Review

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Foreword

I am pleased to introduce this new edition of the Concawe *Review*, which focuses mainly on topics related to the potential contribution of the fuel manufacturing industry and the role of liquid fuels to the energy transition towards a low greenhouse gas economy.

The first article refers to the renewal of an essential tool, Concawe's linear programming (LP) model representing the EU refining industry, which is used to evaluate the economic impact on the refining sector of changes in EU legislation or market demand. The current LP model, representing the combination of all refineries operating in the EU-27 + Norway, Switzerland and the UK, was limited to traditional refining processes and could not integrate the low-carbon processes which will be at the heart of the refining transition. The article describes the new LP model, which has been developed as a more flexible and reliable tool that is now able to integrate and simulate the new processes for low-carbon fuels pathways, green hydrogen and carbon capture, and integrate the RED (Renewable Energy Directive) targets.

E-fuels—synthetic fuels produced by the combination of hydrogen from water electrolysis powered by renewable electricity and captured CO_2—are identified as one of the essential elements for the decarbonisation of hard-to-abate sectors (aviation, maritime, etc.). The second article summarises an update of a techno-environmental and economic analysis of the different e-fuels production pathways in different regions of the world. It integrates an assessment of the impact of intermittency and seasonality of renewable energy supply on storage requirements, synthesis plant sizing and production costs, which was not evaluated in our previous study, as well as a comparison of e-fuels production costs versus fossil fuels/biofuels/e-fuels produced from nuclear electricity.

In a previous Concawe *Review* (Vol. 32, No. 1), we described the project which led to the development of the passenger car CO_2 comparator (available on Concawe's website), which is recognized as one of the best tools available to compare the CO_2 emissions of different powertrains as a function of the type of technology, region, driver's profile, energy carrier, etc. The third article in this *Review* describes the development of a similar life-cycle assessment tool for heavy-duty vehicles, which was developed with the help of IFPEN. This easy-to-use interactive tool to compare the CO_2 intensity of various heavy-duty transport technology and usage options is also available on the Concawe website.

The fourth article provides a summary of a 'deep dive' study on the decarbonisation of the aviation industry. Part of Concawe's Low Carbon Pathways project, the study integrates the anticipated developments in aircraft technologies and their deployment pathways, and highlights the challenges associated with the decarbonisation of this hard-to-abate sector, and the essential role of drop-in sustainable aviation fuels in reaching this objective.

I thank the authors for sharing their valuable insights into one of the biggest challenges faced by our industry and society in general.

Jean-Marc Sohier

Concawe Director

Contents

The production of liquid fuels in Europe is evolving to embrace the low-carbon economy transition as presented by the European Commission ('Fit for 55', 'EU Green deal', etc.). Therefore, a flexible and reliable tool is needed to anticipate and simulate the potential evolution of the current refining system and the alternatives for low-carbon liquid fuels production.

Since the mid-90s Concawe has operated a refinery linear programming (LP) model representing the combination of all refineries operating in the EU-27 + Norway, Switzerland and the UK, most of which are members of Concawe.

This model was originally developed to estimate the cost to EU refiners of EU legislation (mostly affecting product quality) and of expected changes in EU market demands, and the structure of this model has been perfectly suitable for the studies carried out until now. However, to accommodate additional features such as the low-carbon fuels pathways, green hydrogen, carbon capture or RED (Renewable Energy Directive) targets for transport fuels would involve a disproportionate amount of time and effort.

In 2022, Concawe decided to build a new LP model, capable of addressing the upcoming challenges faced by the European refining system in the context of the low-carbon economy transition, and flexible enough to be upgraded more easily and more quickly.

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This updated study presents a twofold analysis — techno-environmental and economical — of the different e-fuels production pathways in Europe (northern, central and southern Europe), and the Middle East and North Africa regions, in 2020, 2030 and 2050 with assessments of sensitivities to multiple key techno-economic parameters. The key focus of this update was an assessment of the impact of intermittency and seasonality of renewable energy supply on storage requirements, synthesis plant sizing and production costs. The results provided inputs for the broad assumptions used in chapters 1 and 2 including the mix of solar PV and wind, the amount of renewable curtailment and the size of storage elements. These include electricity storage based on battery systems, hydrogen storage, and CO_2 storage necessary for e-fuels production, along with the cost impacts of production flexibility.

The updated study presents:

- an assessment of stand-alone units versus e-plants integrated with oil refineries;
- a comparison of e-fuels production costs versus fossil fuels/biofuels/e-fuels produced from nuclear electricity;
- an assessment of the impact of intermittency and seasonality of renewable energy supply on storage requirements, synthesis plant sizing and production costs;
- an analysis of the context of e-fuels in the future in Europe; and
- a deep dive into the safety and environmental considerations, societal acceptance, barriers to deployment and regulation.

The e-fuels pathways included in the scope of this study are: e-hydrogen (liquefied and compressed), e-methane (liquefied and compressed), e-methanol, e-polyoxymethylene dimethyl ethers (abbreviated as OME_{3-5}), e-methanol to gasoline, e-methanol to kerosene, e-ammonia, and e-Fischer-Tropsch kerosene/diesel (low temperature reaction). The e-hydrogen is considered a final fuel but also as a feedstock for producing other e-fuels.

