Concawe

Environmental Science
for European Refining

Working Plan

The *Low Carbon Pathways* Project.

A holistic framework to explore the role of liquid fuels in future EU low-emission mobility (2050).

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THE *LOW CARBON PATHWAYS* PROJECT

A HOLISTIC FRAMEWORK TO EXPLORE THE ROLE OF LIQUID FUELS IN THE FUTURE LOW-EMISSION MOBILITY (2050)

CONCAWE WORKING PLAN

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ABSTRACT

This working plan is the first publication in a series planned to assess the technology developments across different transport sectors that will contribute to the EU decarbonisation goals and defines the basis for a new **cross-cutting area of research in Concawe: the *Low Carbon Pathways*** project. The series of reports will ultimately allow us to share quantitative assessments of the overall potential for CO_2 emissions reduction from the combination of more carbon efficient vehicles and fuels, the potential evolution of the liquid fuels industry and the changing role of the refinery.

This first document focuses on the passenger vehicle sector and provides a first high level assessment of the technical readiness of emerging developments in vehicle drivetrains and future liquid fuels. A holistic view looking across the different technologies identified is used to estimate the potential CO_2 intensity improvement that could be achieved.

As a result of this work, Concawe has initiated a new cross-cutting working plan (*Low Carbon Pathways* project) to provide better scientific understanding in different transport sectors. This will lead to different research projects within Concawe and in collaboration with others, covering key areas such as fuel products, production processes and refining technologies and their impact on both CO_2 emissions and Air Quality and Water. The results of these projects will provide more robustness to the preliminary numbers included in this first assessment.

KEYWORDS

CO_2, Refining, Low carbon liquid fuels, pathways, 2050, decarbonization, Well-to-Wheels, WTW, g CO_2/km.

INTERNET

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

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EXECUTIVE SUMMARY

The **European Union** has clear ambitions to **significantly reduce CO_2** across the economy and society including the transport sector. In the short term, the EU has set the target to reduce greenhouse gas emissions by 40% for 2030. By 2050, the EU also has the ambition to achieve 80-95% reduction compared with 1990, with sub-targets of 83-87% for industry and 54-67% for transport. **Achieving these ambitions while maintaining the competitiveness of its economy and the quality of life** of its citizens represents an enormous **challenge** for the European Union. This will require an adaptation of the entire EU energy system and consumer behaviour. It will entail innovative solutions, requiring both technological excellence to develop them, and financial means to fund the necessary investments.

Low-carbon liquids will be of vital importance in the drive to reduce emissions in European energy and transport systems: not only during the transitional period, where liquid fuels are required to allow for efficient and affordable energy for transport and thus the functioning of the economy and the society, but also in the longer-term future subject, depending on the **ability to reduce the Well-To-Wheels carbon intensity** of a liquid-fuels-based transport sector in an affordable and efficient manner.

When looking at mobility across all sectors, amongst a wide range of fuels options with a lower carbon intensity, the currently most promising ones in terms of their theoretical potential to achieve even net-zero emissions in transport, are electricity (if produced fully renewable), advanced bio-fuels, e-fuels (if produced by using “green electricity”) or CCS or combinations of these. However, which of those options for which sector of transport will be best suited to continue to enable affordable, efficient and low-carbon mobility is not clear yet. This will also depend amongst other factors on capital investment required, availability of raw materials and energy sources from increasingly growing but fluctuating renewable sources, customer acceptance and policy support.

Concawe has started to investigate into the **low-carbon opportunities across all modes of transport** with a current focus on road and passenger car transport. The current preliminary assessment for the road transport passenger car sector reveals a significant reduction potential of vehicle CO_2 emissions through further efficiency improvements of the vehicle and engine technology primarily enabled by an increasing share of hybridization of the drivetrain. In addition to the vehicle related CO_2 reduction potential, providing fuels with a lower carbon intensity, compared with today’s fuels, have the potential to finally achieve lower overall CO_2 emissions in transport on a Well-To-Wheels basis.

This **first assessment identifies new areas of research and testing within Concawe** (*Working Plan*) and, therefore, the preliminary results presented in this document are subject to change and will be updated as the outcome of on-going and new projects become available.

The new ***Low Carbon Pathways*** project is also intended to be a **live tool** to produce a **picture** of different low carbon technologies at various *Technology Readiness Levels* (TRL). As such, the development of both existing and new pathways will be continuously followed within the scope of the project and the associated GHG performance, abatement cost and TRL regularly up-date. According to the working plan, a first holistic view across different transport sectors informed by a sound science based assessment will be ready by end 2019.

1. WHOLE SYSTEM OPPORTUNITIES FOR LOW-CARBON LIQUID PRODUCTS TO CONTRIBUTE TO A LOW CARBON MOBILITY: THE *LOW CARBON PATHWAYS* PROJECT.

This working plan is the first publication in a series planned to assess the technology developments across different transport sectors that will contribute to the EU decarbonisation goals and defines the basis for a new **cross-cutting area of research in Concawe: the *Low Carbon Pathways*** project. The series of reports will ultimately allow us to share quantitative assessments of the overall potential for CO_2 emissions reduction from the combination of more carbon efficient vehicles and fuels, the potential evolution of the liquid fuels industry and the changing role of the refinery.

This first publication focuses on the passenger vehicle sector and provides a high level assessment of the technical readiness of emerging developments in vehicle drivetrains and future liquid fuels. A holistic view looking across the different technologies identified is used to estimate the potential CO_2 intensity improvement that could be achieved. Where appropriate we also highlight the potential for some of these developments to cross-over to different transport sectors. This first assessment identifies new areas of research and testing within Concawe and, therefore, the preliminary results presented in this document are subject to change and will be updated as the outcome of on-going and new projects become available.

Further reports are also planned which will extend this study by focusing on other transport sectors including heavy duty road transport, aviation and marine. The findings will identify the impact of different technology options on the ability to reduce CO_2 from transport with an assessment of the evolution of supply contributions from petroleum based products, biofuels and "power to liquid" fuels (*efuels*).

1.1. THE LOW CARBON PATHWAYS PROJECT: NEW CROSS-CUTTING AREAS OF RESEARCH IN CONCAWE.

Over the last decades, different pathways such as biofuels have emerged as viable options to reduce the life-cycle carbon emissions from the production and use of liquid hydrocarbon fuels as well as feedstock for petrochemicals, lubricants and waxes. Concawe has conducted a high level assessment of the potential integration of these different pathways to produce a holistic picture of the potential role of liquid fuels in the future EU low-carbon economy.

This assessment explores the potential WTW CO_2 intensity reduction that could be achieved in the medium (2030) and longer-term 2050+, and estimates the associated abatement costs from the different pathways with the potential to significantly contribute to reduce the CO_2 intensity of the final fuels. The possibilities identified have been clustered in **five main pathways**:

- CO_2 **efficiency improvement** at the production site (upstream + Refining)
- **Fuel quality** modifications
- Alternative **low-carbon liquid fuels**
- **Vehicle/engine** efficiency enhancement
- **Other** technologies or international initiatives.

As a result of this work, Concawe initiated a new cross-cutting working plan (*Low Carbon Pathways* project) to provide better scientific understanding in these areas. This will lead to different research projects within Concawe and in collaboration with others, covering key areas such as fuel products, production processes and refining technologies and their impact on both CO_2 emissions and Air Quality.

The results of these projects will provide more robustness to the preliminary numbers included in this first assessment. According to the working plan, a holistic view across different transport sectors informed by a sound science based assessment will be ready by end 2019.

As a first step to define the current working plan, the current preliminary assessment is focused on the opportunities for the passenger car segment and the potential for liquid fuels in the future to deliver significant CO_2 savings. Future projects will expand the scope of this analysis to produce similar assessments for the Heavy Duty, Marine and Aviation sectors, including the integration of both liquid and gaseous fuels.

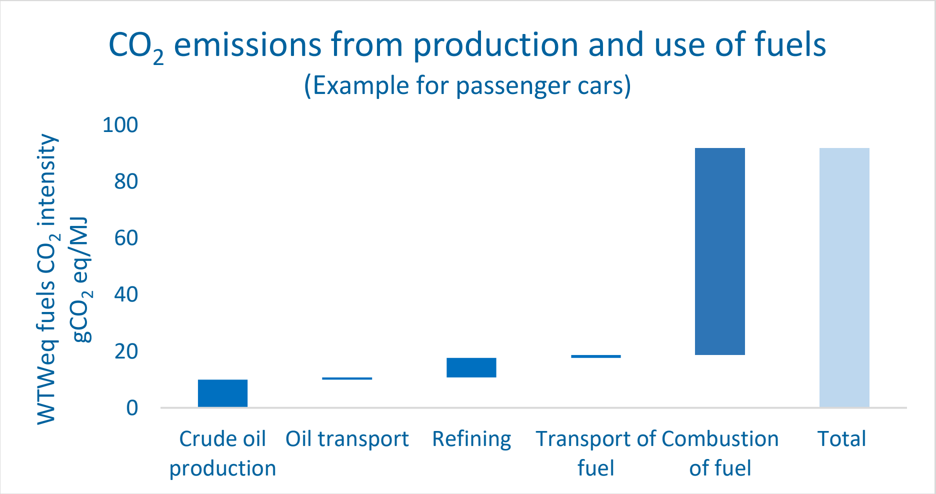
New reports addressing the main areas for further work/research identified will be published with the objective to contribute to inform both the scientific community, Member States and general society in this important topic.

1.2. THE WELL-TO-WHEELS APPROACH

When comparing different technologies for the reduction of CO_2 emissions it is important to consider the energy consumption and consequent CO_2 emissions in every step of the process from the production of crude oil, or other feedstocks materials, through transportation, refining, formulation and distribution of the finished fuels (the “Well-to-Tank”), to the consumption of the fuel in the vehicle (the “Tank-to-Wheels”).

The “**Well-To-Wheels**” (WTW) approach breaks down the CO_2 emissions associated with mobility into different stages. As an example, for the passenger vehicle segment, the CO_2 emissions associated with diesel and gasoline can be summarised as follows:

Figure 1 Well-to-Wheels approach



Source: Concawe based on JEC v4 and own data (Average values).

Note. Main contributors to the carbon intensity of liquid fuels (Passenger car. Simplified Well-to-Wheels. The combustion part considers only the emissions associated to the theoretical combustion of the fuels)

- ≈ 12% of the CO_2 emissions are released during the production and transport of crude oil (“upstream emissions”).
- ≈ 8% of the CO_2 emissions are generated in refineries during the processing of crude oil into petroleum products and from the transport of the fuel to the petrol pump.
- ≈ 80% of the CO_2 emissions are generated during the combustion of the fuels (theoretical value without considering any engine or vehicle specific energy efficiencies).

This analysis shows that whilst the greatest potential to reduce carbon emissions is during the combustion stage, the earlier stages are key enablers of further improvement:

- The “***Well-to-Tan****k*” (WTT) phase, encompasses the production and transport of crude oil and then refining the crude to produce the required fuels. As these processes are common to all transport sectors, reducing emissions during this phase will improve the carbon intensity of all fuels produced and, thus, the environmental performance across the whole existing fleet.
- In contrast, to reduce emissions during the “***Tank-to-Wheels***” (TTW) phase, solutions specific to each transport sector, or even segments within a sector (e.g. coastal shipping compared with transoceanic shipping) are required. In passenger vehicles, hybrid drive trains or even fully battery powered vehicles are already options for the motorist. However, current emerging technologies leading to the full substitution of the use of hydrocarbons in either Marine or Aviation are not expected to be commercially available by 2050. As the tailpipe emissions are associated to the carbon content of the fuel combusted, drop-in fuels with a high renewable content (biofuels and efuels from renewable electricity) can also contribute to compensate the TTW CO_2 emissions across all sectors.

A Well-to-Wheels approach can leverage the full potential of both low-emission fuels combined with the most efficient combustion technologies, offering different alternatives to customers (individual or countries) with the potential to effectively contribute to mitigate climate change.

The evolution towards a low-carbon mobility in all means of transport can be achieved by optimizing the energy consumption/CO_2 emissions at every single step of the Well-To-Wheels chain:

- from the production of low-carbon fuels
- through the optimization of the refining and distribution system
- to the final combustion point - where the design of the engines and the vehicles themselves, together with the quality of the fuels, play a major role.

1.3. BEYOND PASSENGER CARS: A QUICK LOOK INTO DIFFERENT TRANSPORT SECTORS.

Concawe has started to investigate into low-carbon opportunities across all modes of transport in their new *Low Carbon Pathways* project with a current focus on road and passenger car transport (*Section 3*). The next section provides a brief overview of other transport sectors (marine, aviation, heavy duty and light duty), estimating their associated fuel demand (current and forecasted future) along with potential opportunities to reduce their CO_2 intensity. This overview will be the basis to conduct a more deep analysis of the role of low-carbon fuels to contribute to decarbonize EU mobility by 2050. According to the working plan, a first holistic view across different transport sectors informed by a sound science based assessment will be ready by end 2019.

In this context, a look into decarbonisation of the transport sector highlights some relevant considerations that should be taken into account:

- ***Refineries produce a broad range of hydrocarbon products:***
  An inherent efficiency of crude oil refining is that it enables the production of a full range of hydrocarbons for fuel and non-fuel uses ranging from lighter products (such as naphtha used as the base component in gasoline, kerosene's for jet fuel, gasoil for diesel, base oils for lubes and waxes) to heavier products such as bitumen for roads and roofing.The complete replacement of a single fuel with alternatives on a one to one comparison without looking at the whole production scheme, has the risk of distorting the balance as the refinery will still need to operate – in a high efficient way - to deliver the other range of products required by society.
- ***Multiple pathways can contribute:***
  Different low-carbon technologies, at different stages of development, can be envisaged for each specific transport sectors.
- ***Boundaries beyond Europe:***
  The nature of Marine and Aviation transport means that approaches for decarbonisation within these transport sectors has to be considered on a global level as well as the European level.

The potential evolution of the refinery will need to take all these considerations into account to produce sustainable and reliable pathways towards decarbonization while continuing to meet societies demand for energy and products.

1.3.1. Marine

Globally, the marine sector is projecting growth in marine traffic, leading to an increase in demand for mainly hydrocarbon based marine fuels by 2050. To reduce global emissions the IMO[1] are exploring different pathways to reduce their CO_2 emissions, considering an overall reduction in the CO_2 intensity of 50% by 2050 compared to 2008, measured in CO_2 per tonne of cargo carried per km.

- Reductions in CO_2 emissions from marine transport may be achieved through a combination of different measures including route optimization and the design of new ships with better hydrodynamics, along with more efficient engine and propulsion technologies.
- The formulation of marine diesels, increasingly substituting conventional petroleum based fuel oils and diesels with sustainable biofuels and e-fuels (such as synthetic methanol) as these become available.
- The employment of alternative fuels, particularly LNG and hydrogen, require engines that are specifically designed for these fuels or modifications on existing ones. Such engines are likely to take an increasing share of new ships or during a major refit in older ships.
- Other concepts such as on-board CO_2 capture may become technically feasible for large ships, powered by diesel, LNG or alternative liquid synthetic fuels.
- Alternative energy sources such as nuclear power, on-ship wind turbines and electric / combustion hybrid systems are in development.

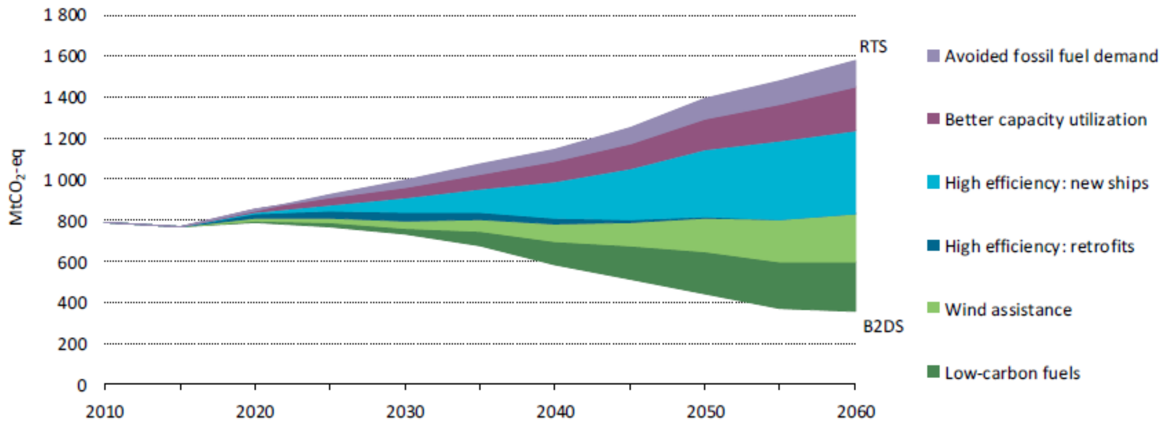
[1] https://www.iea.org/media/news/2017/ISWGGHG2214.pdf

- Individually, none of the approaches summarised above are likely to be deployed on a sufficient scale to fully substitute for petroleum based marine fuels. However, collectively, the combination of these technologies could make a significant contribution to the decarbonisation of marine transport.

