waste		75			80	70	85	100	110
					Algae		0			0	0	0	0	0
					Total		**175**			**190**	**190**	**215**	**320**	**360**
	Advancefuel ✓	2018	EU	ETIP Bioenergy. H2020	Agriculture		40			60	320		110	280
					Forestry		50			50	220		50	260
					Waste		40			90	60		50	60
					Algae		0			0	0			
					Total		**130**			**200**	**600**		**210**	**600**
Global	**ICCT. A reassessment of global bioenergy potential**	2014	Global	ICCT	**Total**							**955**		**2150**
	IRENA. Innovation outlook 🔄 🔄	2016	Global	IRENA	Agriculture		2150			3583			4538	
					Forestry		167			478			955	
					Waste		191			717			1194	
					Algae		0			119			478	
					Total		**2508**			**4896**			**7165**	
	IEA. Tech Road Map 🔄	2017	Global	IEA	Agriculture								2532	4657
					Forestry								358	717
					Waste								239	358
					Algae								0	0
					Total								**3129**	**5732**
	ICCT. Bioenergy can solve 🔄 (2)	2018	Global	ICCT	**Total**							955		**2150**
	SSI. Biofuels in Shipping ✎	2019	Global	SSI	**Total**							**1194**		**2388**
	DG RTD. A sustainable bioeconomy for EU	2019	Global	DGRTD	**Total**									**2149**

Legend:

Change of units: 🔄 1 toe = 42 GJ

✎ (1) ICCT data:

	HHV (MJ/kg) dry	toe/t
Energy crop	19	0.45
Forestry	17.5	0.42
MSW	17	0.41
Average		0.43

✎ (2) JRC data:

	GJ/t	toe/t
Energy crop	16	0.38
Forestry	16	0.38
MSW + animal waste	14.4	0.34
Average	15.8	0.38

Units providen in Mtoe/y ✓

More details can be found in the Concawe article *A look into the maximum potential availability and demand for low-carbon feedstocks/fuels in Europe (2020-2050) (literature review)* [2019][65].

The studies analysed provide different conclusions and show a wide variability in their potential estimate. Some of the key assumptions, among others, that generates this wide variability are:

- The type of feedstocks considered (e.g. waste, forestry and agricultural residues).
- The amount that could be economically used for the bio-economy while complying with different sustainability requirements.
- The estimates on future land availability (e.g. how much land might be used to produce energy crops based on factors such as uncertainties around future food demand or use (and definition) of marginal lands).
- Future R&D developments to increase yields, improve forestry management practices, etc.

Relevant issues such as the sustainable development of the whole value chain, land availability and competition among sectors are key aspects to be further investigated when leveraging the whole potential of advanced biofuels in Europe. A Concawe's in-depth analysis is on-going and a future publication will contribute to inform this subject.

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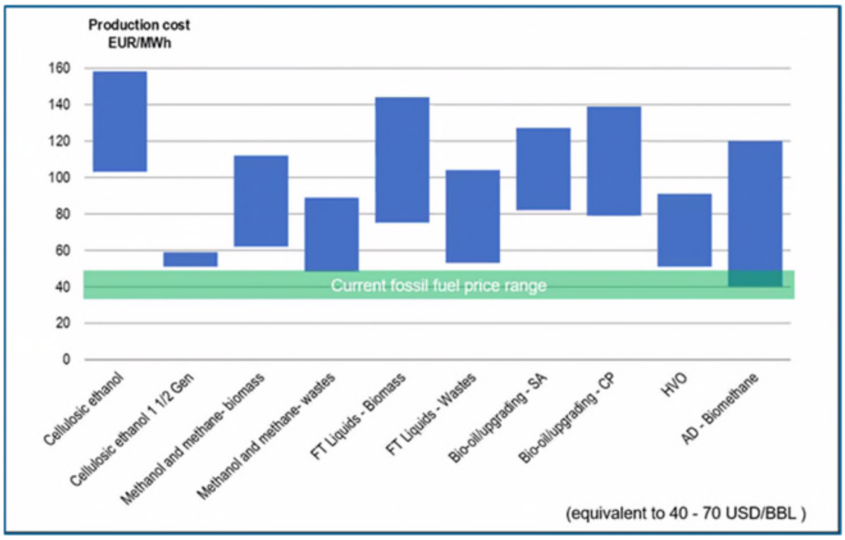
[65] https://www.concawe.eu/wp-content/uploads/Feedstocks-1.pdf