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New Concawe linear programming model

Concawe's linear programming model was completely rebuilt in 2022 to provide the capability needed to address the upcoming challenges faced by the European refining system in the context of the low-carbon economy transition. It can now be used to anticipate and simulate the potential evolution of the current refining system and the alternatives for low-carbon liquid fuels production, and is flexible enough to be upgraded more easily and more quickly as needed in the future.

Author
Iván Rodriguez (Concawe)

What is an LP model and why is it used in the refining industry?

Linear programming is a mathematical modelling technique used to maximise or minimise a function of several variables subject to a number of constraints. The functions being optimised and the constraints are linear, meaning that the constraint does not contain a variable squared, cubed or raised to any power other than one, a term divided by a variable, or variables multiplied by each other. Also, proportionality must exist. In other words, for every unit increase or decrease in a variable, the value of the constraint increases or decreases by a fixed amount.

General linear programming deals with the allocation of resources, seeking their optimisation.[1]

The purpose of an oil refinery is to turn crude oil into marketable products in the most efficient and economical way. A particular refinery generally supplies particular markets which set the quality of the products to be supplied and, to an extent, the amount of each grade. Depending on the geographical location of the refinery, there can also be opportunities to export to other markets. The refinery has access to certain crude oils and other feedstocks, the range of which is a function of its location and the way it is supplied (e.g. by ships or pipelines). Finally, the refinery features a given combination of process units (generally referred to as its 'configuration').

Refinery operation is thus characterised by multiple real constraints arising from feedstock supply, product demand (quantity and quality) and process unit limitations. Yet, there are many ways of operating within these constraints and refiners have always strived to optimise their operation in order to maximise profit or minimise costs to supply a given market demand within a given set of product prices and input costs. The tool used to that end by refiners worldwide is known as linear programming which, given a quantity to be optimised, aims at identifying the optimum solution amongst the myriad of possible solutions to a complex problem.

For a given set of desired products, the LP solution tells the refiner how much of each available feedstock should be processed, the level at which each refinery process unit will be utilised and, more generally, which amongst all the constraints will actually be binding. Crucially, it also provides information on the impact on the objective function of a marginal change in each of the binding constraints (the so-called 'marginal values'). This last property of an LP solution was used, for instance, to assess the CO_2 intensities of refining products in a Concawe study undertaken in 2017.[2]

Given the complexity of a refinery model, which in the case of the current Concawe LP model has more than 6,500 variables and nearly 7,000 equations for the EU single region configuration, and is more than 10 times bigger for the EU multi-region configuration, specialised software developed and commercialised by third parties is used to run LP models.

Generally, this software has three main features: an input interface where the LP developer/user creates and builds the model and introduces the input data to run the model; an optimisation algorithm that solves the mathematical problem (a matrix formed by equations as rows and variables as columns, where the intersections are simply the coefficients that apply to unknowns or variables in each equation, which are part of the input data the user provides); and an output interface that allows the user to visualise and manipulate all the data generated in the solution.

History of the LP model in Concawe

Concawe has been using refinery LP models for more than 30 years, evaluating various topics and subjects that were important to the refining industry at the time, some more practical such as the effect of the evolution of the refined product demand,[3,4,5] and others more theoretical such as the implications of producing a notional high-octane petrol grade[6] to improve engine efficiency and thus CO_2 emissions.

In 1989, a Concawe LP model was used to assess the impact of limiting the benzene content up to 1% volume in gasoline[7] and sulphur content up to 500 wppm in diesel fuel.[8] Thereafter, in 1999 it was used to anticipate the implications of changing gasoline and diesel fuel characteristics[9] given in the Fuels Directive (98/70/EC),[10] where aromatic content in gasoline was limited to 35% volume and sulphur in diesel up to 50 wppm.

After a European Commission consultation in 2000 to reduce the sulphur content of petrol and diesel fuels even further (up to 30 or 10 wppm), Concawe estimated, by using an LP model, the consequences for the EU refining industry in terms of additional costs as well as CO_2 emissions.[11] This study was updated in 2005.[12]

For the maritime sector, Concawe has analysed the evolution of the legislative measures adopted by the International Maritime Organization (IMO) since the introduction of 'sulphur emissions control areas' (SECAs) in 2006, [13,14] up to the implementation of a sulphur cap of 0.5 wt% in the high sulphur bunker fuel specification in 2020.[15]

Another important use of the Concawe LP model has been estimating the CO_2 emissions associated with the production of individual oil products, where Concawe developed a new methodology to produce a consistent set of CO_2 intensities for all refinery products.[16]

In the coming months, the Concawe LP model will be used to carry out a techno-economic assessment of the economical impact for our industry of the reduction of aromatics and naphthalenes in the production of fossil jet fuels in the EU-27 + 3[1] refining system, and, within the framework of the Refinery 2050[17] study, it will help to assess how much low-carbon fuels can be blended into transport fuels while meeting the required commercial grade quality.

[1] The 27 member countries of the European Union plus Norway, Switzerland and the United Kingdom.