It should be noted that to provide fuels that meet the IMO global 0.5% sulphur specification CO_2 emissions from EU refineries will increase by as much as +8 million tonnes per annum (+4%) (LP modelling result, mean scenario, Concawe "*2020 Marine Fuels Supply study*" assuming minor scrubber installation).

The figure below[2] provides a visual representation of how different solutions could contribute to reduce GHG emissions in international shipping from the baseline defined by the IEA *Reference Technology Scenario* (RTS) to reach the *Beyond 2°C Scenario* (B2DS). The opportunities identified by IEA are primarily focused on optimizing the ratio of utilization of available shipping capacity and the maximization of energy savings through improved energy efficiency. The role of future low-carbon fuels is also envisaged playing an important role beyond 2030.

Figure 2 Well-to-Wheel GHG emission reduction in international shipping.



Source. IEA Energy Technology Perspectives 2017

Within Europe the EU Commission has committed to reduce CO_2 emissions from maritime transport in EU waters by at least 40% and, if feasible, by 50% vs 1990 (Commission 2011 white paper on transport[3]). The EU requirement for Monitoring, reporting and verification of CO_2 emissions from large ships using EU ports came into effect in January 2018.

1.3.2. Aviation

Globally, the aviation sector is also projecting significant growth in traffic, with a resulting increase in demand for aviation fuels by 2050. To manage emissions, IATA[4] have committed to

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020
- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth)
- A reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 level

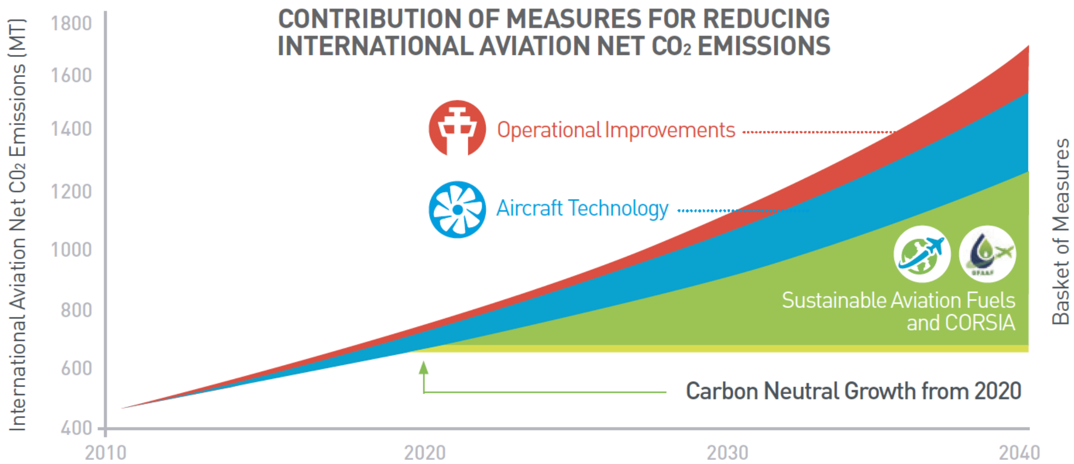
[2] IEA/IMO https://www.iea.org/media/news/2017/ISWGGHG2214.pdf
[3] http://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:52011DC0144&from=EN
[4] https://www.iea.org/media/news/2017/ISWGGHG2214.pdf

IATA considers the following innovations will contribute to reductions in CO_2 emissions from aviation

- Improved technology, including the deployment of sustainable low-carbon fuels
- More efficient aircraft operations (ground handling)
- Infrastructure improvements, including modernized air traffic management systems
- A single global market-based measure, to fill the remaining emissions gap (offsetting)

Within Europe, the *European Flightpath 2050 project*[5] aims for a 75% reduction in CO_2 emissions per passenger per km flown by 2050 (relative to the capabilities of typical new aircraft in 2000**)**. A significant amount of low-carbon liquid fuels will be required to meet this objective, potentially including low-carbon intensity kerosene as bio-jet or -efuel.

Figure 3 Contribution of Measures for reducing International Aviation Net CO_2 emissions



Source: ICAO. Draft resolution text on a Carbon Offsetting Scheme for International Aviation (COSIA)[6].

1.3.3. Heavy Duty (HD) Road Transport

The **EU GHG target** for 2050 will require a yearly reduction of, at least 3% on the CO_2 emissions associated to HD7. This amount is equivalent to a reduction of the demand for Heavy Duty Vehicles of around 55% in the period 2012-2050. In order to achieve such ambitious goals, both ERTRAC[8] and a group of industry associations' led by ACEA[9] are exploring different measures.

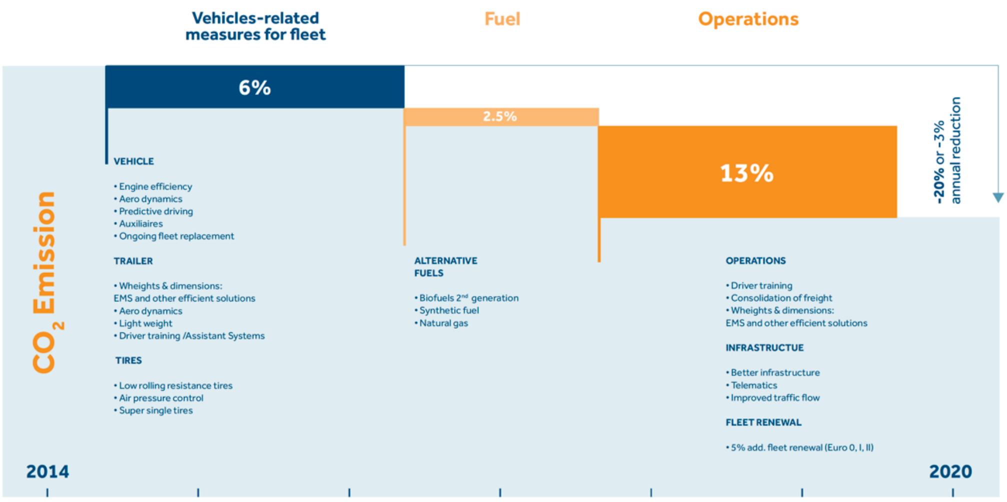
[5] http://www.acare4europe.org/sria/flightpath-2050-goals/protecting-environment-and-energy-supply-0
[6] https://www.icao.int/environmental-protection/Documents/CorsiaBrochure_8Panels-ENG-Web.pdf
[7]https://www.avl.com/documents/10138/1131828/141119_PDiM_Electromobility+for+Commercial+Vehicles+%E2%80%93%20Challenges+%26+Opportunities_Svenningstorp.pdf/4f631607-dd8a-4616-a935-480d8e37ba9c
[8] ERTRAC roadmap (June 2016), Heavy duty truck roadmap (2012) http://www.ertrac.org/uploads/documentsearch/id42/2016-06-09_Future%20ICE_Powertrain_Technologies_final.pdf and http://www.ertrac.org/uploads/documentsearch/id4/heavy-duty-truck-1_0_66.pdf
[9] ACEA (Integrated approach report, 2017), http://reducingco2together.eu/assets/pdf/trucks.pdf

The ACEA-led study highlights the importance of following an integrated approach including different opportunities and stakeholders (vehicle, trailers and tyres; more efficient engines, fuels and alternative fuels; operations - infrastructure and logistics) which could hold the potential to cut 20% of CO_2 emissions from road transport by 2020, compared to 2014, unlocking the full potential of joint future CO_2 reduction efforts. Among the initial measures identified in the ACEA-led study:

- 6% CO_2 potential savings are vehicle-related including optimization of vehicle engines, trailers and tyres.
- 2.5% corresponds to the use of alternative fuels (including biofuels, synthetic fuels and natural gas).
- And 13% is assigned to operational changes, including better infrastructure-related ones and fleet renewal.

In the long term, alternative fuels such as synthetic fuels or Hydrogen may have the potential to release a much higher CO_2 reduction potential, subject to the development of the relevant technologies.

Figure 4 An integrated approach to reduce CO_2 emissions from Heavy-Duty vehicles



Source. ACEA and TML, 2015[10]

Additional R&D programs exploring new engine technologies for Heavy Duty may have the potential to leverage additional CO_2 savings (e.g**.** *CryoPower*[11] engine technology developed by Ricardo is claimed to improve fuel efficiency and CO_2 emissions by 30%).

1.3.4. Passenger cars and Light duty commercial vehicles

Many analysts predict that the stock of passenger cars is expected to increase from today levels, both worldwide and in Europe. For passenger cars, the *EU Reference Scenario 2016* predicts an increase in the activity (total mileage driven) up to 2030 and a continuous activity growth post-2030, albeit at lower rates as a result of an almost stagnant population after 2040.

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[10] http://www.tmleuven.be/project/hgvco2/ReportonHDVemissionreductionmeasuresv9.pdf
[11] https://innovations.ricardo.com/projects/cryopower-en

As fuel combustion represents 80% of the total WTW CO_2 emissions, there are two type of initiatives that could be implemented to reduce their associated CO_2 emissions in the long term:

- ***Vehicle related opportunities (TTW)***

  Vehicle-related opportunities have the potential to reduce TTW emissions associated to this transport sector by means of different measures:

  - Engine improvement.

    New R&D programs[12,13]show potential opportunities to move the internal combustion engine design forward, integrated together with other vehicle-related measures to reduce the fuel consumption such as thermal management of powertrain/vehicles systems and waste heat recovery. These improvements could also be leveraged in HD vehicles.

  - Alternative powertrains

    - *Electric vehicles (*EV), in their different forms, will play a major role subject to the decarbonization of the electricity mix. Different combinations of electric motors with optimized internal combustion engines (Hybrid Vehicles) including *plug-in-hybrid electric* vehicles (PHEV) and fully *battery electric* ones (BEV) are now options for the motorist.
    - Hydrogen produced from renewable electricity and consumed in *Fuel Cell Hydrogen cars* (FCHV) also offers an alternative to contribute to the partial electrification of the passenger car segment.

  - Other vehicle improvements (e.g. weight reduction or improved tyres) can contribute to improve energy efficiency further independently of the powertrain technology considered.

- ***Low-carbon fuels (WTW)***

  Sustainable low carbon fuels including both biofuels and efuels produced from renewable electricity have also the potential to compensate tailpipe emissions effectively when a WTW approach is followed.

  Even in optimistic scenarios of high penetration of alternative powertrain technologies, liquid fuels will continue to be required for many passenger cars and light duty commercial vehicles (see section 2.1 for further details).

The use of liquid fuels with an optimized carbon intensity in the most efficient ICE and Hybrid passenger car vehicles could offer a potential complementary alternative to full electrification in this sector. It is the scope of this working plan to evaluate the options and their contribution in terms of CO_2 reduction on basis of an integrated approach including low-emission petroleum based fuels (produced in optimized oil fields and refineries) and bio and synthetic fuels produced from renewable sources including “green" electricity.

As a result of this first look into mobility, there is not a single option which will deliver low emission mobility across all transport sectors. However there are a number of emerging technologies which in total will deliver the most sustainable low-emission fuels (low GHG intensity oil-based fuels, biofuels, syn-fuels, e-fuels) for consumption in the next generation of the highly efficient engines. An effective industrial collaboration in Europe, supported by the right R&D framework, will be required to develop these technologies along with the highly integrated supply and distribution networks.

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[12]https://www.reuters.com/article/us-mazda-strategy/mazda-announces-breakthrough-in-long-coveted-engine-technology-idUSKBN1AO0E7

[13] https://techxplore.com/news/2018-03-valve-technology-cheaper-greener.html

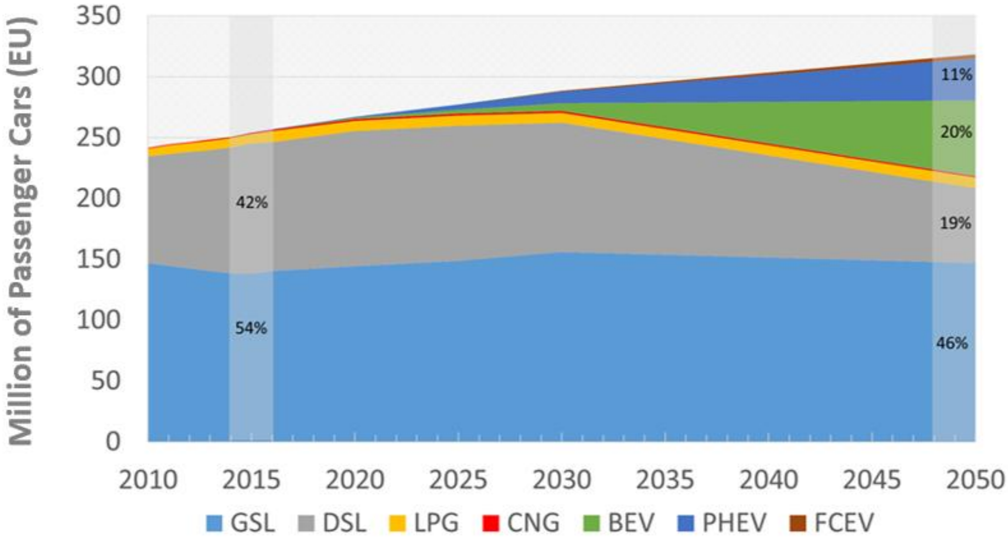
2. A HOLISTIC VIEW TO EXPLORE LOW-CARBON PATHWAYS IN THE PASSENGER CAR SEGMENT

2.1. ROLE OF LIQUID FUELS IN THE PASSENGER CAR SEGMENT: LONG-TERM VIEW

The prevalence of the internal combustion engine in the existing car fleet together with the high share of new vehicles predicts that liquid hydrocarbons will be needed for passenger vehicles through to 2050. In the coming decades, improvements in the efficiency of the internal combustion engine, leading to lower fuel consumption and lower CO_2 emissions, will be an important contribution to the EU decarbonisation objectives for transport.

Some analysts and fleet modelling experts have developed new baselines assessing the potential composition of the passenger car segment in the long term considering a progressive penetration of alternative powertrains. Specifically, EMISIA, a spin-off company of the Aristotle University of Thessaloniki, has recently updated its SIBYL baseline (based on COPERT, a software tool used world-wide to calculate air pollutant and greenhouse gas emissions from road transport), defining the potential evolution of the fleet based on data and scenarios published by the EU Commission, other Institutions and stakeholders (such as the *European Road Transport Research Advisory Council*, ERTRAC). As a result of this update, different scenarios foreseen liquid fuels to be required as internal combustion engine technologies will constitute the main drivetrain technology beyond 2030 (Gasoline + Diesel representing around 60% of the total passenger car segment) even by 2050.

Figure 5 SIBYL baseline as an example of EU Fleet composition towards 2050 (Passenger car)



Note. ICE (GSL) / Diesel (DSL)

Source. EMISIA (SIBYL updated baseline)

Collaboration between OEMs developing ever more efficient combustion engines and the companies producing low carbon liquid fuels purposely designed for such engines, will be key to reduce the carbon emissions associated to road transport.

2.2. LOW CARBON PATHWAYS FOR MOBILITY: A LOOK INTO THE FUTURE ROLE OF LIQUID FUELS FOR PASSENGER CARS.

2.2.1. A general overview

2.2.1.1. Approach

This **first high level assessment** explores different pathways to reduce the WTW CO_2 intensity of liquid fuels in the passenger car segment which can be clustered in 5 main categories:

- **Vehicle-efficiency enhancement:** The future evolution of vehicle designs and internal combustion engines, optimized for efficient combustion of fuels designed for these engines (e.g. higher octane number in gasolines). Such fuels could be produced within the existing refineries and use the existing infrastructure.
- **Extraction of crude oil and refining into products:** Opportunities to improve energy and CO_2 efficiency, during both extraction of crude oil (upstream) and refining the crude into the full range of products (downstream) have been assessed.
- **Alternative low-carbon liquid fuels:** Exploring the potential WTW reduction through the effective deployment of sustainable and low carbon bio and synthetic fuels, including power-to-liquids technologies (*e-fuels*).
- **Improving fuel quality of petroleum-based fuels:** The modification of some fuel properties to optimize these for the latest internal combustion engines (e.g. high octane gasoline).
- **Other technologies/options**, at very early stages of development, could potentially be envisaged to enable on-board capture and later conversion/storage of the final CO_2 emitted at the tailpipe as the final step of the GHG mitigation chain. The potential role of international forest credits will also be explored.