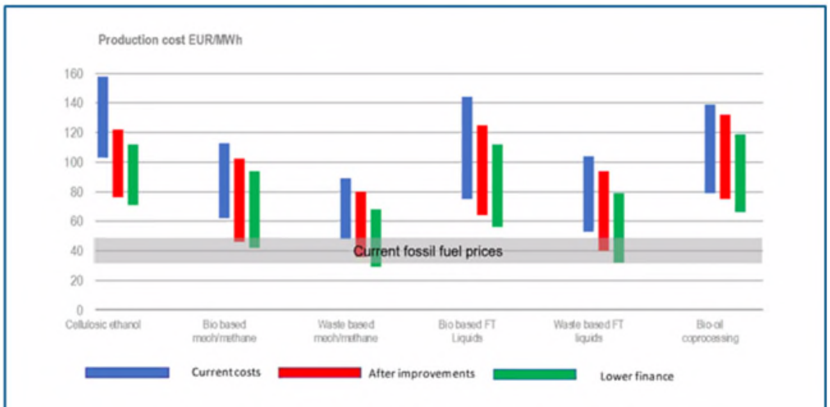
APPENDIX 2. BIOFUEL PRODUCTION AND COST REDUCTION ESTIMATE

Figure A.2.1 Production costs for different low carbon fuels (including BTL and HVO ('bio-oil'). Source: [IEA 2019[66]].

Current cost estimates



Cost reduction - medium term



- Cost reduction 10 - 27% for capital/operating costs
- Further 5-16 % for improved capital charges

Indicating that production costs lie in the range of 65 to 158 EUR/MWh for production based on biomass feedstocks and 48 to 104 EUR/MWh for waste-based production.

There is scope for medium-term cost reductions of between 20-50% due to technical advances and improved financing terms.

In the longer term, higher cost reduction potential due to learning effects in scenario of extensive deployment of production capacity. Besides this, IEA projects a gap between advanced biofuels and fossil fuels which could be narrowed in the context of different policy mechanisms.

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[66] https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf

APPENDIX 3. 2030 FLEET COMPOSITION - ASSUMPTIONS

The total energy demand in road transport has been estimated as a result of the composition of the fleet and the fuel efficiency improvement towards 2030. The modelling exercise conducted considers:

- The improvement in terms of energy efficiency of conventional powertrains (Internal Combustion Engines, ICEs), running on either gasoline or diesel-like fuel, as well as the projections in terms of new sales (assuming to have an annual growth of 0.2%), activity levels (~5% reduction in average mileage per vehicle estimated in the case of passenger cars) or scrappage rate of old vehicles.

- The progressive penetration of new types of powertrains towards 2030.

  The composition of 2030 new sales has been defined based on market trends and experts' estimate, in compliance with the 2030 CO_2 intensity targets for new sales in road transport (NEDC):

  - Passenger cars: 95 g CO_2/km in 2021 and further 37.5% reduction from 2030 onwards (equivalent to 66.5 g CO_2/km in the 2030 baseline).
  - Light commercial vehicles (vans): 147 g CO_2/km in 2020 and being 31% less TTW intensive than in 2021 (equivalent to 103 g CO_2/km in the 2030 baseline).
  - Heavy-duty: 15% reduction from 2025 onwards and a value of 565.2 g CO_2/km as average for heavy-duty commercial vehicles in 2030.