Characteristics of the Concawe LP model

The Concawe LP model has been developed in-house from the outset, using internal know-how with the support of Concawe member companies and the help of third parties, such as technology providers and consultants, who have provided some of the immense amount of input data that an LP model demands. Every aspect of an LP model—the relationships, equations, variables, constraints, etc.—have to be input and set by the developer/user; the LP optimiser algorithm only solves the mathematical problem.

The model features a full library of refinery process units represented by a number of operating modes including feedstock type, product yield structure, utilities consumption and all relevant quality parameters. From this information, a refinery can be modelled with any combination of process units.

A range of crude oils is available, representing the diversity of grades available to EU refiners.

A blending module allows finished products to be prepared according to the required quality specifications from selected intermediate streams.

In the Concawe LP model, there is the capability to run as a single EU region (all EU refining systems aggregated into one single large refinery model) or to run in multi-region mode, where the EU is divided into nine regions (see Table 1), each region represented by a single refinery having the aggregated capacity, crude intake, process configuration and product demand of all physical refineries in that region.

The number of nine regions is a trade-off between granularity of results and the anonymisation of individual sites/refineries, making it impossible to identify any specific refinery or refining company from the outcome of the LP model.

Table 1: Concawe LP regions and countries

LP region	Countries
Baltic	Denmark, Finland, Estonia, Latvia, Lithuania, Norway, Sweden
Benelux	Belgium, Netherlands, Luxemburg
Germany	Germany
Central Europe	Austria, Czech Republic, Slovakia, Poland, Hungary, Switzerland
UK and Ireland	United Kingdom, Ireland
France	France
Iberia	Portugal, Spain
Mediterranean	Italy, Greece, Malta
South-East Europe	Croatia, Slovenia, Romania, Bulgaria, Cyprus

Aggregated LP models are expected to over-optimise in the sense that such a model considers the entire region as a single site refinery, allowing the transfer of streams between units without considering the logistical constraints that exist due to refineries being in different locations. To address and minimise this issue, the Concawe LP model is calibrated to match the operation of a particular single year, representing the regional operations at a macro-level for another reference period as long as there are no material differences in the available installed unit capacities, process technologies, global crude balances and regional product qualities. Necessary adjustments would be made for a different reference period if the changes in these aspects of model calibration are known to be significant.

Upgrading the Concawe LP model structure

Until recently, the Concawe LP model has been completely linear, meaning that each feedstock had its own set of yields and stream properties in each process unit and along the model; this made the introduction of a new crude, process units or feedstock highly data- and time-demanding.

Faced with the need to incorporate new feedstocks and processes such as lipid co-processing or bio- or e-refineries, Concawe undertook a complete rewrite of the LP model from scratch to provide it with greater flexibility and adapt it to the latest LP techniques.

The new LP model retains certain features of the previous model, such as having all conventional refining processes modelled to allow for different refinery schemes, the capability to run in EU single- or multi-region mode, and the unique ability to estimate the carbon, hydrogen, sulphur and nitrogen balance in each stream and model unit process, which enables estimation of the CO_2 intensities of the products.[2]

The introduction of pooling structures in the new LP model allows the number of streams to be reduced, for example in the hydrocracker unit, there is now a single feedstock stream, which is the output of the hydrocracker feedstock pool that aggregates all streams that were previously going individually to the hydrocracker.

Another LP technique that has been implemented in the new LP model, which couples perfectly with the pooling structures, is the delta-base modelling, where the yields of a process unit can change linearly according to certain parameters of the feedstock (i.e. the hydrogen consumption in a hydrotreatment unit will increase if the sulphur content of the feedstock is higher than a base case).

With these two techniques, the new LP model is more flexible and adaptable than the previous one. However, it increases the complexity of the model/matrix with more equations (relationships between variables) and non-linearities (a variable multiplied or divided by another variable, as is the case in pooling schemes). Nevertheless, these issues can be addressed by the current LP software packages that include mathematical techniques such as 'distributive recursion', a non-linear technique used to model non-linearities by approximating them with linear segments, which are presumed in advance. An 'LP matrix' is then updated after every recursion. The updated LP matrix is considered to give a sufficiently good approximation of the non-linear model when the differences between the presumed and the real values of the variables are within predefined tolerances.

New features for the upcoming energy transition.

Other new features have been incorporated in the new Concawe LP model: similar to estimating the carbon balance in each stream, it will now be possible to estimate the bioenergy content of the products and intermediate streams to assess how to comply with the policy targets set in RED III, ReFuelEU Aviation[2] and FuelEU Maritime.[3]

Co-processing is also included, focusing on three insertion points in the refinery configuration (distillates hydrotreater, hydrocracker and fluid catalytic cracking units),[18] using data from the literature and complemented with third-party databases.

Green hydrogen and carbon capture are expected to play a key role in decarbonising refinery emissions in the near future, hence a simplified model of an electrolyser as well as a carbon capture plant have been included in the LP model as a representation of these technologies.

Biorefineries are characterised in the Concawe LP model by the main known processes and technologies that currently have enough data to be modelled: lipids to hydrotreatment (HVO[4]/HEFA[5]), biomass to gasification/FT /hydrocracker, pyrolysis (biomass) to hydrotreatment, e-fuels (hydrolysis/carbon capture + FT/hydrocracker) and alcohol to fuels.

Needless to say, the Concawe LP model is one that will be adapted and modified to meet the demands of each study, and will therefore evolve as the fuel manufacturing industry does.