The estimated potential CO_2 savings, the *Technology Readiness Level* (TRL) as well as the main challenges that would need to be overcome to deploy the full potential of these opportunities are described in the following chapters.

A preliminary assessment on what can be achieved for 2030, which is just over a decade away is presented below. An in-house modelling tool developed within the scope of the *Low Carbon Pathways* project integrates the technical potential of each individual pathway, in terms of their individual GHG performance, along with the future availability/deployment based on their current TRL. Thus, this model allows Concawe to assess all the opportunities and their relative contribution in a single overview as a result of the combination of both their potential CO_2 reduction and future penetration. This may reasonably represent an aggregated industry outlook, but any single company is unlikely to deploy all the different options in combination. As with any developing technology, some of the options considered are likely to be deployed widely, others may only find limited deployment and some may not be deemed viable in the longer term.

The level of uncertainty on the potential contribution of different technologies increases as we look further out towards 2050. The EU mid-century policy framework, the future EU energy prices and the level of support given by the future EU industrial strategy and R&D programmes will all influence the level of deployment of a range of technologies. However, even with a high level of uncertainty, it is possible to show directionally the potential CO_2 emissions achievable through the effective deployment of these technologies as far out as 2050.

Further research needed to improve the understanding of the potential impact and costs of identified pathways has been included in Concawe *Low Carbon pathways* working plan.

As a final remark, the *Low* Carbon *Pathways*:

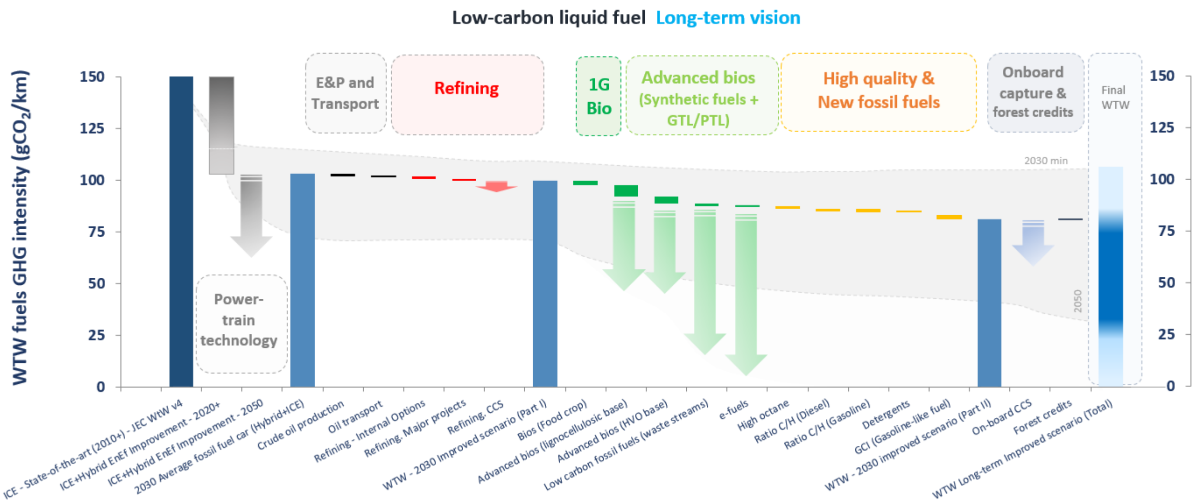
- Is **NOT** intended to be a roadmap or a forecast of the future.
- **DOES** picture a high level assessment illustrating the potential for a wide variety of technologies to contribute to achieve lower WTW CO_2 intensity liquid fuels in the long-term.
- The level of CO_2 reduction that can be achieved by 2050 will depend on different factors (such as technology development, economic, consumer choice and policy support) for different pathways to effectively overcome existing challenges and barriers across Europe.
- Does **NOT** show final results but a future perspective for the potential contribution of different pathways to the future of liquid fuels.
- **IS** intended to be a **live tool** to inform Concawe and other stakeholders.
- **DOES** highlight the importance of a cross-sectorial approach, required to integrate different technologies in a production and supply network. In this context, industrial collaboration is vital in developing and deploying the whole potential of future low-carbon liquid fuels in transport.

2.2.1.2. High level assessment. I. CO_2 intensity potential improvement

The high level assessment provides a framework to produce an integrated WTW view on how different technologies can be used to deliver further CO_2 savings associated with the use of liquid fuels in the passenger cars segment. As mentioned, the in-house modelling tool developed explores the combination of two key parameters: the individual CO_2 reduction potential and the penetration/deployment of different options combined in a single overview.

To compare the relative contribution of each distinct contributions, on a WTW basis, all the emissions are expressed as gCO_2/km travelled. Different scenarios around a 2030 base case explore the impact of the potential penetration of different technologies towards 2050 (2030 Low case and 2050 case). The preliminary results of the 2030 as a reference case, are illustrated below showing the potential role of different individual pathways in the long-term vision for low carbon liquid fuels:

Figure 6 Concawe Low Carbon Pathways model – High level assessment (Passenger cars. C-segment).



Source: Concawe based on different sources referenced in the individual sections of this working plan.

The JEC modelling work (WTW v4) defines the state-of-the art 2010 technology as the basis for average C-segment vehicle. The gasoline and diesel mix used is aligned with the *2016 EU Reference Scenario*. These basis have been used as the starting point for developing different scenarios:

i. <u>2030 Reference Scenario (Bar Chart).</u>

The **colour bars** reflect the potential 2030 reference scenario. As each individual step on the path is based on the combination of the individual CO_2 potential savings (WTW) and their potential availability for deployment, some projects will not realise their full potential by 2030 (e.g. CCS is not expected to be significantly deployed before 2030). In each case there are a number of assumptions made, and these are detailed in the specific sections of this document.

In the early years to 2030, the chart captures the emission reduction resulting from the deployment of technologies that are in the late stages of their *Technical Readiness Levels* for deployment:

- The main contribution arises from higher efficiency internal combustion engines including different level of hybridization and synergies from the second and third generation of hybridisation technologies.
- The most immediate opportunities upstream are the reduction of flaring in crude oil production
- Within refineries, projects targeting energy efficiency improvements have the most impact short term.

Under the assumptions on deployment and technical CO_2 reduction potential in this scenario, this first assessment shows that the combination of the individual contributions of the technologies considered could potentially deliver, an average GHG intensity on a WTW basis of ≈80 g CO_2/km by 2030 for the passenger car fleet in Europe (ICE and Hybrids).

ii. Sensitivity cases are represented by the grey area (Boundaries of the Min 2030/ Mean 2050 uptake scenarios).

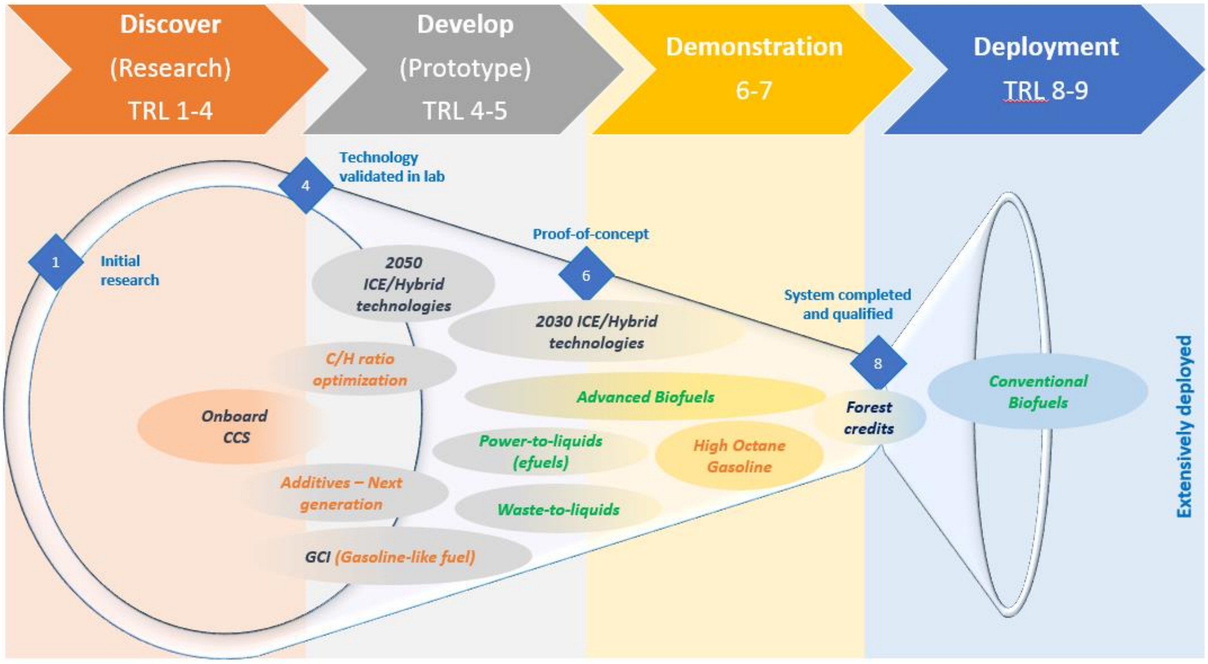
- The **minimum 2030 scenario** represents a future sensitivity case with limited further development of improvements of internal combustion engines and little availability of additional low-carbon fuels. Therefore, the potential improvement for ICEs has been capped to 2020 values (with little further improvement beyond). The availability of biofuels has been heavily constrained without a real development of sustainable advanced biofuels or power-to-liquid fuels. This scenario only achieves a limited improvement of the C-segment technology reaching values close to 110 g CO_2/km.
- A mean **2050 scenario** assumes a higher deployment of all pathways. The aggregation of these different pathways could achieve final WTW values lower than 40 g CO_2/km.

iii. Long-term potential of individual technologies (Arrows).

The **arrows** shows the long term (2050+) potential of the individual technologies without any constraints in terms of availability or future deployment (more details in sections 2.2+). Therefore, they are not accumulative, but are used to show the potential (WTW CO_2/km intensity) for individual pathways to evolve from 2030.

An approach to the *Technology Readiness Levels* (TRL) of the different pathways identified is included below, illustrating how further R&D across EU would be required to release the full potential of the technologies identified:

Figure 7 A comparison of Technology Readiness Levels (TRL) of different pathways



Source: Concawe.

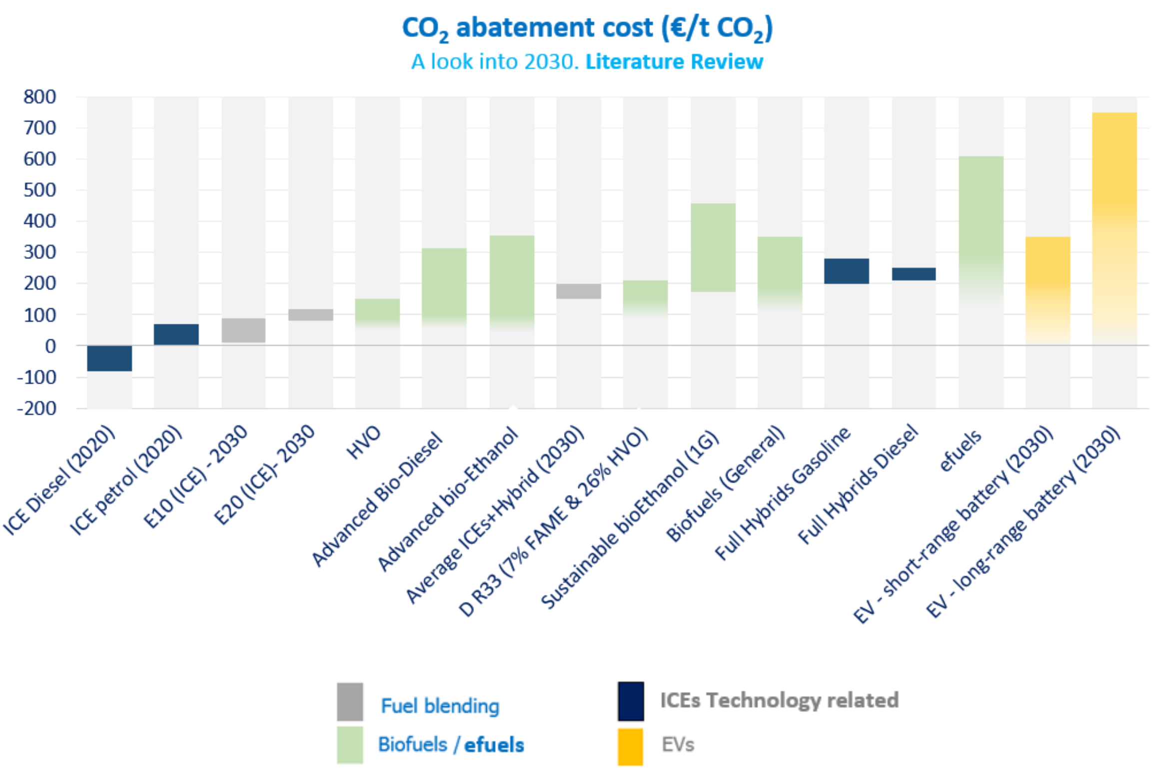
The low-carbon pathways could offer different options for OEMs to meet future CO_2 targets for new cars. This will provide them with options and will complement other alternatives such as PHEVs. It would require that the current transport legislation, based on tailpipe emissions (TTW), is modified to allow the Well-to-Wheel benefits of low-carbon fuels to be factored-in).

2.2.1.3. High level assessment. II. CO_2 abatement costs

Complementing this picture, a preliminary assessment of the CO_2 abatement costs of the identified technologies was conducted using published data. At this stage, the CO_2 abatement cost has been chosen as the cost metric because of its potential to compare different carbon emissions abatement options versus the same basis. When the methodology behind the abatement cost calculation is applied across different technologies, the outcome reflects the economics of an individual pathway (*CAPEX required as potential extra investment* vs OPEX as *fuel savings*) in order to leverage the same level of CO_2 emissions savings. Thus, it was found that the methodology is extremely sensitive to the aggressiveness of the assumptions made and factors such as future fuel and electricity prices (and their evolution towards 2050), the boundaries of the analysis specifically defined as well as other financial parameters heavily affect the final outcome. Therefore, the CO_2 abatement cost has been used at this stage as a tool for comparing technology on a same economical basis but it should not be considered as a financial criterion for deciding investments. Our Concawe final holistic picture of the low carbon pathways will integrate all the CO_2 abatement cost of different technology across all transport sectors.

On this basis, the comparison presented below illustrates the wide range of abatement costs presented in the literature:

Figure 8 A look into 2030 CO_2 abatement costs of different low carbon fuels and powertrain technologies. C-class vehicle



Source: Concawe based on different sources: Roland Berger (Gasoline ICE vehicle as the reference), VividsEconomics, LBST, dena, ePURE, EU DG.

Note. This picture is intended to show a cost comparison for a C-class vehicle. The vehicle-related costs will vary depending on the segment considered.

As highlighted in the figure above, there are a number of different technologies expected to deliver significant CO_2 savings at a reasonable CO_2 abatement costs by 2030. Beyond that timeline, there is a notable uncertainty around the real penetration and market success of such technologies driven by economic factors such as the future price of electricity, the future production costs of alternative fuels and the forecasted price of battery packages – expecting to bring the electric powertrains down in the forthcoming years (This has been reflecting in the above figure by a degradation in the colour scheme used).

Future economics of new technologies – especially e-fuels or electric vehicles – are controversial as they are heavily influenced by policy choices. Therefore, further sensitivity analysis will be performed to explore the potential impact of key factors such as the expected reduction in battery costs – reaching values below 100 $/kWh as forecasted by different analysts – to be progressively contrasted with the real evolution of these costs in the future.

2.2.1.4. High level assessment. III. Life-Cycle Analysis (LCA)

A Well-to-Wheels analysis is useful in comparing the emissions generated in the production and consumption of different liquid fuels and does allow a full comparison of distinct energy / propulsion alternatives such as diesel and ICE comparisons with electricity and electric drivetrains.