  Overall, the share of non-ICE powertrains (using liquid fuels) in new sales for road transport accounts for ~24% for passenger cars and ranging from 10 to 15% for heavy-duty (depending on the category) up to 20% in the case of buses and coaches.

Table A.3.1 Example. 2030 new sales in Passenger cars – Comparison of some of the investigated sources

2030	Concawe '1.5' scenario	Roland Berger[67]	Other Sources	
	Proposal	Scenario B	*PFA study[68] (2030)*	*FEV Consulting[69]*
PHEVs	13%	6%	*7%*	*7-21%*
BEVs	7%	4%	*15%*	*10-24%*
CNG/LNG/LPG	3.6%	3.7%	*2.5%*	*3-5%*
Fuel cell (H_2)	0.3%[70]	0.2%	-	*1-3%*

Note. Some relevant assumptions for passenger cars:

- **Full hybrids and mild hybrids**

  The 2030 gasoline sales were split between 60% Internal Combustion Engines (ICE) and 40% Mild Hybrid (MH), as used in the French Automotive Organization (*La Plateforme automo*bile – PFA) (PFA, 2018). The gasoline full hybrid figure at 3%, is an average value between Roland Berger (~1.4%) and a higher value from ACEA ranging between 5 to 7%.

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[67] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwirq4nwpPLrAhVOsaQKHRv6DDMQFjAAegQIBxAB&url=https%3A%2F%2Fwww.rolandberger.com%2Fpublications%2Fpublication_pdf%2Froland_berger_integrated_fuels_and_vehicles_roadmap_to_2030_v2_20160428.pdf&usg=AOvVaw0BRRl7POcHo5U0halAvncV

[68] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj3_LXUsPLrAhUGwKQKHa_NB3YQFjAAegQIBBAB&url=https%3A%2F%2Fwww.pfa-auto.fr%2Fwp-content%2Fuploads%2F2017%2F12%2FCRA2_PTF_01_01V2017-11-2.pdf&usg=AOvVaw38Ai_253IKPyBh1JpS_IAU

[69] https://www.fev-consulting.com/fileadmin/user_upload/Consulting/Downloads/Publikationen/The_Future_Drives_Electric.pdf

[70] 0.3% new sales as proposed in F&F to reach 100,000 FCEV by 2030.

- **Electric Vehicle (BEV / PHEV) shares**

  The 2030 xEVs (BEVs/PHEVs) share in new sales has been assumed to be ~20%. The different splits proposed by various sources were explored (e.g. ERTRAC low assumption (ERTRAC), ACEA 2025, PFA). Within this study, a **ratio 2/3 PHEV & 1/3 BEV** is used (consistent with all the studies except the PFA, where the considered ratio is the opposite; 2/3 BEV and 1/3 PHEV). In the most recent statistics, the BEV/PHEV ratio seems to have been shifting towards higher BEVs; however, the 95% e-mode driving of PHEV considered in 2030 makes the differences negligible for the scope of this exercise.
- **Diesel share**