Most of the data used to build the new Concawe LP model comes from the previous LP model as well as from literature and third-party databases, while Concawe member companies have helped fine-tune these data to provide the most representative values of the current practice in the industry.

What to expect from the Concawe LP model?

The output of the LP model is a complete, unit wise, material balance in weight of all refinery units, comprising the unit capacities available and utilised, the feedstocks available and used for processing or blending, the utilities (fuel, electricity, steam) consumption for all processing units and for the overall refinery, as well as the blend composition of all products and the properties of blended products, and an economic summary including the cost of crude, other feedstocks, utilities consumed and the prices of blended finished product.

2 https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en

3 https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

4 Hydrotreated vegetable oils

5 Hydroprocessed esters and fatty acids

Sometimes, the output of the LP model is not intended as the final target of the study but rather serves as an intermediate step for further calculations, for example the marginal CO_2 intensities of refined products.[2]

Ultimately, when developing and running LP models, there are two unwritten principles among the LP community that have to be considered. First is the concept of 'garbage in, garbage out', used to express the idea that incorrect or poor-quality input data will produce faulty output data, and second is that the LP is a tool but the LP user is 'THE' tool, meaning that the user is responsible for the input data treatment and output analysis, and the rest is just mathematics.

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E-fuels: a techno-economic assessment of European domestic production and imports towards 2050

This article summarises the findings of a new study commissioned to provide a detailed techno-environmental analysis of e-fuels production efficiency, energy consumption and mass balance, as well as the carbon intensity of the produced e-fuels, in different regions and for different time frames. In addition, an economic analysis considers the costs of e-fuel supply for nine e-fuels, in four geographies and over three time frames. Both parts of the study incorporate sensitivity analyses which consider the impact of a range of key technical and economic parameters.

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Concawe and Aramco have jointly commissioned a study[1] to provide a techno-environmental (Part 1) and economic (Part 2) analysis of different e-fuels pathways produced in different regions of the world (northern, central and southern Europe, as well as the Middle East and North Africa) in 2020, 2030 and 2050, with assessments of sensitivities to multiple key techno-economic parameters.

The e-fuels pathways included in the scope of this study are: e-hydrogen (liquefied and compressed); e-methane (liquefied and compressed); e-methanol; e-polyoxymethylene dimethyl ethers (abbreviated as OME_{3-5}); e-methanol to gasoline; e-methanol to kerosene; e-ammonia; and e-Fischer-Tropsch kerosene/diesel (low temperature reaction). The e-hydrogen is considered as a final fuel but also as a feedstock for producing other e-fuels.

The study also includes:

- an assessment of stand-alone units versus e-plants integrated with oil refineries;
- a comparison of e-fuels production costs versus fossil fuels/biofuels/e-fuels produced from nuclear electricity;
- an assessment of the impact of intermittency and seasonality of renewable energy supply on storage requirements, synthesis plant sizing and production costs;
- an analysis of the context of e-fuels in the future in Europe (potential demand, CAPEX, renewable electricity potential, land requirement, feedstocks requirements); and
- a deep dive into the safety and environmental considerations, societal acceptance, barriers to deployment and regulation.

The e-fuels techno-environmental assessment (Part 1 of the analysis) has been developed by Concawe and Aramco, using the Sphera GaBi platform as a modelling tool, and the e-fuels economical and context assessment (Part 2 of the analysis) has been conducted by the consultants LBST and E4tech, under the supervision of Concawe and Aramco. All the assumptions are fully aligned between both parts of the study.

For the base cases, it is assumed that the e-fuel plant produces 1 million tonnes of e-diesel equivalent (based on conventional diesel EN 590) per year. Hence, the nameplate capacities of hydrogen generation via water electrolysis and downstream processes depend on the characteristics of the regional renewable electricity supply.