Life-Cycle Analysis broaden the scope to also compare the embedded CO_2 emissions associated to the production and disposal of the materials used in production of the car and then for electric vehicles, the battery. Currently there is a **lack of data** from manufacturers and a recognized **standardized basis** for conducting LCAs for vehicles (especially for batteries). Whilst these limitations prevent LCA methodology from being used more widely, it is still feasible to use the LCA methodology covering:

Figure 9 LCA analysis: A Bigger Picture.

Source: Ricardo (2018).

When comparing different electric vehicles with conventional powertrains, the relative impacts associated with the energy or fuel generation, materials extraction, manufacturing and production phase, the contribution to the total life cycle emissions are distinct. As an example, based on a recent analysis conducted by Ricardo:

Table 1 Percentage (%) of non-in use emissions of different powertrains

Type of vehicle	% CO_2 emissions vs total LCA	Main factors affecting the % of non-use CO_2 emissions vs total (LCA)
Internal Combustion Engines	20-30%	Materials, manufacturing and fuel production
Electric and H_2 fuel cell	30 – 70%	Depending on battery size, carbon grid intensity & mileage.

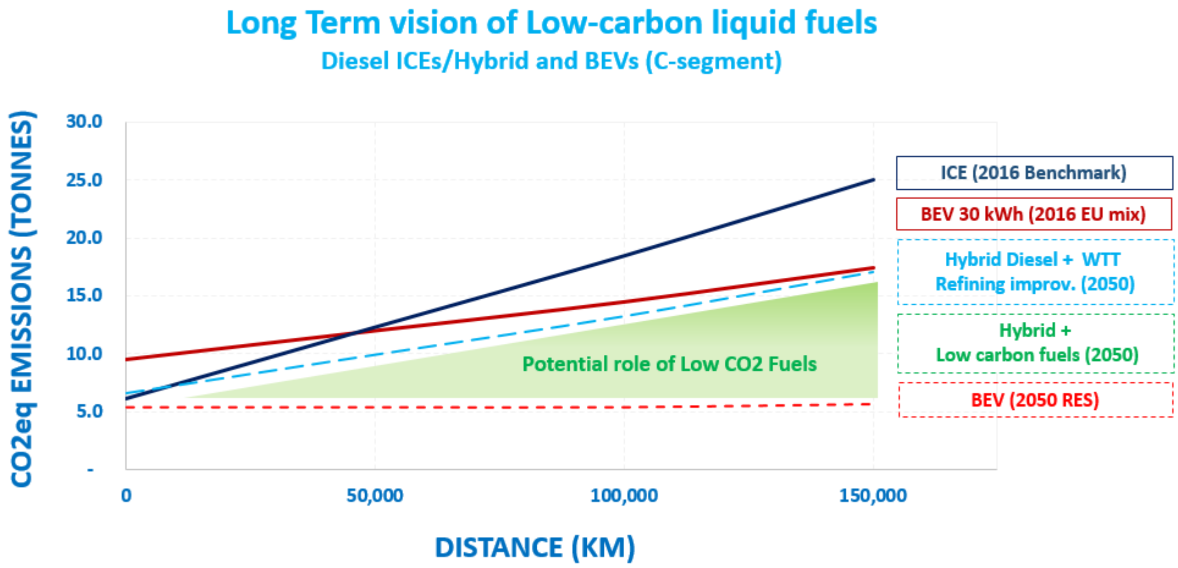
Depending on the powertrain considered, a LCA approach can be used to assess how the environmental impacts are allocated over the life of a vehicle and also to identify areas for further improvement.

The manufacture of batteries for Electric Vehicles is highly energy intensive, which means that the CO_2 emissions generated during the production of Electric Vehicles (so called embedded emissions) are significantly higher that than the equivalent Internal Combustion Engines (ICE) based vehicles. The embedded emissions from battery manufacturing will depend on the size of the battery installed as well as the specific location for the production plant and due to the battery manufacturing. Steps are being taken to reduce the embedded emissions, for instance by locating the battery manufacturing sites in areas with a high renewable content in the electricity supply and via research to improve the energy density of batteries.

In **Figure 11**, Concawe present a preliminary assessment of different powertrains (C-segment vehicle) where a Battery Electric Vehicle (solid red line) would have embedded emissions double that of the equivalent diesel ICE vehicle (solid blue line) associated to the battery manufacturing process. However, this example shows that once in use and during the first 50,000 km driven, the emissions from the diesel fuelled vehicle would remain lower than the overall emissions from an EV when the anticipated 2030 EU average electricity mix is considered. In countries where the electricity mix has a higher than average share of renewables the EV advantage would increase, but vice versa in countries where there is a high proportion of coal power in the mix, the advantage would shift over the lifetime of the vehicle. **Figure 11** is also used to show, on a conceptual basis, how the future higher efficiency internal combustion engine technologies, combined with low-carbon fuels, have the potential of delivering significant CO_2 potential savings (dotted blue and green lines).

This combination may well give overall CO_2 emissions comparable with forecasted figures for future (2050) improved battery EVs using mainly renewable generated electricity (dotted red line).

Figure 10 Potential role of Low Carbon fuels in a LCA (Conceptual approach)



Source: Concawe internal work based on data from NTNU[14], IVL[15], COM data adapted from **BMVI[16].**

Assumption: one battery along the whole lifetime (CO_2 intensity for battery production: 150 kg CO_{2eq}/kWh battery)

The life cycle analysis of different future fuel and vehicles combinations enables informed decisions to guide research and broaden the options available in meeting the EU decarbonisation goals. Concawe is currently exploring the total LCA impact of these future powertrains, to guide the development of these future fuels. Concawe is willing to engage with external stakeholders to assist in defining a standard LCA methodology to be applied to fuels and powertrains in the future.

[14] NTNU. https://www.concawe.eu/wp-content/uploads/2017/03/Ellingsen-LCA-of-BEVs_edited-for-publication.pdf
[15] Romare& Dahllof, IVL Sweden. *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries.*
[16] BMVI (2016), publ. Final report: Assessment of the feasibility and environmental impacts of electric vehicles.

2.2.2. Power-train technologies. The evolution of the Internal Combustion Engine (ICEs).

Next generation of Internal Combustion Engines

- **Potential CO_2 savings**: The internal combustion engine has the potential for progressive improvement towards 2050. Opportunities such as light-weighting, waste heat recovery and increasing levels of hybridization will give much improved fuel efficiency and a consequential reduction in the TTW CO_2 intensity of ICE vehicles. An energy consumption equivalent to 60 g/km, (TTW) over an NEDC equivalent cycle at 2050 seems to be realistically achievable for next-generation of C-class ICE and hybrid vehicles. In future powertrains, diesel and gasoline technologies are likely to converge progressively towards 2050.
- **TRL**: 3 - 7.
- **Challenges**: OEMs have initiated R&D programs to design the next generation of Internal Combustion Engines.
- **Areas for further work (Concawe)**: Work with OEMs (Companies and Associations) and other stakeholders to explore the maximum potential of the combination of low-carbon fuels in the most efficient engines.

2.2.2.1. Internal Combustion Engines: Energy efficiency enhancements and incorporation of electrification.

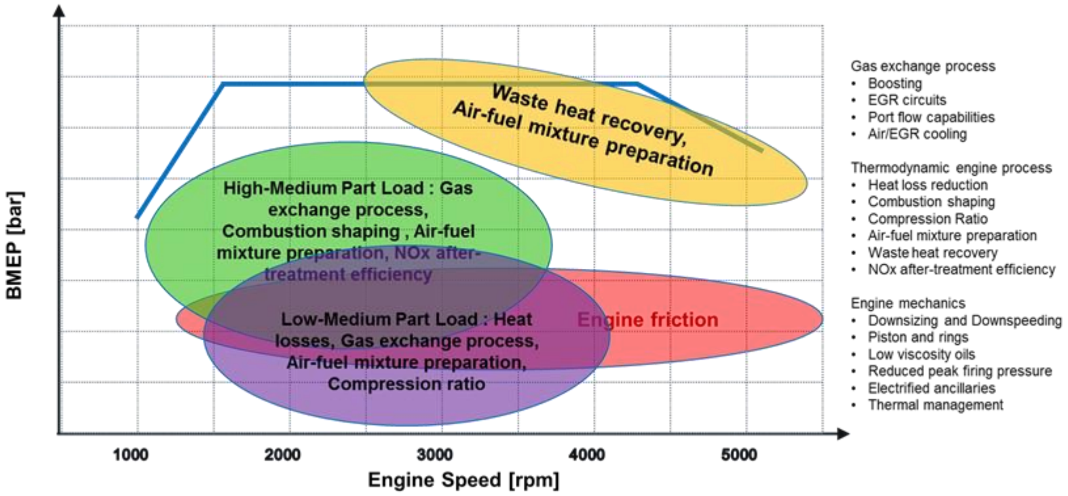
Internal combustion engines have been used as the basis of the powertrains for cars during the last century. Europe has led the development of diesel technology resulting in around 50% of the EU passenger fleet being diesel, while in most other parts of the world gasoline dominates the passenger car markets. Diesel technology is superior to gasoline technology in terms of CO_2 reduction and efficiency with comparable power output. Improvements in the combustion process and other vehicle improvements in both gasoline and diesel have gradually reduced the fleet average CO_2 of passenger car vehicles. Hybrid drivetrains, combining a conventional powered internal combustion engine with the capability to be driven electrically have also been developed. Hybrid vehicles can be used in electric mode in urban driving environments, and in ICE mode for intercity or rural use giving them a similar driving range to their diesel counterpart. In addition battery electric vehicles are also being developed for passenger cars with shorter ranges.

This trend is likely to continue, such that by 2050, the majority of passenger cars are likely to have some sort of electrification included and Hybrids and so called Plug in Hybrid vehicles or PHEVs are likely to play an increasing role in the future.

Nevertheless there are still further opportunities for improving the efficiency of the Internal Combustion Engine, for example by the combination of multiple solutions:-

a) Downsizing of the engine and total weight reduction
b) Maximizing heat recovery, implementing new advanced thermal management Devices (see different solutions included in **Figure 13**).
c) Maximizing efficiency across the performance curve

Figure 11 Multiple solutions for recovery heat losses (ICE)

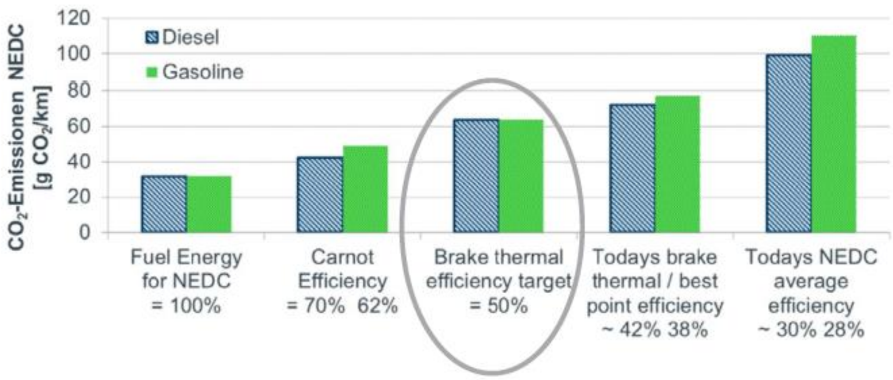


Source: ERTRAC[17] (2016)

[17] Future Light and Heavy Duty ICE Powertrain Technologies. ERTRAC (2016)
http://www.ertrac.org/uploads/documentsearch/id42/2016-06-09_Future%20ICE_Powertrain_Technologies_final.pdf

The following figure produced by ERTRAC in 2015 provides a clear understanding of the minimum TTW CO_2 intensity that is theoretically achievable:

Figure 12 Theoretical analysis of the potential TTW improvement of ICEs. Mid-class vehicle of 1360 kg (NEDC).



Source: ERTRAC[18] (2016).

Note. It is important to note that the g CO_2/km values (Y-axes) are calculated assuming a constant Brake Thermal Efficiency (BTE) map (Flat curve on the engine speed-load map). Under real world conditions, the efficiency map will not achieve the best BTE at all points and, depending on the speed, the engine will operate at lower efficiency conditions, thus, emit higher CO_2 emissions. The latest development of the engines and gear boxes are targeted to flatten this engine speed-load curve as much as possible while delivering maximum efficiency across different driving modes.

2.2.2.2. A look into 2030 technologies: JEC consortium[18], Roland Berger & PE International

Within the scope of the JEC consortium, a modelling work to compare the TTW CO_2 intensity of different types of fuels within current and new powertrains is conducted exploring the combination of both improved vehicles and engine technologies. This has been used in this study to identify which combinations achieve the lowest CO_2 emissions. The previous JEC WTW v4 study detailed the TTW values for the state-of-the-art technology in 2010 and the potential for improvement by 2020 and beyond:

Table 2 Technology walk for 'ICE only' powertrain configurations. State of the art technologies (NEDC). Modelling basis (JEC WTW v4)

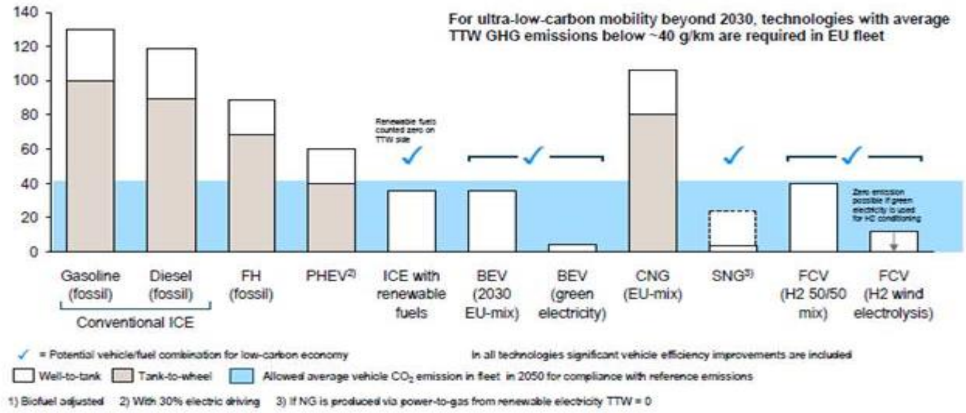
Powertrains (g CO_2/km) State-of-the-art	2010	2020+
Gasoline PISI - ICE	155.1	110.2
Gasoline DISI - ICE	149.6	104.5
Gasoline DISI - Hybrid	104.9	69.0
Diesel DICI - ICE	119.0	86.8
Diesel DICI - Hybrid	104.9	69.0

Note. The results of the modelling work of a 2010 state-of-the-art technology have been assumed as the starting point for our Concawe high-level assessment. JEC is currently updating the WTW study and EUCAR - working with AVL- is modelling the 2016/2025+ ICEs and Hybrids technologies. The TTW results of this process will be integrated in this assessment.

[18] JEC WTW v4. http://iet.jrc.ec.europa.eu/about-jec/downloads

Other studies, such as **Roland Berger**[19] show similar levels of estimated GHG intensity for pure ICEs and other powertrains with different levels of hybridization, assuming that 2020+ technology will be effectively deployed by 2030:

Figure 13 WTW GHG Efficiencies by technology (Average C-segment vehicle 2030 [g CO_2/km])



Source. JEC, Roland Berger (2016)

Note. It has to be remarked that, in this analysis, TTW CO_2 intensity of biofuels were set to zero (the CO_2 emissions generated during their production is considered within the WTT analysis).

The level of development of the 2030 technology will be highly dependent on the OEM's continued R&D investments in Internal Combustion Engines and, PE International[20] in their Low CVP report, present two different 2030 scenarios considering a typical case that shows lower potential improvement for ICEs than the best one:

Table 3 Comparison of 2030 typical vs Best Case (PE International)

	Type of vehicle	Current	2030 Typical Case		2030 Best case	
		l/100 km	% improvement in fuel consumption	l/100 km	% improvement in fuel consumption	l/100 km
ICEs	Mid-size petrol (Megane)	5.83	13%	4.93	19%	4.7
Hybrid	Mid-size full hybrid (Toyota Auris)	4	14%	3.46	16%	3.4

Therefore, the development of ICE to realise the real potential for efficiency improvement, achieving higher CO_2 savings in the medium term, will require ongoing long-term R&D investment.