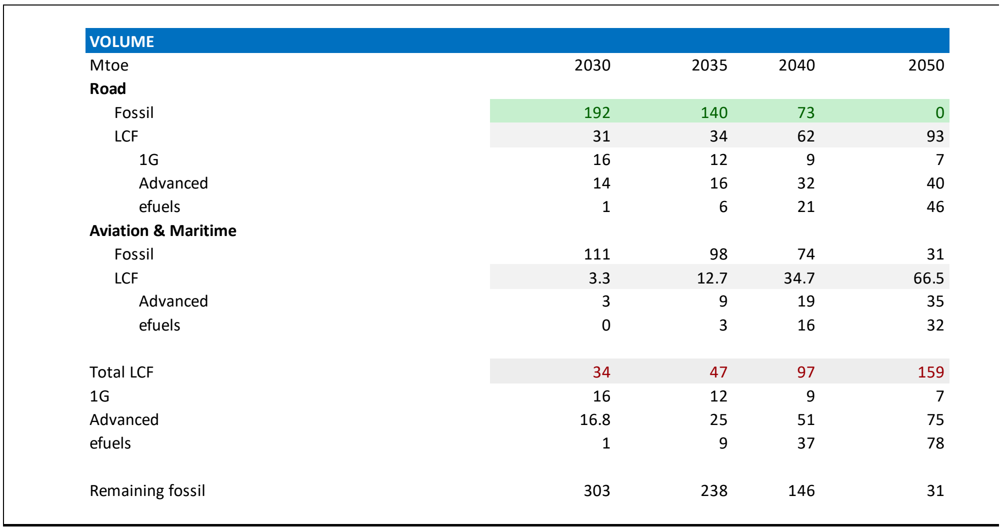
  The proposed baseline for the 2019 model shows a reduction of new diesel sales, but with the expectation that sales will recover somewhat from present values. Looking at 2030 new sales, the 34% of diesel new car registrations are split 18% diesel and 16% Diesel hybrid, this is broadly in line with the PFA study. Diesel PHEV's are grouped separately in the PHEV assumptions.
- **Gaseous fuels: CNG, LPG, H_2.**

  For CNG, 3% new registrations were assumed for 2030, in line with the JEC Alternative Fuel Study [JEC, 2011] and Roland Berger [RB 2016]. It is assumed that Fuel Cell Vehicles will reach 100,000 by 2030, figures aligned with Roland Berger. This assumption is in line with Roland Berger assumptions.