Techno-environmental assessment

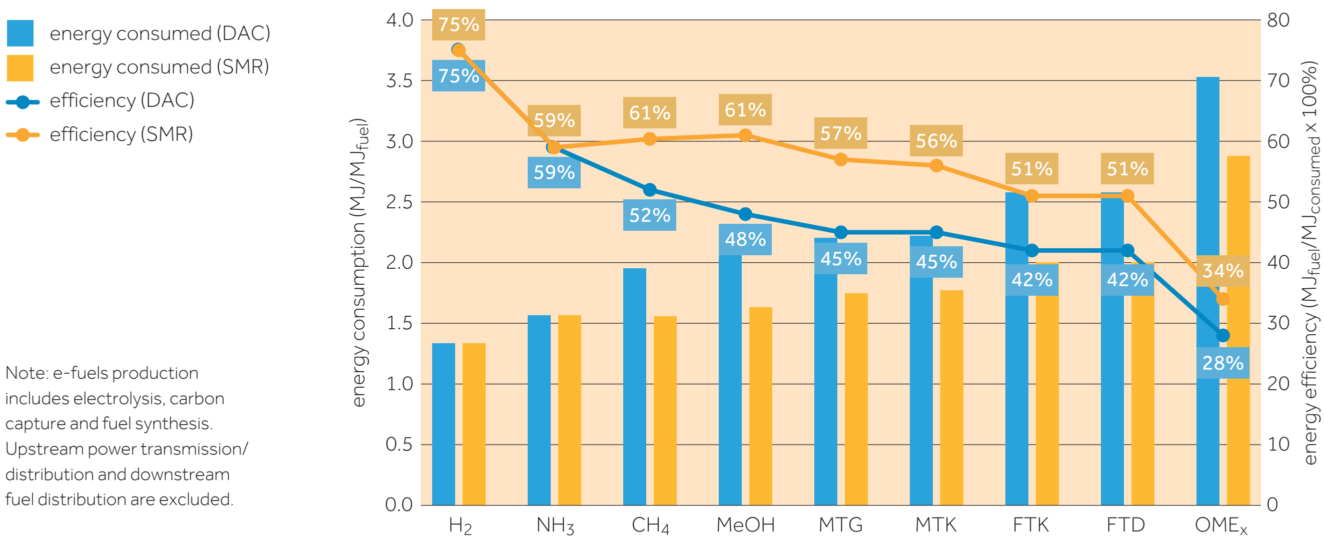
In Part 1 of the analysis, a detailed analysis of the e-fuels production efficiency, energy consumption, mass balance and carbon intensity of the e-fuels produced has been conducted in the different regions and time frames. In addition, sensitivity analyses of relevant technical parameters, such as technology development, electricity power sources (including the grid), carbon sources, carbon capturing location and hydrogen transportation via hydrogen vectors have been included.

For the base cases, a 100% concentrated (point) unavoidable CO_2 source is considered in 2020 and 2030, while only direct air capture (DAC) is considered in 2050. The choice of 100% DAC in 2050 was made for the sake of compliance with announced restrictions concerning the origin of CO_2 for e-fuels[2] and assuming that the unavoidable and sustainable CO_2 sources in 2050 would be limited.

Figure 1 shows that the energy consumption for e-fuels production increases depending on the length and complexity of the synthesised molecules. The simplest molecules, like hydrogen, require less energy consumption for their production than the more complex ones. As an example, for fuels synthesised from air-captured CO_2 (DAC), 1 MJ of Fischer Tropsch (FT) e-diesel requires 2.4 times the energy needed to produce 1 MJ of e-hydrogen, while 1 MJ of the more complex molecule e-OME_{3-5} needs 3.6 times that amount.

Accordingly, the opposite trend is observed for the e-fuel efficiency, defined as the ratio between the energy contained in the fuel and the energy used to produce the fuel. The simplest molecule, e-hydrogen, has an energy efficiency of 75% driven by the electrolysis efficiency (alkaline electrolyser). The efficiency continues to drop as hydrogen is combined with nitrogen, carbon or oxygen to produce larger fuel molecules. The reduction in efficiency from shorter to longer carbon chains is not proportional: the energy efficiency of the simplest fuel containing a carbon atom, e-methane, is 52% when produced from air-captured CO_2, but it drops to 42% for more complex molecules like FT e-diesel or FT e-kerosene. The lowest efficiency comes from the e-OME_{3-5} (OME_x), a non-drop-in fuel and an exception compared to the other molecules, estimated at 28%. This is due to the higher complexity of the process for OME_x that requires more energy consumption compared to other e-fuels.

Figure 1: Comparison of energy consumption and energy efficiency for e-fuels production when using CO_2 from DAC and a concentrated CO_2 source (steam methane reforming—SMR) (Timeline: 2050)



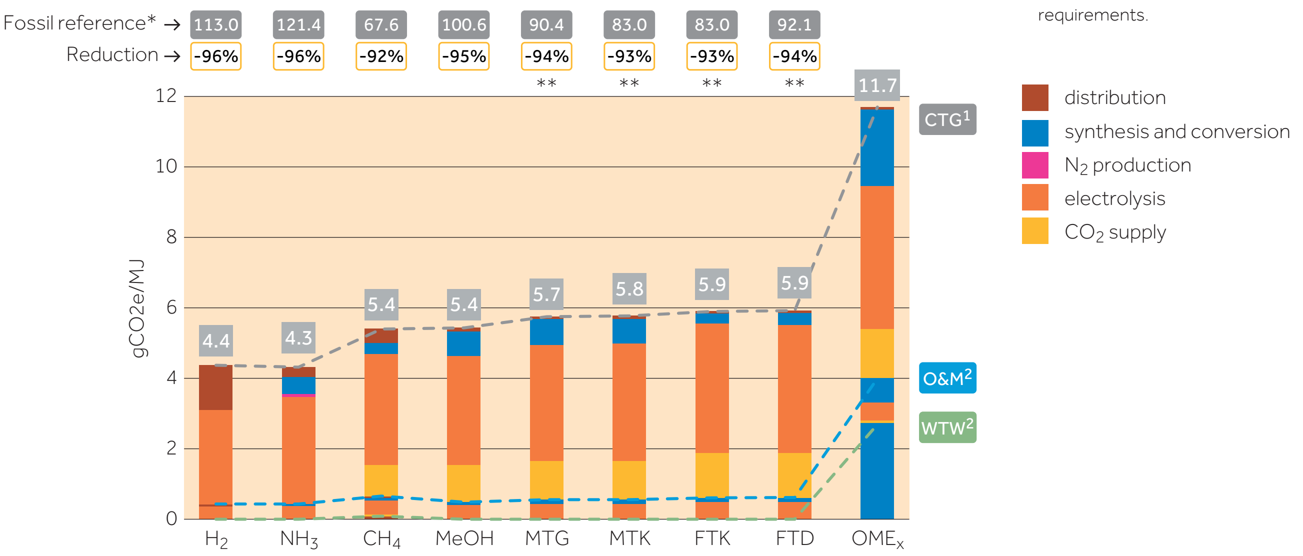
Note: e-fuels production includes electrolysis, carbon capture and fuel synthesis. Upstream power transmission/ distribution and downstream fuel distribution are excluded.