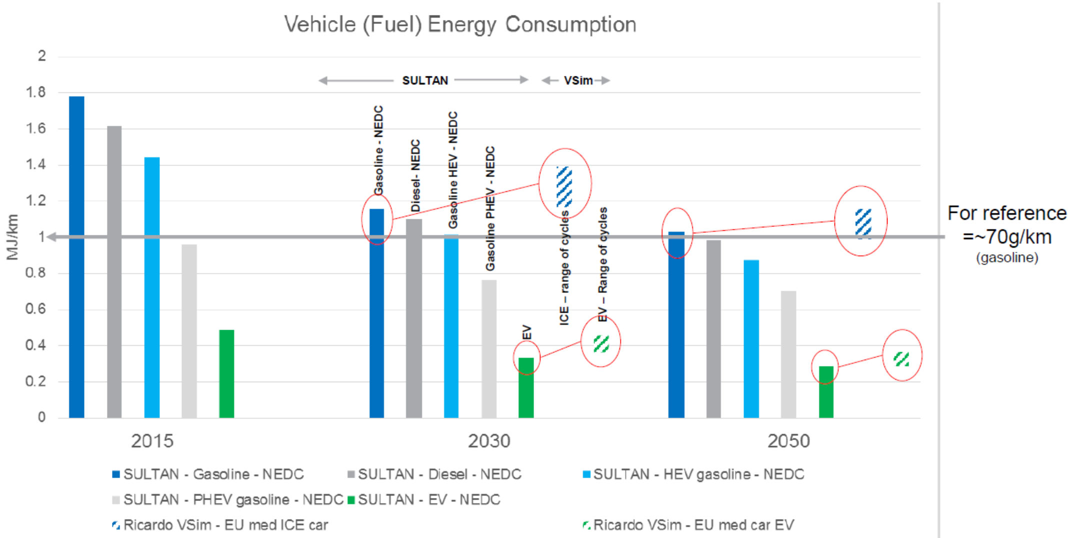
[19] Roland Berger. Integrated fuels and vehicles roadmap to 2030+ (2016)
https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&ved=0ahUKEwi8y5_t6JzWAhUKEVAKHQ2KBzkQFghIMAQ&url=https%3A%2F%2Fwww.rolandberger.com%2Fpublications%2Fpublication_pdf%2Froland_berger_integrated_fuels_and_vehicles_roadmap_to_2030_v2_20160428.pdf&usg=AFQjCNFVPi7zdfXxcgHb7SKCk4lvB682fg
[20] PE international/LowCvp (Life Cycle CO2e Assessment of Low Carbon cars 2020-2030). (2013)
http://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwipi5nW1aHTAhUFiRoKHY8qDLYQFggkMAA&url=http%3A%2F%2Fwww.lowcvp.org.uk%2Fassets%2Freports%2FCONFERENCE%252013%2520Final%2520Report_Lifecycle%2520CO2%2520Assessment%2520of%2520Low%2520Carbon%2520Cars%25202020-2030_PEJuly2013.pdf&usg=AFQjCNEwG37h6xo0luB0DyNWpDRha4w3bQ&bvm=bv.152180690,d.d2s

2.2.2.3. A look into 2050: ERTRAC & Ricardo.

Beyond 2030, ERTRAC is currently conducting a public assessment of different technologies exploring the 2050 framework. Preliminary results from their modelling study shows that a new engine map with 50% peak engine efficiency could be reached by reducing both pumping, friction and heat losses. ERTRAC modelling gives similar results to those presented by Ricardo for the 2050 TTW CO_2 intensity.

Similarly, a recent analysis conducted for Concawe by Ricardo also shows that, on average, a value of **60 g CO_2/km** (equivalent NEDC) could potentially be achieved with certain level of hybridization by 2050.

Figure 14 Results of the SULTAN ICE and EV energy assumptions for medium EU passenger car at 2030 and 2050



Source: Ricardo – Ad-hoc study for Concawe (2018)

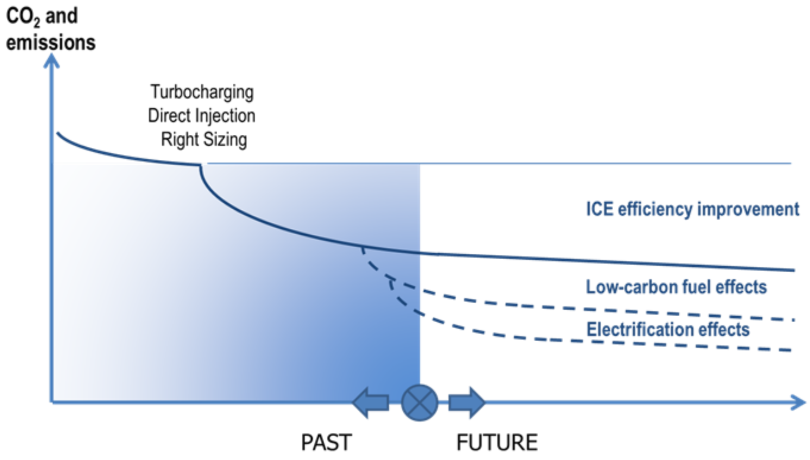
Note. Ricardo *VSimanalysis* uses assumptions about future BSFC maps, transmission efficiency, vehicle mass, aerodynamic drag and rolling resistance to calculate energy consumption over a range of cycles. (SULTAN is Ricardo's transport policy analysis tool).

Different companies are also investing in new technologies and prototypes of new internal combustion engines with the potential to be more efficient than existing ones. One example of this type of technologies is the next-generation two-stroke compression-ignition opposed-piston (OPGCI) engines being developed by companies such as *AchatesPower*[21], based in the USA with the goal of 50% more efficient than conventional gasoline engines. The *Oil & Gas Climate Change Initiative* (OGCI), a CEO-led initiative of 10 oil and gas companies, has recently announced an investment of $29.8 million to accelerate the commercialization and continued development of this technology with clear synergies with alternative Heavy Duty opposed-piston engines22.

The effective combination of more efficient engines with different levels of hybridizations – along with the potential role of low-carbon liquid fuels – is shown in the figure below, highlighting how an integrated approach could lead to a major CO_2 emissions savings:

[21] http://achatespower.com/opgci-an-evolution-that-revolutionizes-the-internal-combustion-engine/
[22] http://www.greencarcongress.com/2017/10/20171027-achates.html

Figure 15 Expected development of the ICE (ERTRAC 2016)[23]



Based on the data detailed above, for the preliminary assessment of the potential contribution of low-carbon fuels to achieve an even higher CO_2 savings, the following premises have been assumed:

- Beyond 2030, the new sales of gasoline and diesel vehicles will be mostly hybrids based on the most efficient internal combustion engines (with a moderate penetration of electric vehicles).
- It is expected that the size – and the weight – of the vehicles will be reduced and, therefore, a compact vehicle (C-class) will be representative of the passenger car segment.
- In passenger cars, the ratio of gasoline to diesel engine vehicles determines the overall efficiency of the whole fleet. A range of reference sources indicate that a ratio 40%/60% of gasoline/diesel is likely for the 2030-2050 timeframe. More recent indications suggest that this ratio may change, so it will be important to conduct some sensitivity analyses for different ratios. However, towards 2050, the efficiency of gasoline and diesel hybrid technologies are expected to progressively converge such that the potential WTW impact of this ratio may become less important in the future.

2.2.3. Production of oil-based products. Reduction of WTT CO_2 intensity

2.2.3.1. Oil production & Transport (Upstream)

Potential CO_2 savings from Oil Production (Upstream) & Transport

- **Upstream**: The potential opportunities to reduce the total WTT CO_2 intensity of oil-based fuels have been estimated to range from 5% by 2030 up to 10% by 2050 (g CO_2/MJ) subject to the development and implementation of different technologies and Energy Management Plans in the upstream fields. For the emissions associated to the transport of crude oil, a conservative potential reduction of 10% in 2030 to 20% by 2050 has been considered.
- **Challenges**: In the upstream sector, further research based on better CO_2 and energy inventories would be needed to perform a more precise assessment of the real opportunities. The successful implementation of initiatives such as zero-routine flaring one will result in higher savings.
- **TRL**: TRL > 7
- **Areas for further work:** Monitor progress on upstream emissions reductions

[23] http://www.ertrac.org/uploads/documentsearch/id42/2016-06-09_Future%20ICE_Powertrain_Technologies_final.pdf

As mentioned before, at EU level, 12% of the CO_2 emissions are released during the production and transport of crude oil. The basis for this assumption comes from a model of different oil production fields: the OPGEE model (*Oil production greenhouse gas emissions estimator*) contracted by DG CLIMA[24] and developed by ICCT, working with Stanford University, Energy Redefined and *Defense Terre* This predictive model accounts for production, processing and transport of crude petroleum, including seven process stages in its scope: Exploration; Drilling and Development; Production and Extraction; Surface Processing; Maintenance; Waste Disposal; Crude Transport.

The OPGEE model output was calibrated against data from individual oil fields to provide estimates of the carbon intensity of the different oils supplied to the EU in 2010, and the potential for future improvement. Some of the data used for this calibration was not publicly available and, therefore, some assumptions and default values were included in the analysis. As and when more data becomes publicly available, the calibration of the OPGEE model may be improved. Despite these uncertainties, the OPGEE models provides an estimate of the carbon intensity of the average upstream carbon intensity of oil supplied to the European Union in 2010.

1. Production of crude oil

As mentioned above, the opportunities to reduce the CO_2 emissions are associated with a number of different process stages from the production process itself – at the oil field – to the surface processing facilities. Different initiatives to reduce the CO_2 emissions have been put in place at international level, such as the "*Zero Routine Flaring by 2030*"[25] initiative introduced by the World Bank, bringing together governments, oil companies and development institutions who agree to cooperate to eliminate routine flaring by 2030. This has the potential to reduce emissions to the atmosphere by more than 300 Mt CO_2. The implementation of effective *Energy Management Systems*, including energy audits to identify further potential energy efficiency and CO_2eq reduction projects could also decrease the total CO_2 savings associated with this stage.

The implementation of effective *Energy Management Systems*, including energy audits to identify further potential energy efficiency and CO_2eq reduction projects could have the potential to decrease the total CO_2 savings associated to this stage.

Although the estimate of the potential savings would require further detailed work beyond the scope of Concawe's activities a potential of 5% CO_2 intensity reduction by 2050 and 10% by 2050 has been assumed as a preliminary estimate. This is based on the potential savings associated with the broad implementation of *Energy Management Systems* at the oil fields.

2. Transport of crude oil

A variety of transport modes including pipelines, shipping and road transport are used to transfer crude oil to the refining facilities. There is not sufficient information available to identify the potential CO_2 savings associated with all aspects of this stage.

One reference that is available is from vessel efficiency programmes within the shipping industry. This can be considered to be a representative indication of different initiatives to mitigate the emissions associated with the transport of crude oil. As an example, the Energy Efficiency Design Index (EEDI) which

[24] CLIMA.C.2/SER/2011/0032r on the Upstream Emissions of Fossil Fuel Feedstocks for Transport Fuels Consumed in the EU.
https://circabc.europa.eu/sd/a/6215286e-eb5f-4870-b92f-26acff386156/ICCT_Upstream-emissions-of-EU-crude_May2014.pdf
[25] http://www.worldbank.org/en/programs/zero-routine-flaring-by-2030

measures a ship's CO_2 emissions per capacity mile, is expected to be reduced by 10% in 2020 and 30% by 2025. This includes unconventional and innovative opportunities in the ships' designs. Given the current rate of fleet renewal, the time taken for new technologies to be deployed throughout the shipping fleet, together with the uncertainty associated with other means of transport, a more conservative potential for emissions saving has been assumed in this study (10% in the 2030 mean scenario). Further research would be required to better estimate such potential savings. The assumptions of this preliminary assessment will be updated as new data becomes available in the future.

2.2.3.2. Refining

Potential CO_2 savings from Refining

- **Refining:** During the refining stage, when all options are exercised, the total EU refinery CO_2 emission intensity can potentially be reduced by 20 to 30% by 2030 and up to 70% by 2050, compared to the 2030 reference case.
- **Challenges**: Whilst there are a number of energy efficiency opportunities, two factors with a high emissions reduction potential in the refinery. These are the decarbonisation of the electricity grid and the effective deployment of CCS/CCU across Europe. A third opportunity will be the integration of different production routes for low carbon fuels. Supported for R&D in this area will be critical.
- **TRL**: 4 – 9.
- **Areas for further work** :
  - Concawe study on CO_2 efficiency in the EU refining system (2030/2050). Concawe report 7/18.
  - Potential synergies of the refining industry with other low-carbon pathways.

The potential reduction of the Well-to-Tank CO_2 emissions associated with the production of final refined products – is explored in this section, identifying areas and a number of opportunities that have the potential to reduce the final WTW CO_2 intensity of oil-based fuels and products (See figure 1 for reference).

The processing of crude oil into petroleum products is energy intensive and currently accounts for ≈ 7% of the total WTW CO_2 intensity of oil-based fuels (g CO_2/MJ). A number of opportunities to reduce the CO_2 intensity of oil based fuels have been identified. These fall into three categories:

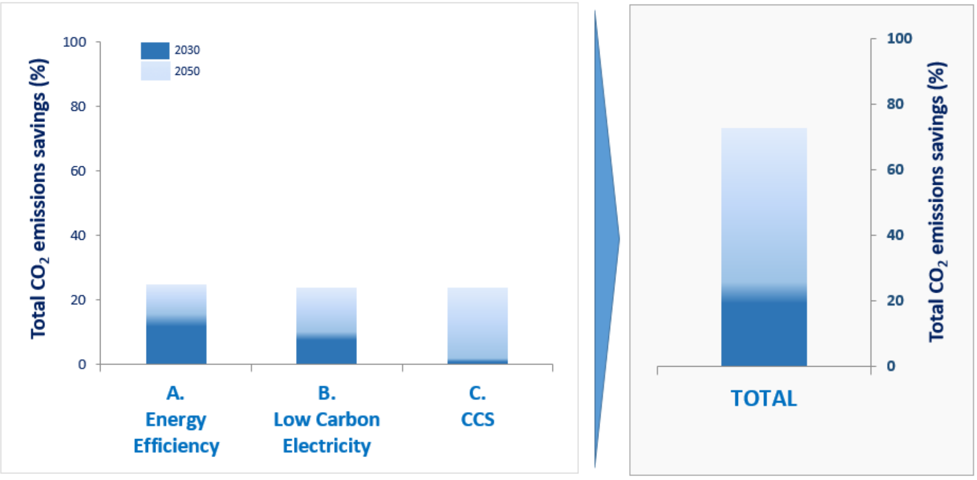
a) Refinery process efficiency including, for example, an increased recovery of refinery low-grade heat to produce electricity as well as major capital projects reflecting changes to the technical configuration of individual refineries.
b) Use of low carbon energy sources being progressively implemented in the refineries as the electricity and gas mix is progressively decarbonized.
c) CO_2 capture for further storage (CCS) and / or use (CCU).

Hydrogen is used in several refinery processes, including hydrotreating to remove Sulphur from middle distillates, as well as hydrocracking to upgrade lower value vacuum gasoils and heavier residues from the distillation process. Hydrogen is produced as a by-product in the naphtha reforming process or in dedicated hydrogen production units such as Steam Methane reforming.

The production of *green* hydrogen within the refinery, for instance through the electrolysation of water using electricity from renewable sources provides one option to reduce the carbon-intensity of refinery products. Other alternatives such as the production using natural gas as the raw material in Steam Methane Reforming units coupled with a CCS/CCU scheme are also considered.

Figure 16 shows the cumulative total emissions savings (i.e. including emissions from production of imported electricity) for the main opportunities identified. Each bar shows the cumulated potential for a specific group under different scenarios from 2030 Low to 2050 High.

Figure 16 Potential CO_2 emissions savings for the EU refining system.



Source. Concawe ***7/18 report***. *Low Carbon Pathways CO_2 efficiency in the EU Refining System. 2030 / 2050. Executive Summary (Interim report).*

When all options are deployed, the total **EU refinery CO_2 emissions** have the potential to be reduced by approximately **20 to 30% by 2030 and up to 70% by 2050**, compared to the 2030 reference case. Whilst this will be representative of the industry as a whole, we cannot assume that every option will be appropriate in every refinery. Different refineries are likely to make different investment decisions based on their individual characteristics and their overall business model. However it is clear that there is there is potential to reduce the CO_2 intensity of individual products derived from crude oil.

This approach, already described in the **1/17 Concawe report**[26] is proposed to properly estimate the potential evolution of the CO_2 intensity factors of all refining products.

Table 4 WTT CO_2 intensity factors per type of fuel (Basis to estimate future WTW CO_2 intensity reductions).

WTT CO_2 intensity factors g CO_{2eq}/MJ	Concawe values 1/17 report
LPG	5.2
Gasoline	5.5
Kerosene	6.1
Diesel	7.2
Marine Gasoil	2.9

Note. Concawe 1/17 report. Study case representing EU refining in 2010

When the reductions in CO_2 intensity both gasoline and diesel fuels are combined with the likely improvements in efficiency of the internal combustion engines it is possible to express the refinery CO_2 savings in the form of Well-To-Wheels savings for the passenger car segment.