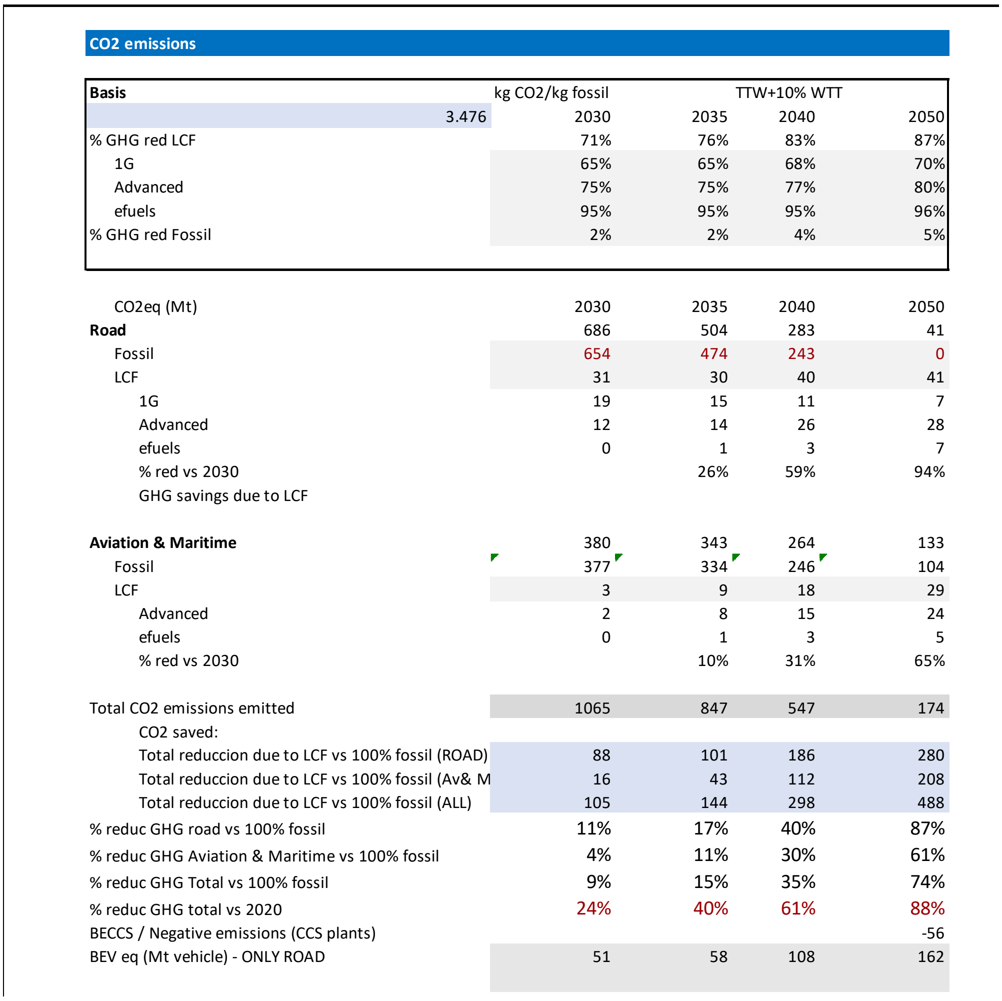
APPENDIX 4. ALTERNATIVE 1.5°C SCENARIOS. DETAILED RESULTS

The following tables include all the detailed information regarding the 3 scenarios considered:

Table A.4.1 Scenario 1. Details



VOLUME				
Mtoe	2030	2035	2040	2050
Road				
Fossil	192	140	73	0
LCF	31	34	62	93
1G	16	12	9	7
Advanced	14	16	32	40
efuels	1	6	21	46
Aviation & Maritime				
Fossil	111	98	74	31
LCF	3.3	12.7	34.7	66.5
Advanced	3	9	19	35
efuels	0	3	16	32
Total LCF	34	47	97	159
1G	16	12	9	7
Advanced	16.8	25	51	75
efuels	1	9	37	78
Remaining fossil	303	238	146	31



CO2 emissions				
Basis	kg CO2/kg fossil		TTW+10% WTT	
3.476	2030	2035	2040	2050
% GHG red LCF	71%	76%	83%	87%
1G	65%	65%	68%	70%
Advanced	75%	75%	77%	80%
efuels	95%	95%	95%	96%
% GHG red Fossil	2%	2%	4%	5%
CO2eq (Mt)	2030	2035	2040	2050
Road	686	504	283	41
Fossil	654	474	243	0
LCF	31	30	40	41
1G	19	15	11	7
Advanced	12	14	26	28
efuels	0	1	3	7
% red vs 2030		26%	59%	94%
GHG savings due to LCF				
Aviation & Maritime	380	343	264	133
Fossil	377	334	246	104
LCF	3	9	18	29
Advanced	2	8	15	24
efuels	0	1	3	5
% red vs 2030		10%	31%	65%
Total CO2 emissions emitted	1065	847	547	174
CO2 saved:				
Total reduccion due to LCF vs 100% fossil (ROAD)	88	101	186	280
Total reduccion due to LCF vs 100% fossil (Av& M	16	43	112	208
Total reduccion due to LCF vs 100% fossil (ALL)	105	144	298	488
% reduc GHG road vs 100% fossil	11%	17%	40%	87%
% reduc GHG Aviation & Maritime vs 100% fossil	4%	11%	30%	61%
% reduc GHG Total vs 100% fossil	9%	15%	35%	74%
% reduc GHG total vs 2020	24%	40%	61%	88%
BECCS / Negative emissions (CCS plants)				-56
BEV eq (Mt vehicle) - ONLY ROAD	51	58	108	162

Table A.4.2 Scenario 2. Details

VOLUMES				
Mtoe	2030	2035	2040	2050
Road				
Fossil	192	140	65	0
LCF	31	34	62	40
1G	16	12	9	3
Advanced	14	16	32.45	24.1014977
efuels	1	6	21	13.1275
Aviation & Maritime				
Fossil	111	98	74	31
LCF	3.3	12.7	34.7	66.5
Advanced	3	9	19	35
efuels	0	3	16	32
Total LCF	34	47	97	107
1G	16	12	9	3
Advanced	16.8	25	51	59
efuels	1	9	37	45
Remaining fossil	303	238	138	31