These values correspond to the cases with carbon capture from DAC in the 2050 timeline. If the carbon capture is obtained from a concentrated source, the Fischer-Tropsch diesel and kerosene (FTD and FTK) efficiencies increase up to 51%, and for polyoxymethyl dimethyl ethers (OME_{3-5}) they increase to 34%. The energy efficiencies of the production pathways were improved by assuming heat integration between the fuel synthesis and the carbon capture process, whenever possible. Additional potential efficiency improvements, like heat recovery from low temperature electrolysis, were not considered in the base cases.

In Figure 2 it can be observed that, taking northern Europe as an example, the net greenhouse gas (GHG) emissions of the different e-fuels pathways on a cradle-to-grave (CTG) basis are around 4.3–6 gCO_2eq/MJ (except for the e-OME_{3-5}) and around 0.5 gCO_2eq/MJ if only the emissions from operation and maintenance (O&M) are counted. The well-to-wheels (WTW) emissions are almost zero because of the use of renewable energy for all operations except power for distribution. These values are in the same order of magnitude for all the e-fuels pathways, as e-fuels that are less energy-intensive to produce (such as e-hydrogen) are more energy-intensive to transport than drop-in fuels such as e-gasoline or e-diesel.

Figure 2 also shows that GHG emissions come mainly from electrolysis, with a share of roughly 65–80% of the CTG impact (except for OME_{3-5}, where it accounts for around 40%). The emissions from O&M represent between 9–12% of the total CTG emissions (around 35% for OME_{3-5}). This means that roughly 90% of the total emissions from e-fuels are associated with the infrastructure required, mainly for renewable electricity.

Figure 2: Cradle-to-grave GHG emissions of different e-fuel pathways (Case: North EU, 2050 as an example (details for the other regions and timelines are included in section 1.6 of the full report[1]



Notes on Figure 2:

* JEC WTT Study v5,[3] GaBi Database.

** Additional reduction if RED II fossil fuel comparator (94 gCO_2eq/MJ) is used.

1 CTG includes O&M emissions plus emissions from building the infrastructure to produce the e-fuels, emissions from their feedstocks, and their energy requirements.

2 O&M includes WTW emissions plus emissions from maintaining the infrastructure to produce the e-fuels, emissions from their feedstocks, and their energy requirements.

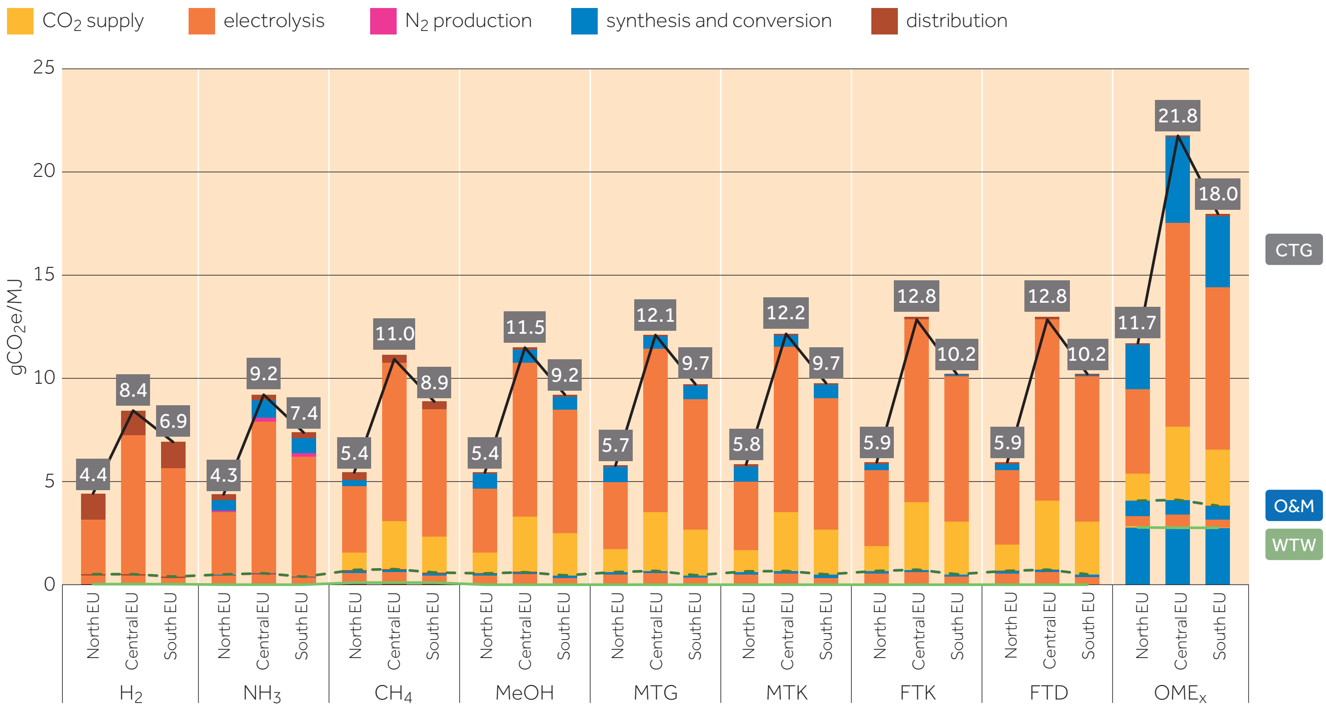
3 WTW includes emissions from production, transport and use of the e-fuels, emissions from their feedstocks, and their energy requirements.