[26]https://www.concawe.eu/wp-content/uploads/2017/04/Rpt_17-1-1.pdf

2.2.4. Alternative low-carbon liquid fuels: Biofuels and efuels

Alternative low-carbon fuels (2030/2050)

- **Potential CO_2 savings**: A first look into the 2030 timeframe considers the two factors: the potential availability per type of sustainable biofuels based on what the industry could potentially deliver by 2030 (*Conservative Scenario* defined by SGAB) combined with the WTW CO_2 intensity of the associated individual bio-pathways (Based on the latest report published by JEC). It has been estimated that the combination of both factors could potentially leverage a further WTW reduction of 12%. Beyond 2030, different pathways (e.g. efuels) have the potential to achieve higher CO_2 reductions when they are individually considered (See figure 6 and 20 for additional references) and the real impact will be heavily dependent on the effective deployment of the most promising and less CO_2 intensive bio-technologies identified.
- **TRL**: 4 - 9
- **Challenges**: Improve conversion efficiencies, achieve cost reduction and ensure sustainable availability of raw materials. Cross-sectorial challenges including mobilization of waste and residue biomass material. A stable policy framework and industrial R&D programmes to support the effective development and deployment.
- **Areas for further work (Concawe)**: A) Update of the JEC WTW v5 including the WTT assessment of new pathways. B) Assessment of the potential improvement of bio-based fuel technologies towards 2050. C) Exploring the role of e-fuels in the whole EU economy (2030-2050 framework). D) The role of negative emissions to be explored. E) Exploring synergies with existing refining facilities. F) A holistic look across all transport sectors.

2.2.4.1. Sustainable biofuels and efuels: Potential CO_2 savings and sustainable availability

Sustainable biofuels, subject to the updated sustainability criteria currently proposed by the European Commission[27], are one of the main low-carbon liquid alternatives to petroleum based fuels for transport, as they are easily deployable using existing transport infrastructure.

The *Renewable Energy Directive*[28] (RED) and the related directive which brings together the RED and the Fuels Quality Directive (FQD)[29] - the so called “iLUC Directive”[30] set out biofuels sustainability criteria for all biofuels produced or consumed in the EU to ensure that they are produced in a sustainable and environmentally friendly manner. Until 2020, there is a 7% cap on conventional biofuels, including biofuels produced from energy crops, to count towards the renewable energy directive targets regarding final consumption of energy in transport in 2020. Secondly, the directives set an indicative 0.5% target for advanced biofuels as a reference for national targets which were set by EU countries in 2017. Thirdly, the directives harmonized the list of feedstocks for biofuels across the EU whose contribution would count double towards the 2020 target of 10% for renewable energy in transport (Annex IX). These directives required that biofuels produced in new installations emit at least 60% fewer greenhouse gases than fossil fuels. A follow on from the RED which will apply from 2021 – 2030 is currently being discussed between the European Commission, Parliament and Council. Gasoline fuels in Europe typically contain up to 10% bio-derived oxygenates usually in the form of ethanol, while diesels can contain up to 7% fatty acid methyl ester although other bio-derived components are also being increasingly used.

[27] https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria
[28] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009, Brussels: Office of European Union.
[29] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009, Brussels: Office of European Union.
[30] Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Official Journal of European Union.

The combination of the most-efficient power trains with low-carbon fuels, based on sustainable bio-based materials, wastes or renewable electricity, has the potential to achieve significant WTW CO_2 savings across all transport sectors.

Future advanced biofuels and efuels are heavily dependent on the evolution of existing technologies which will require R&D to **improve conversion efficiencies** and **achieve cost reduction.** Ensuring **future sustainable availability** of existing – and new - raw materials will be key and future feedstocks are expected to be based on a wider variety of sustainable feedstocks including biomass residues, wastes and micro/macro algae. The future contribution of these technologies to reduce the final WTW intensity of ICEs in the 2030-2050 framework will be heavily dependent on two factors: the future availability of raw materials and the CO_2 savings associated to the most effective and extensively deployed conversion pathways. .

The assessment of different types of biofuels and efuels, their synergies with respect to the ability to co-process or locate new plant within existing refineries will help realise their potential contribution to the decarbonisation of all transport modes. This will be further explored as part of Concawe's working plan.

For this preliminary assessment, the work is focused on technologies with the ability to contribute to the 2050 low-carbon economy, assessing the potential contribution of different pathways to reduce the CO_2 intensity of transport by 2050 and the future availability of raw material. The work conducted under the *JEC consortium* (JRC – EUCAR – Concawe) and the recent report published by the *Sustainable Group on Advanced Biofuels* (SGAB) are the main inputs considered to define a preliminary 2030 picture with the ability to support the vision towards 2050.

a) <u>Technologies / R&D</u>

First generation biofuels are already used in formulations with petroleum streams to produce fuels with a lower carbon intensity. As they become available, advanced biofuels and power-to-liquid fuels will enable further decarbonisation of liquid fuels.

- ***Sustainable bio-fuels (biomass-based)***

  Emissions resulting from combustion of sustainably produced and processed biomass can be recognized as virtually zero emissions over time (*combustion credit*), as new biomass is grown to replace it, effectively recycling the CO_2 released during combustion.

  Some form of advanced biofuels are already produced in sufficient scale to demonstrate their potential. Whilst some new sources, such as algae, are currently being scaled-up, others are at an earlier stage of development.

  - **New sustainable raw materials** – further R&D is required to identify and develop new algae varieties with enhanced lipid production and viable growth rates.
  - **New or improved conversion processes** to give better efficiency and higher conversion ratios are needed to improve the economics. Different gasification or lipid routes may have the potential to deliver WTW intensities lower than 20 g CO_2/MJ by 2030, with a 25% further improvement by 2050 (including all opportunities such as the decarbonization of electricity used in the production and processing of these fuels).

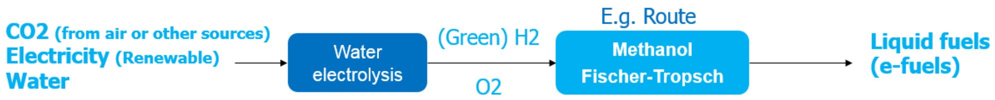
- ***Waste-to-fuels***

  The evolution of the waste management and treatment pathways is required in order to implement effectively *circular-economy* concept across Europe. The development of new technologies to adapt waste processing streams such as plastics or municipal waste materials for use as raw materials for the production of final fuels may contribute to both the EU circular economy as well as the decarbonisation goals.

- ***efuels***

  The production of synthetic fuels using renewable electricity represents another pathway to decarbonise liquid fuels, for example using industrial waste flue gases as a source of carbon. Using renewable electricity to produce "green" hydrogen through the electrolysis of water is one of the most promising power-to-fuels routes. Whilst these technologies have been successfully demonstrated at pilot plant scale[31] the future challenges are in the scalability and in the accessibility to low cost renewable electricity. This is a rich area for development as fuels can achieve WTW CO_2 intensities as low as 15 g CO_2/km[32] in a diesel engine. Furthermore e-fuels offer a means of storing energy in a stable and transportable form.

Figure 17 Simple scheme of the e-fuels route (Concawe). Example for liquid efuels



Different reports have been recently published exploring in more detail this concept introducing innovative ideas such as the potential import of efuels produced at places with favourable weather conditions for producing renewable electricity[33].

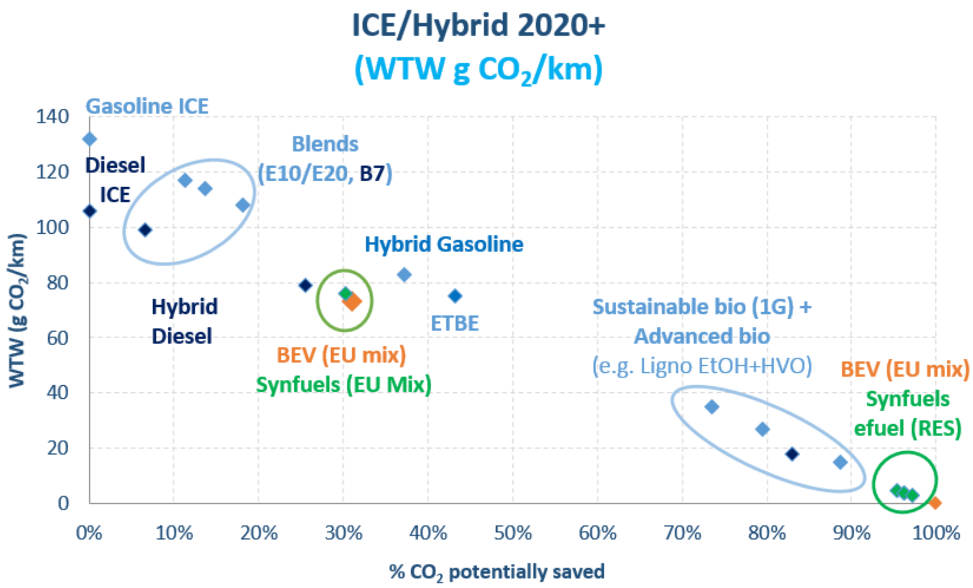
As a reference for the potential technologies available by 2030, the **Sub Group on Advanced Biofuels** (SGAB) of the *Sustainable Transport Forum* (STF) published in 2016 a very comprehensive report identifying different technologies, their TRL and their potential contribution towards this timeframe (see *Annex 1* for more insights regarding the detailed table).

b) <u>CO_2 potential savings</u>

The figure below illustrates how different advanced biofuels and power-to-liquid fuels have the potential to achieve significant CO_2 potential savings based on 2020 power-train technologies and start-of the-art biofuel production facilities (JEC data):

[31] SUNFIRE technology. http://www.greencarcongress.com/2014/11/20141114-audibluecrude.html
[32] Alternative Fuels CO2-neutral into the future. MTZ worldwide 06|2017. https://www.springerprofessional.de/en/alternative-fuels-co2-neutral-into-the-future/12280642
[33] Power-to-Liquids. Potentials and perspectives for the future supply of renewable aviation fuel (LBST, 2016) http://www.lbst.de/ressources/docs2016/161005_uba_hintergrund_ptl_barrierrefrei.pdf

Figure 18 Comparison of WTW impact of different powertrains combined with liquid fuels and BEVs

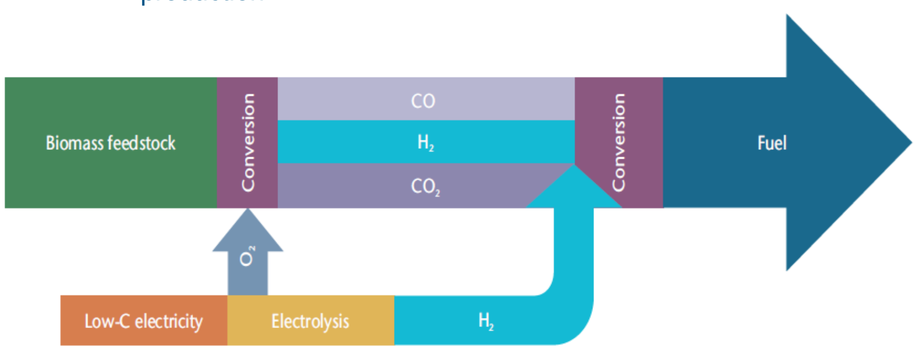


Source. Concawe internal work based on JEC data WTW v4

Exploring how these technologies may evolve by 2050 affecting the future pattern of biofuel production (heavily based on biofuels with better GHG performance) is an important area of ongoing work for Concawe.

The conversion ratio of the biomass gasification process can be significantly increased by injecting green hydrogen in to the synthesis gas stream. This will reduce the raw material feedstock (biomass) needed to supply the same final energy requirement and will also reduce the final WTW CO_2 intensity of final products. As renewable electricity becomes the prevalent source of electricity, more examples of synergies such as this will arise.

Figure 19 Example of how to use green hydrogen to increase biofuel production.



Notes: CO = carbon monoxide, CO_2 = carbon dioxide, H_2 = hydrogen, O_2 = oxygen.
Source: Hannula (2016), Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment.

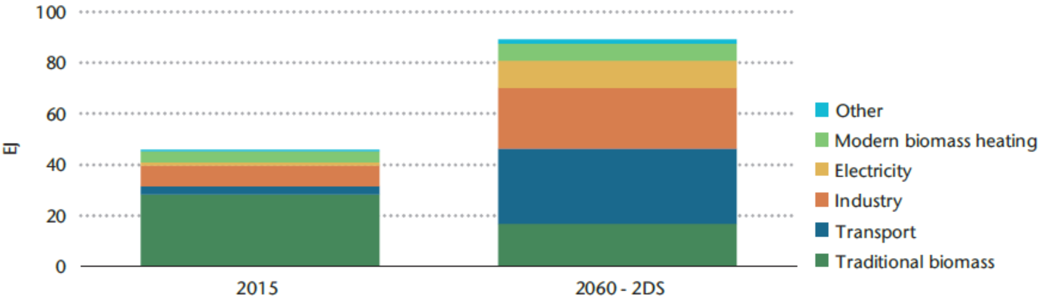
Source. Hannula, 2016; IEA Bioenergy, 2017b[34]

[34] IEA Technology roadmap – Bioenergy (2017)
https://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

c) **Sustainable Availability. Potential role of biofuels/efuels in 2030/2050**

Worldwide, the recently published *IEA Technology Roadmap* presents a 2 degree scenario (2DS) where the role of bioenergy grows significantly towards 2060, mostly in the transport sector where its contribution to final energy demand increases massively from 2015 levels (nearly 10 times) providing 29% of total transport final energy demand.

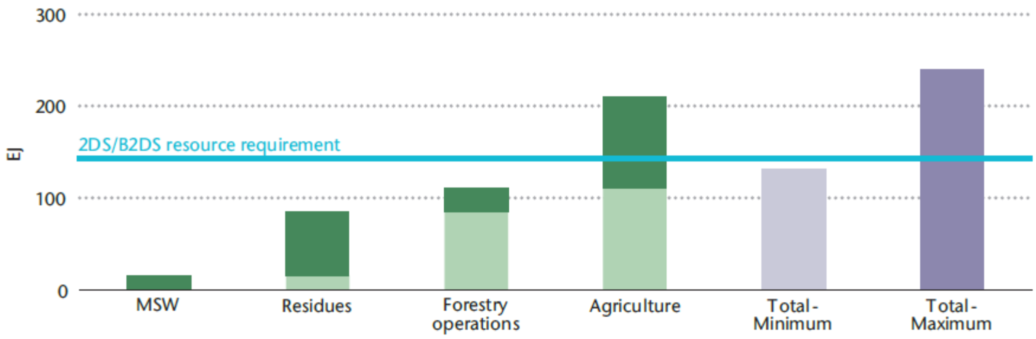
Figure 20 Contribution of bioenergy to final energy demand in 2015



Source. IEA Bioenergy (2017)

Different sources show a wide range of biomass availability, depend on the resources included in the scope (wastes, agricultural and forestry residues, other forestry materials, algae, etc.) and on the constraints to biomass supply that are applied. The *IEA Technology Roadmap on Sustainable Bioenergy*, estimates that at least **100 EJ could be sustainably available in 2050 or 2060** worldwide, with the potential to achieve even higher values, which will exceed the primary energy requirements for bioenergy and biofuels, as defined in the 2-degree (*2DS*) (and beyond the 2 degree (*B2DS)*) scenarios:

Figure 21 Potential sustainable biomass resources (Worldwide)



Source. IEA Technology roadmap (2017).

Note. Colour scheme reflecting the potential ranges detailed in the table below.