CO2 emissions				
Basis	kg CO2/kg fossil	TTW+10% WTT		
3.476	2030	2035	2040	2050
% GHG red LCF	71%	76%	83%	86%
1G	65%	65%	68%	70%
Advanced	75%	75%	77%	80%
efuels	95%	95%	95%	96%
% GHG red Fossil	2%	2%	4%	5%

CO2eq (Mt)	2030	2035	2040	2050
Road	686	504	256	22
Fossil	654	474	217	0
LCF	31	30	40	22
1G	19	15	10	3
Advanced	12	14	26	17
efuels	0	1	3	2
% red vs 2030		26%	63%	97%
Aviation & Maritime	380	343	264	133
Fossil	377	334	246	104
LCF	3	9	18	29
Advanced	2	8	15	24
efuels	0	1	3	5
% red vs 2030		10%	31%	65%
Total CO2 emissions emitted	1065	847	520	154
CO2 saved:				
Total reduccion due to LCF vs 100% fossil (ROAD)	88	101	186	117
Total reduccion due to LCF vs 100% fossil (Av& Maritime)	16	43	112	208
Total reduccion due to LCF vs 100% fossil (ALL)	105	144	298	325
% reduc GHG road vs 100% fossil	11%	17%	42%	85%
% reduc GHG Aviation & Maritime vs 100% fossil	4%	11%	30%	61%
% reduc GHG Total vs 100% fossil	9%	15%	36%	68%
% reduc GHG total vs 2020	24%	40%	63%	89%
BECCS / Negative emissions (CCS plants)				-34
BEV eq (Mt vehicle) - ONLY ROAD	51	58	108	68

Table A.4.3 Scenario 3. **Details**

VOLUME				
Mtoe	2030	2035	2040	2050
Road				
Fossil	203	162	90	0
LCF	19	12	7	0
1G	16	12	7	0
Advanced	3.75	0	0	0
efuels	0	0	0	0
Aviation & Maritime				
Fossil	111	98	77	31
LCF	3.3	12.7	31.0	66.5
Advanced	3	9	21	38
efuels	0	3	10	28
Total LCF	23	25	38	67
1G	16	12	7	0
Advanced	6.5	9	21	38
efuels	0	3	10	28
Remaining fossil	314	260	167	31

CO2 emissions				
Basis	kg CO2/kg fossil		TTW+10% WTT	
3.476	2030	2035	2040	2050
% GHG red LCF	69%	73%	80%	87%
1G	65%	65%	68%	70%
Advanced	75%	75%	77%	80%
efuels	95%	95%	95%	96%
% GHG red Fossil	2%	2%	4%	5%

CO2eq (Mt)	2030	2035	2040	2050
Road	715	564	310	0
Fossil	693	549	303	0
LCF	22	15	8	0
1G	19	15	8	0
Advanced	3	0	0	0
efuels	0	0	0	0
% red vs 2030		18%	55%	100%
Aviation & Maritime	380	343	277	135
Fossil	377	334	259	104
LCF	3	9	19	31
Advanced	2	8	17	27
efuels	0	1	2	4
% red vs 2030		10%	27%	64%
Total CO2 emissions emitted	1095	907	588	135
CO2 saved:				
Total reduccion due to LCF vs 100% fossil (ROAD)	59	41	27	0
Total reduccion due to LCF vs 100% fossil (Av& Maritime)	16	43	99	206
Total reduccion due to LCF vs 100% fossil (ALL)	75	84	126	206
% reduc GHG road vs 100% fossil	8%	7%	8%	100%
% reduc GHG Aviation & Maritime vs 100% fossil	4%	11%	26%	60%
% reduc GHG Total vs 100% fossil	6%	8%	18%	60%
% reduc GHG total vs 2020	22%	36%	58%	90%
BECCS / Negative emissions (CCS plants)				-18
BEV eq (Mt vehicle) - ONLY ROAD	34	24	16	0

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ISBN 978-2-87567-144-8