All the e-fuels pathways (except e-OME_{3-5}) achieve a GHG reduction higher than 92% versus the fossil alternative (without emission reductions). All the e-fuels pathways comply with the RED II emissions limit for 'renewable fuels of non-biological origin' (RFNBO) (28.2 gCO_2eq/MJ), which mandates a 70% reduction in GHG versus the fossil reference defined in the RED II (94 gCO_2eq/MJ). This reduction is reached even considering a CTG basis. This might suggest that some more economical schemes might be possible, which are not 100% dependent on green power as the sole energy input but accept some use of fossil energy while staying within the limit. However, any kind of fossil-green mixed versions of e-fuels is out of the scope of this study. It is important to note that the reduction rates assumed in the present study consider CTG emissions from all feedstocks, including renewable electricity. If emissions from the manufacturing of the solar panels or wind turbines are excluded (i.e. not a CTG basis), the GHG reduction would be even higher.

GHG emissions from e-OME_{3-5} production are around 11.7 gCO_2eq/MJ. The emissions are more than twice those of the other e-fuels due to the higher complexity of the process that requires more energy consumption, while still being compliant by far with the RED II criteria for sustainable e-fuels (28.2 gCO_2eq/MJ). OME_{3-5} presents other benefits when blending with diesel components, such as the low soot and NO_x emissions[4] that could be considered for commercial fuel blending.

Figure 3 shows that GHG emissions from O&M are very similar among regions for all the e-fuels pathways in 2050 (around 0.5 gCO_2eq/MJ for northern Europe).

Figure 3: Cradle-to-grave GHG emissions from e-fuels production by European region in 2050