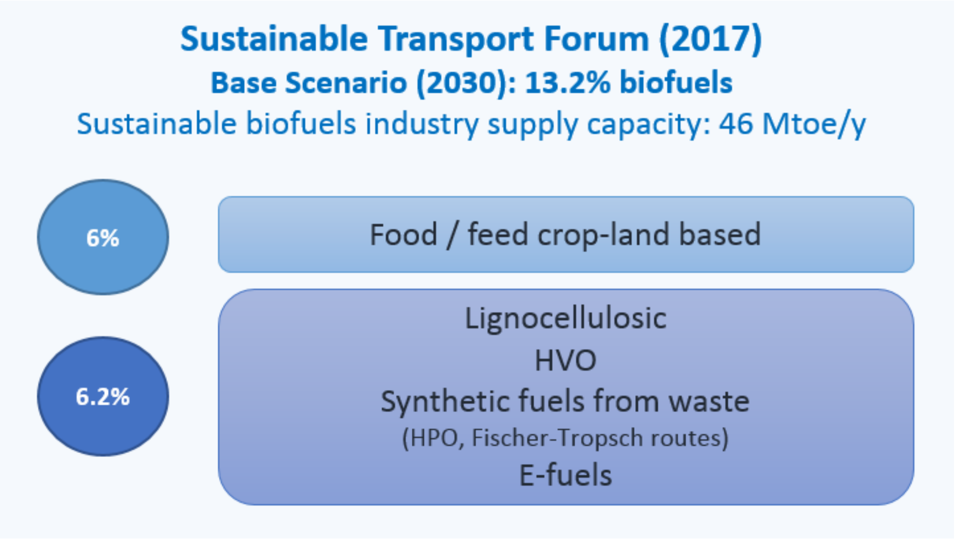
Table 5 Summary of sustainable biomass resources (Extract from IEA Technology roadmap).

Bioenergy resource	Conditions for sustainability	Potential in 2060 (EJ)
Municipal wastes (MWS)	Taking into account waste prevention, minimization and recycling in economies as they develop.	10 -15
Agricultural wastes, residues and processing residues from wood and agro-industry	Respecting animal feed and soil protection, consistent with other uses.	46 -95
Wood harvesting residues co-products	Used within the context of a sustainable forestry plan.	15 -30
Agriculture	Produced on lands in ways do not threaten food availability or ILUC issues. Crop or forestry production on degraded land.	60 -100

In Europe, the **Sub Group on Advanced Biofuels** (SGAB[35]) estimates the amounts of different alternative biofuels (including efuels) that the bio-industry could deliver by 2030. This amount of biofuels exceeds the current capacity installed in Europe, including commercial plans or facilities under construction.

In Europe, the Sustainable Transport Forum estimated that the bio-fuel industry could deliver 46 Mtoe/y by 2030.

Figure 22 Future potential industrial availability of biofuels/efuels in Europe in 2030 and resource estimate (EU context). Summary.



[35] Sub Group on Advanced Biofuels – Building up the future (2017) http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33288&no=1

Table 6 Resource estimate and potential biofuel production (EU Context)

Report	Resource estimate[36]		Resulting biofuels potential		Displacement in road transport fuels
	tonnes, Mtoe per year as provided in reports	**expressed in PJ primary energy per year**	**In tonnes advanced biofuels per year**	**in PJ advanced biofuels per year**	
Biofrontiers, 2016	140 million tonnes of wastes and residue feedstocks		27 million in 2020		7% in 2020
Advanced Biofuel Feedstocks – An Assessment of Sustainability, 2014	2,961 million wet			5,500 in 2020 (eq. to 128 Mtoe)	
Biomass Futures, Atlas of EU biomass potentials, 2012. Resource potentials are for total bioenergy utilisations.	314 Mtoe (2012) 375-429 (2020) * 353-411 (2030) *	13,100 15,700-18,000 14,800-17,200			
* In Biomass Futures project for 2020 and 2030 two scenarios have been explored: a reference scenario (higher potentials) and a sustainability scenario (lower potentials), resulting in different levels of resource mobilization. For information please refer to the Biomass Futures reports.					

Source. SGAB (2016)[36]

Note. Comparison of different biofuels and efuels including raw material, technology and current TRL included in Annex 1.

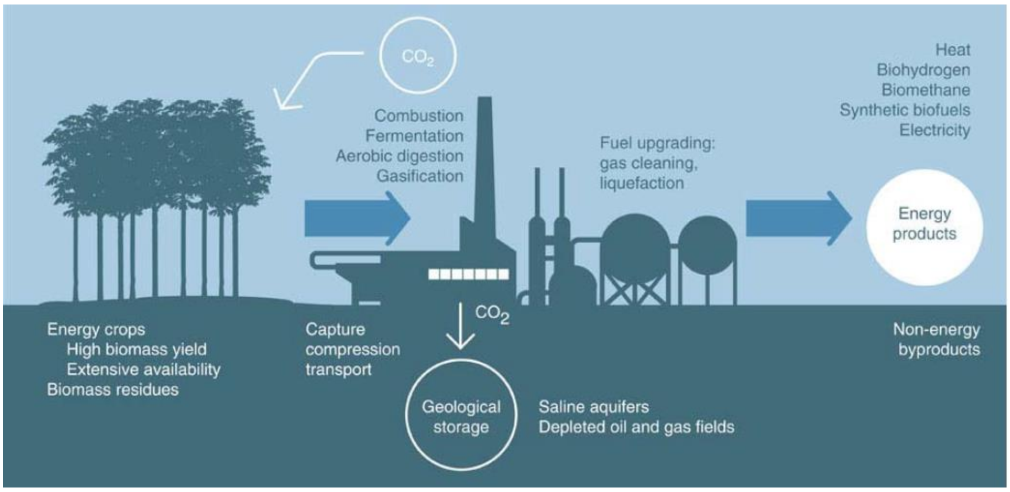
Whilst not in the scope of the SGAB, the maximum potential availability of biofuels in Europe beyond the 2030 timeframe is currently being investigated by an Ecorys-led consortium37 - commissioned by the European Commission (DG Research & Innovation). The objective of the project is to conduct a technical assessment of the whole biofuel value chain from biomass availability to conversion technologies and final demand for transport with the objective to estimate the maximum technical potential for a sustainable penetration of advanced biofuels in Europe. When published, the report is expected to provide very detailed insights regarding the future availability of biomass and the key R&D enabling areas that would need to be incentivized to reach an effectively deployment across Europe.

2.2.4.2. A quick look into negative emissions

In the context of this work plan, a potential evolution of the role of biofuels to mitigate climate change - the *negative emissions* concept - is gaining more attention in recent research publications. The idea behind this is that when the CO_2 emitted in sustainable biofuel processes is captured and stored (CCS), carbon-negative value chains are attained as CO_2 sequestered from air as biomass grow is not returned to atmosphere[38]. Overall, more CO_2 is withdrawn from the atmosphere than emitted from the tailpipe potentially contributing to a low-CO_2 transport future.

[36] Sub Group on Advanced Biofuels – *Building up the future* (2017) http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33288&no=1
[37] http://www.ecorys.com/news/ecorys-assess-potential-advanced-biofuels-mid-term-2030-and-long-term-2050-perspective
[38] *Biomass and CCS – Guidance for accounting for negative emissions.* IEAGHG (2014) http://www.ieaghg.org/docs/General_Docs/Reports/2014-05.pdf

Figure 23 Concept of bio-CCS



Source. IEAGHG (2016[39])

There are different combination of technologies where these negative emissions could be achieved. Second generation biofuels produced by the gasification of woody biomass associated with CO_2 capture *(Fisher-Tropsch with CO_2 capture)* could offer an interesting opportunity for the industry to explore this concept beyond the conceptual approach.

2.2.5. Fuel quality (oil-based)

Fuel quality improvement

- **Potential CO_2 savings**: As a preliminary number, subject to further R&D work, it has been estimated that the potential savings associated to a series of different opportunities for fuel quality improvement could represent a reduction ≈5% of the total WTW CO_2 intensity.
- **TRL**: 4-6.
- **Challenges**: Modification of engines to take advantage of improved fuels. Modifications of the refining processes.
- **Areas for further work (Concawe)**: Cross-cutting R&D work is required. A) Concawe is currently testing different fuels in new engines assessing the associated CO_2 emissions. B) Integrated refining + fuel CO_2 assessments are also being conducted and will inform the preliminary CO_2 savings included in this report. C) Collaboration with ACEA/OEMs/additive to assess the potential impact in future vehicles.

Over the last 100 years, the refining industry has continuously improved the quality of the fuels delivered to end-market consumers. Many of these improvements were in response to improvements in the vehicle technology, with the result that internal combustion engines are currently optimized for a range of fuel properties agreed by both the refining and automotive industry and defined by fuel specifications. Ongoing R&D is conducted in different tests on real vehicles to assess the potential impact of modifying fuel properties.

[39] *CCS in achieving negative emissions*. IEAGHG (2016).
http://www.ieaghg.org/docs/General_Docs/IEAGHG_Presentations/EU_CCS_Event_CCS_and_Negative_Emissions_IEAGHG_v1.pdf

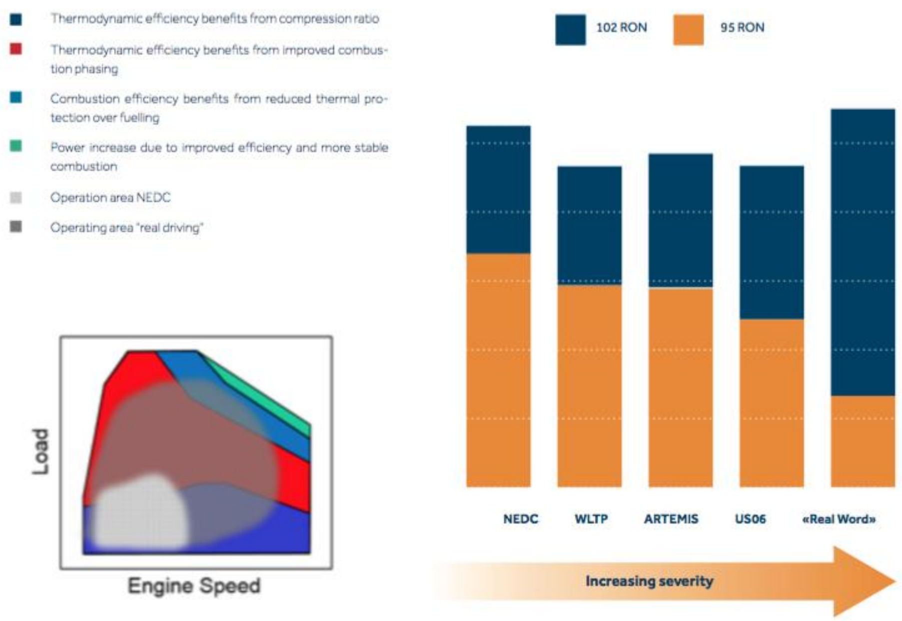
Concawe currently has R&D programs focused on:

- **High octane gasoline**

  High compression ratio engines could potentially contribute to effectively improve the fuel economy of vehicles.

  Currently, both Concawe and JEC are exploring different routes (fossil and bio based pathways) to produce a high RON gasoline, and assessing the WTW CO_2 potential savings that would arise from this increase. The preliminary numbers show that the net reduction in CO_2 emissions at the tailpipe more than compensate for the increase in emissions in producing this new fuel at the refinery site. Work published by BP in 2014 (SAE 2014-01-2610) suggested that when operating on a 102 RON fuel, a demonstrator vehicle with an aggressively downsized 1.2l engine was able to give 4-5% improvements in efficiency relative to 95 RON regardless of the test cycle used and including real-world type test cycles. These benefits were thought to be due to a number of different mechanisms depending on which areas of the load/engine speed map were being operated in. Concawe is continuing this work to try to understand the optimum RON and refinery conditions for potential high octane fuels.

Figure 24 Mechanisms and efficiency improvements



Source. BP study (2014)[40]

- **Carbon/Hydrogen ratio** optimization of fossil diesel and gasoline:

  Results from earlier tests showed that increasing the hydrogen to carbon ratio, by the reduction of density in diesel, or by the aromatics in gasoline, could reduce the CO_2 emissions. These benefits, particularly on gasolines with matched octane were demonstrated as part of the EPEFE (*European Programme on Emissions, Fuels and Engine Technologies*) programme which was conducted in the late 1990's and which was the basis for the current fuel specifications.

[40] http://www.mahle-powertrain.com/media/mahle_powertrain/news-and-press/conference-papers/2014/2014-01-2610-bp-2.pdf. // https://www.sae.org/publications/technical-papers/content/2014-01-2610/

The reduction of density gave mixed results in terms of CO_2 with an overall benefit observed in light duty but increase in heavy duty testing. However, Concawe's more recent work using three modern passenger car vehicles (Euros 4-6) indicated that there could be CO_2 benefits for lower density fuels (SAE 2016-01-2246).

Concawe plans to do more work in this area including an integrated assessment considering the potential CO_2 savings at tailpipe along with low-carbon processes at the refining site in order to produce a better estimate of the potential benefits in terms of total WTW CO_2 emissions.

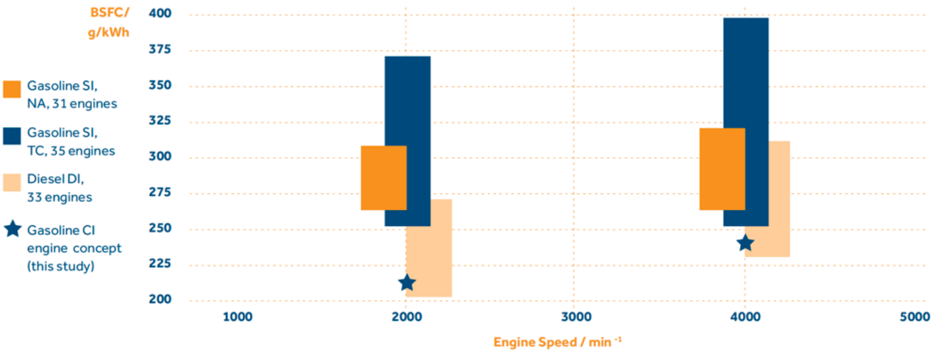
- Existing or new fuels to be used in **GCI (Gasoline Compression Ignition engines):**

  A new promising area of research is associated with so-called GCI engines. These engines take advantage of both the properties of gasoline fuel and the efficiency of the diesel-like combustion to achieve lower particulate matter emissions with higher fuel efficiency compared to modern diesel engines. This technology is related to HCCI (*Homogeneous Charge Compression Ignition*) engines which are already finding their way into the marketplace (e.g. Mazda's *Skyactive – X* engine which will be launched in 2019). Concawe studies continue to attempt to demonstrate gasoline compression ignition using conventional pump gasoline (reference Concawe report 13/14). A number of laboratories across the world are engaged in research in this area including a collaboration between Argonne national lab/Delphi/Achates Power and Saudi Aramco in the US who recently announced a demonstrator vehicle in the form of a Ford F150 using a 3 cylinder 2.7 litre engine with an opposing piston gasoline compression ignition design. *Achates Power* claim than their engine is 30-50% more efficient than the equivalent gasoline and diesel engines. Although this technology requires further development before it will become commercially available, it offers an indication of the potential role of this type of engine in the future.

Figure 25 Break specific fuel consumption of YE2012 state of the art engines including the GCI concept

Source: Concawe report 13/14[41]

The ease of making this technology work could be facilitated by changes in fuel



properties such as lower volatility and lower octane fuels. Although barriers and challenges would need to be overcome to effectively introduce a new fuel into the marketplace, nevertheless, combustion of this type of fuel would be easier to control under the high pressure and high temperature regimes of diesel combustion than traditional gasoline.

The production of a new fuel would modify the utilization of different refining processes and further optimization would be required to ensure that energy efficiency is maximized.

For the preliminary assessment of the potential impact of this technology and although a more detailed WTW analysis of the total GHG emissions would be required, a potential replacement of diesel up to 15% by 2050 is considered, assuming a potential improvement of 5% in the fuel economy of the new GCI vehicles and a neutral transition at refinery level[42].

- **Improved detergent additives**

  Fuel detergents have been used for decades firstly in port fuel injected gasolines and in indirect injection diesels to keep engines clean. More recently they are being used in more modern direct injection technology in both gasoline and diesel engines. R&D on detergent additives is an additional area that could potentially contribute to improve the CO_2 efficiency of existing ICEs enabling them to run at optimum conditions without losing efficiency due to deposits in the injection system. In Europe, detergents are not mandated but are used by some fuel suppliers in gasoline and diesel to keep vehicle fuel injectors clean and to clean-up dirty injectors. Friction modifiers have also been shown to contribute to vehicle efficiency in the past. At this stage, the potential of the next generation of additives has been estimated to offer additional 0.6-1% fuel savings. However, further work is needed to demonstrate that benefits can still be achieved in market average fuels in Europe by increasing the dosage rates of current additive technologies or with the development of new technologies suited to the increasingly common direct injection engines.

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[41] https://www.concawe.eu/wp-content/uploads/2017/01/report13_14-exploring-a-gasoline-compression-ignition-gci-engine-concept.pdf

[42] SAE paper (2016-01-0765). *Potential of NC25 Naphtha-Based fuel to Power Compression Ignition Engines*. ARAMCO

2.2.6. Other technologies & Options

2.2.6.1. CCS On-board passenger vehicles

On-board CCS

- **Potential CO_2 savings**: Overall, CCS systems have been developed which are claimed to capture up to 60% of CO_2 from exhaust gases and store it temporarily on-board the vehicle. For liquid storage materials, different sources claim that, in total, a 25% CO_2 avoidance may be achievable for passenger vehicle and up to 40% for trucks. Due Given the technology developments and the new infrastructure required, this option may not be available by 2050.
- **TRL**: 3-4
- **Challenges**: Improve technology to improve the recovery ratio, reduce costs and an effective deployment of a CCS/CCU infrastructure across Europe.
- **Areas for further work (Concawe)**: A) Assessment of the net CO_2 savings for the whole economy. Generate a better understanding about the link with CCS schemes and their potential costs (infrastructure / vehicle). B) Engage with OEMs and other technology providers to assess the real potential of this technology across all transport sectors.

Capturing carbon dioxide emissions from the tailpipes of road vehicles could help significantly cut overall carbon emissions to the atmosphere, playing a strategic role in the development of a sustainable carbon economy in the longer-term, comparing to CO_2 air capture from the atmosphere.

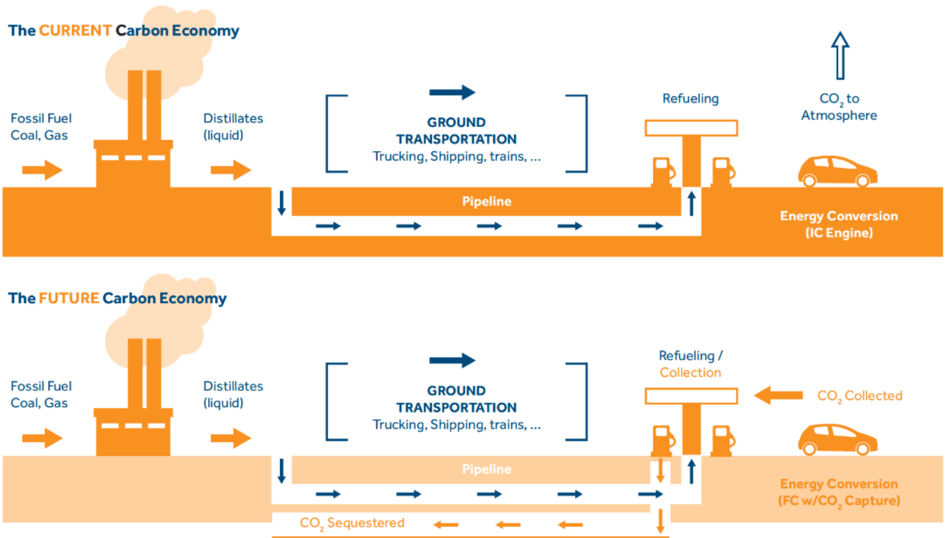
a) **Basis**

In general, CO_2 capture on-board vehicles follows the more traditional *Carbon Capture and Storage* (CCS) technologies, notwithstanding the complexity associated with the miniaturization of the processes.

The concept could be applicable also for road freight and maritime transport, potentially benefiting from space availability. The challenge associated with its effective implementation goes beyond the technology itself as a completely new infrastructure to effectively dispose, transport and store (or use) the captured CO_2 would be required across Europe.

In the case of passenger cars, this could potentially imply an evolution of the concept of the refueling station beyond the existing one, converting the station in a *collection* site integrated within a wider CCS (in geological formations or in solid carbonate form) or CCU centralized system as illustrated in the figure below[43].

Figure 26 Comparison of the potential integration of on-board CCS distributed sources such as road vehicles.



R&D is currently focused on improving the efficiency of CO_2 capture and downsizing the equipment. Further research would be needed to develop closed-loop system with no carbon emissions.

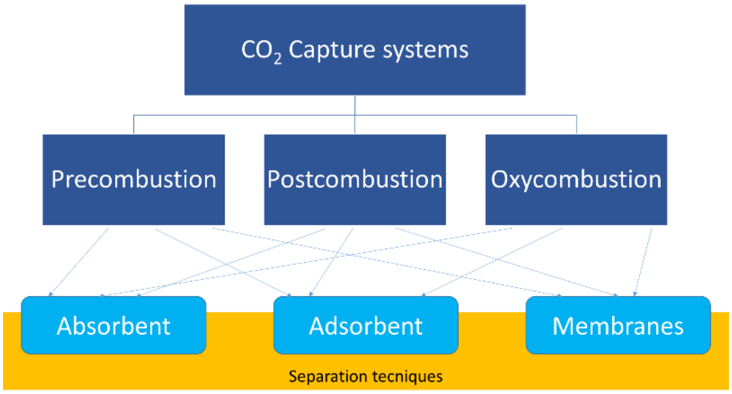
[43] Carbon Capture in Vehicles: a review of general support, available mechanisms and consumer-acceptance. University of Michigan (2012) https://deepblue.lib.umich.edu/bitstream/handle/2027.42/90951/102855.pdf

Although there are different examples of on-board capture prototypes reported[44] [45], this concept is in very early stages of development and specific R&D programs in this area would need to be put in place to develop an effective on-board CCS integrated system, overcoming the vehicle and infrastructure challenges associated to this potential low-carbon pathway.

b) Technologies

The capture of CO_2 in distributed systems - such as passenger cars - can follow three different systems:

Figure 27 Type of separation techniques for CO_2 capture systems



As an example, the pre-combustion system involves first converting solid, liquid or gaseous fuel into a mixture of hydrogen and carbon dioxide (syngas) using one of a number of processes such as ‘gasification’ or ‘**reforming’**. The carbon dioxide is selectively removed leaving hydrogen as the decarbonized fuel. This method already is used in several commercial applications[46]. An alternative method[47] converts a conventional fuel into hydrogen and carbon dioxide, the hydrogen serves as fuel (to be used in fuel cells) and the carbon (in the form of carbon dioxide) is stored in liquid form and discharged into service stations. Another innovative on-board hydrogen-powered fuel cell system converts conventional hydrocarbon fuels (e.g. gasoline, diesel) into hydrogen directly on board the vehicle, eliminating the need for separate facilities for producing and distributing hydrogen. An example of this technology has been developed by the Georgia Team[48] who has created a fuel processor called *CO_2/H_2 Active Membrane Piston (CHAMP) reactor* which is able to separate CO_2 effectively and to storage it in liquefied state on-board the vehicle.

Currently, pre-combustion and post-combustion systems are considered for the application in the field of mobility. The post-combustion system is well suited to internal combustion engines currently used in the transport sector.

[44] Saudi Aramco – Demonstration vehicles. Al-Meshari A.A., Overview of CCS Activities in Saudi Arabia https://www.cslforum.org/cslf/sites/default/files/documents/riyadh2015/Meshari-SaudiArabiaCCSOverview-TG-Riyadh1115.pdf
45 STRATACLEAR™ http://www.ryncosmos.com/news/2-uncategorised/15-co2-capture-in-vehicles-and-home-heating
[46] Source Global CCS Institute, 2011
[47] Source Damm D.L., Fedorov A. G., “Conceptual study of distributed CO2 capture and the sustainable carbon economy”, Energy Conversion and Management 49 (2008) 1674–1683
[48] Source. Georgia University. Carbon Capture Strategy Could Lead To Emission-free Cars (2008). https://www.sciencedaily.com/releases/2008/02/080211134444.htm

2.2.6.2. Forest credits

Forest credits

- **Potential CO_2 savings**: Based on current availability, it is expected that more than 0.4% of the CO_2 associated to the passenger car fleet could be effectively off-set.
- **TRL**: 8.
- **Challenges**: Development of an effective and international forest credits system, certified by third parties. New policy framework around the transport sector to allow this type of schemes to be factored-in.
- **Areas for further work (Concawe)**: Understanding how these forest credits or other mechanisms could be sustainable implemented in the long term.

Ecosystems including forests play an essential part of the global carbon cycle as they are natural sequesters of CO_2 by means of the photosynthesis process.

As detailed in one recent published report from Concawe[49], at a global scale, boreal and temperate forests as a whole are net sinks of carbon whereas, due to deforestation tropical forests, as an aggregate, are net sources. Most deforestation takes place in tropical forests whereas carbon stored in boreal and temperate forests is, overall, increasing, either due to expansion of forested area or increases in standing stock. While deforestation has long been recognised as one of the main sources of CO_2 release to the atmosphere, there is increasing awareness of the role that peatlands play in the global carbon cycle, emitting up to 100 ton CO_2 per hectare (ha) per year depending upon climate and drainage depth when they are drained.

Currently both reforestation, afforestation and preservation of peat lands are widely recognized as enhancers of carbon sequestration. Activities aimed at reducing emissions through preserving ecosystems, in particular when implemented in developing countries, are labelled ‘REDD’ (*Reducing Emissions from Deforestation and Forest Degradation*).

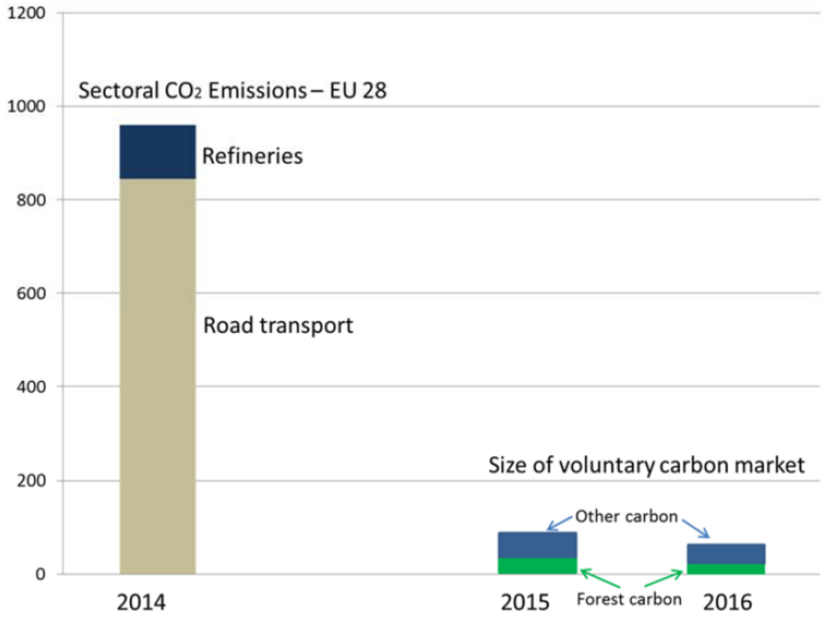
Based on these concepts, different CO_2 markets explore a different range of forest carbon projects involving either forestation (capturing CO_2 from the atmosphere during the growth of the forest) and/or protection of forests that would otherwise be cut. In both cases, the projects can potentially generate credits equivalent to the amount of avoided CO_2 emissions that, once certified by an independent agency, can be sold in the carbon market. Currently, around one third of the credits traded on the CO_2 market are from forest carbon projects, mainly generated in developing countries. Currently, the concept is not totally developed so there is oversupply on the market leading to low prices of carbon credits, ranging from US$ 3 to 10 per ton CO_2 for forest carbon projects.

When comparing the forest credits available in the market vs the total CO_2 emissions by road transport (see **Figure 28** below), the volume is currently not significant enough to make a real difference. However, it is important to remark that the amount of credits actually available may be considerably higher as carbon credit developers may not offer all developed credits on the market because of the lack of demand. Therefore, incentivizing these natural ecosystem projects worldwide may be an effective alternative in the future to continue reducing the CO_2 emissions associated to liquid fuels in Europe.

[49] Using forest carbon credits to offset emissions in the downstream business. Concawe report (2017). https://www.concawe.eu/wp-content/uploads/2017/09/Rpt_17-9.pdf

Based on the potential availability of the voluntary carbon markets – currently with an annual turn-over of around 70-80 million ton CO_2 and expected to increase in the future as this type of markets ground off – it has been estimated that about 0.4% of the future passenger car fleet could be effectively off-set.

Figure 28 Comparison of annual EU carbon emissions in refining and road transport with the annual volume in the global voluntary carbon market (Mt CO_2).



Source. Concawe report 17/9

ANNEX 1. BIOFUEL TECHNOLOGIES (SGAB 2017)

Table 6. Comparison of different biofuels and efuels including raw material, technology and current TRL

Source. SGAB (2016)

Table 6. Classification of BIO, Low carbon fossil, e- & Hydrogen Transport Fuels

	Raw material	Technology	Type of biofuel	Status TRL[1]	Application
Conventional	Sugar*	Fermentation	Ethanol	Commercial	Gasoline blend, E10, E85, ED95£, upgrade to biokerosene
	Starch*				
	Vegetable oils*	Esterification or transesterification	FAME/Biodiesel		Diesel blend, B7, B10, B30
	Fats				
	Food crops	Biogas production & removal of CO2	Biomethane		100% in heavy duty transport, flex fuel vehicles, captive fleets, injected in the gas grid
	Vegetable oils & fats	Hydrotreatment	Hydrogenated		Diesel drop-in or 100%, bio-kerosene$
Advanced	Waste streams of oils & fats	Esterification or transesterification	FAME/Biodiesel	Commercial	Diesel blend, B7, B10, B30
	MSW[2], sewage sludge, animal manures, agricultural residues, energy crops	Biogas or landfill production & removal of CO2	Biomethane		100% in heavy duty transport, flex fuel vehicles, captive fleets, injected in the gas grid
	Used cooking oils, liquid waste streams & effluents[7]	Hydrotreatment	Hydrogenated		Diesel drop-in or 100%, bio-kerosene[5]
	Lignocellulosics,	Enzymatic hydrolysis + fermentation	Ethanol	TRL 8-9	Gasoline blend, E10, E85, ED95, upgrade to biokerosene
			Other alcohols	TRL 6-7	
	MSW, *solid* industrial waste streams/residues[3]	Gasification + fermentation	Ethanol, methanol	TRL 6-7	
	Lignocellulosics, MSW, *liquid* industrial waste streams & effluents[5] or intermediate energy carriers[6]	Gasification + catalytic synthesis	Synthetic[4]	TRL 6-8	Depends on fuel type; can be used for blends or drop-in with diesel, gasoline, kerosene, bunker fuel or as pure biofuel e.g. Biomethane, DME, MD95, FT
	Algal oils[8] and other non-food oils	Hydrotreatment	Hydrogenated	TRL 4-5	Diesel drop-in or 100%, bio-kerosene
		Esterification	FAME/Biodiesel	TRL 5-6	Diesel blend, B7, B10, B30, 100%
	Pyrolysis oils from lignocellulosics, MSW, waste streams	Hydrotreatment	Hydrotreated	TRL 5-6	Diesel drop-in or 100%
		Co-processing in existing petroleum refineries[9]	Petrol, diesel, kerosene	TRL 5-6	All of the above
	Non-lignocellulosic biomass, (algae, non-food biomass)[10]	Various as above	Petrol, diesel, methane,	TRL 4-5	Various as above
	Sugars [11] (cellulosic, non-food)	Microbial	Petrol, diesel, kerosene	TRL 4-6	Diesel drop-in or 100%, bio-kerosene
Low Carbon Fossil Fuels	Steel & Chemical Industry	Fermentation	Ethanol	TRL 6-7	Gasoline blend, E10, E85, E95,
		Upgrading & Catalytic synthesis	Methanol	TRL 5-6	Shipping, blends with gasoline, M95, M100
			Methane	TRL 5-6	100% in heavy duty transport, flex fuel vehicles, captive fleets, injected in the gas grid
	Waste polymers, plastics, non-biodegradable fraction of MSW	Gasification + catalytic synthesis & fermentation	Synthetic[4] & alcohols from fermentation	TRL 6-8	Depends on fuel type; can be used for blends with diesel, gasoline, kerosene, drop-in
e-Fuels	**Supply of H2**	**Technology**	**Type of biofuel**	**Status**	**Application**
	RES electricity	Catalysis	Methanol	TRL 5-6	Shipping, blends with gasoline, M95, M100
	RES electricity		Methane	TRL 5-6	100% in heavy duty transport, flex fuel vehicles, captive fleets, injected in the gas grid
	RES electricity		Synthetic[2]	TRL 5-6	Depends on fuel type; can be used for blends with diesel, gasoline, kerosene, drop-in

ANNEX 2. TECHNOLOGY READINESS LEVEL (TRL). DEFINITION

HORIZON 2020 - General Annexes

G. Technology readiness levels (TRL)

Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

- TRL 1 – basic principles observed.
- TRL 2 – technology concept formulated.
- TRL 3 – experimental proof of concept.
- TRL 4 – technology validated in lab.
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 –system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies: or in space).

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