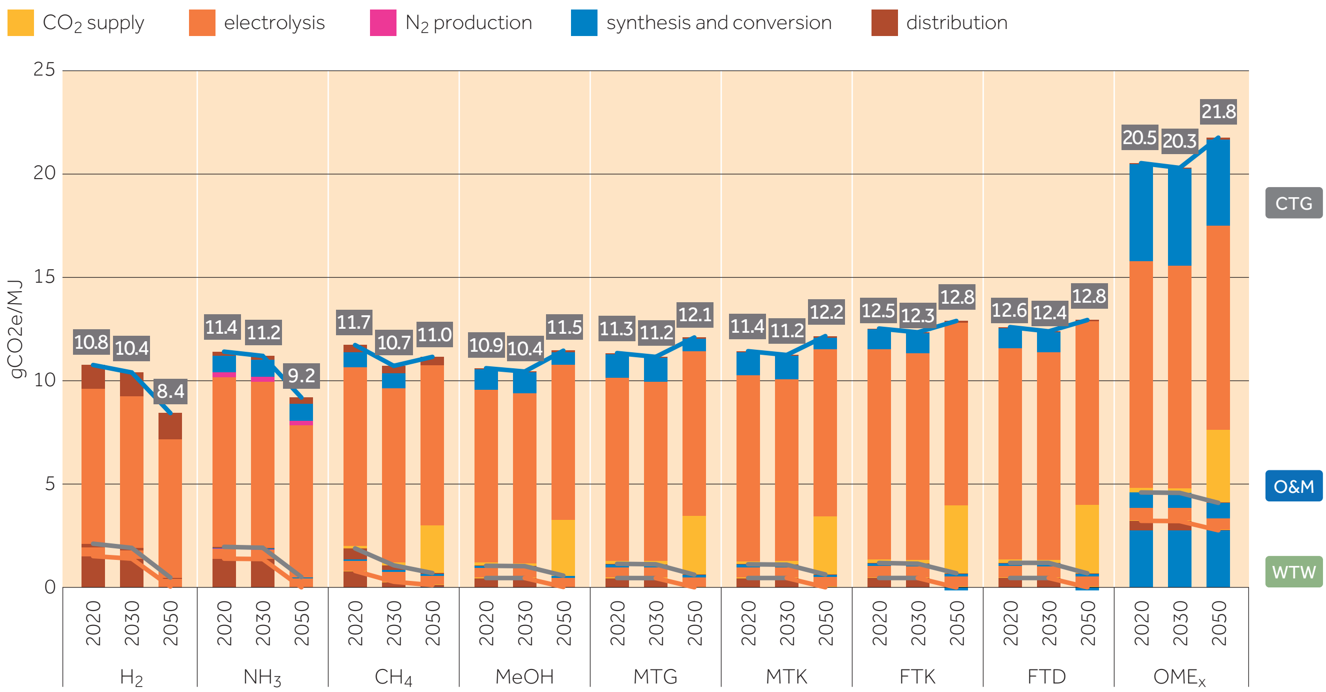


However, the CTG values show lower levels in northern Europe (around 5.5 gCO_2eq/MJ), followed by southern Europe (around 10 gCO_2eq/MJ) and central Europe (around 12.5 gCO_2eq/MJ) in 2050 for all the e-fuels pathways. The highest values observed for central Europe are due to the higher carbon intensity of the available renewable power in the region. This results from the lower full load hours of renewable electricity and the higher contribution of photovoltaic renewable electricity (PV) versus wind renewable electricity. PV presents higher CTG carbon emissions than wind electricity (2.6 to 6 times higher depending on the region).

Long distance transport of fuels is mostly subject to the carbon intensity of the fuel used for ship propulsion, and is not expected to significantly increase the GHG emissions of e-fuels. The carbon intensity of the electricity used for e-fuel production will still be the most dominant factor.

Figure 4 shows that a progressive reduction of CTG GHG emissions is observed over time only for hydrogen and ammonia, while for carbon-based fuels they first drop and then increase. As an example, for FTK the CTG GHG emissions in gCO_2eq/MJ go from 12.5 in 2020 down to 12.3 in 2030 and then up to 12.8 in 2050. This is due to opposite effects overlapping: on one side, an improvement in electrolyser efficiencies and the generalisation of the use of e-fuels for maritime and truck transport favour a decrease over time in emissions from H_2 supply and distribution. On the other hand, the displacement of concentrated sources of CO_2 by the use of DAC requires more energy-intensive operations to capture CO_2 from the atmosphere and results in a net increase in emissions by 2050.

Figure 4: Cradle-to-grave GHG emissions from e-fuels production in central Europe in 2020, 2030 and 2050

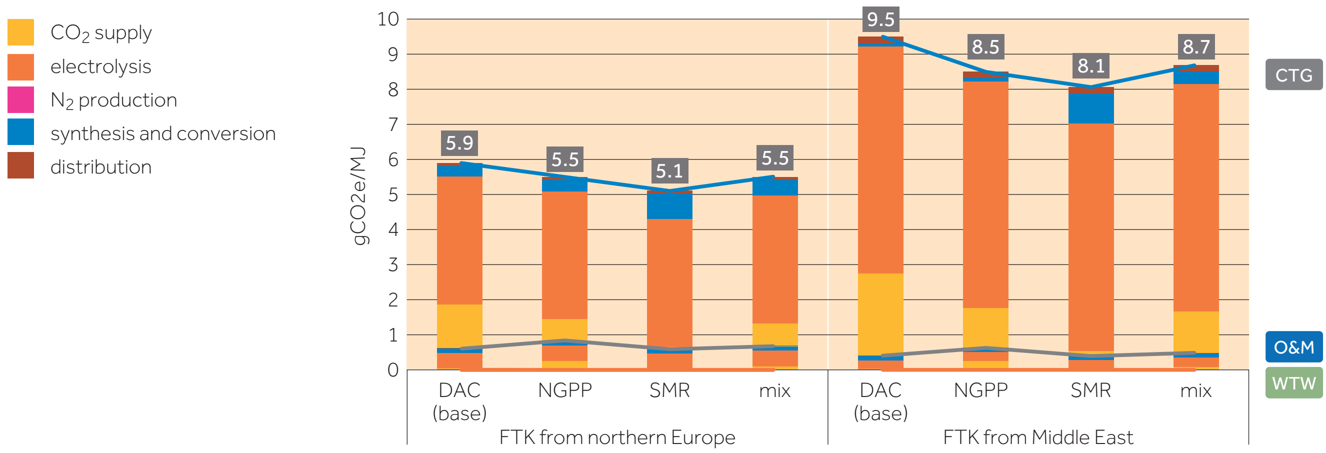


The contribution of O&M remains stable over time (around 0.5 gCO_2eq/MJ for FTK) until 2050. The WTW GHG emissions drop steadily until 2050 for all fuels as the emissions from the additional renewable electricity required for DAC are assumed to be 0 on a WTW basis. Sensitivities to this assumption are included in section 1.7 of the full report.[1]

Figure 5 depicts the impact of switching to different CO_2 sources for e-fuel synthesis. In the FTK pathway, the utilisation of a high CO_2 concentration, like steam methane reforming (SMR) pre-combustion off-gases instead of CO_2 captured from the atmosphere via DAC, reduces the GHG impact by 0.8 to 1.4 gCO_2eq/MJ depending on the geographical location. The use of flue gases from a natural gas power plant (NGPP), which are less concentrated than SMR off-gases but more concentrated than air, also reduces the GHG emissions by 0.4 to 1.0 gCO_2eq/MJ depending on the geographical location.

Other sensitivities are further analysed in the full report,[1] such as the use of different renewable energy sources, the use of CO_2 captured in Europe for e-fuel synthesis in the Middle East and North Africa (MENA), and the impact of using energy carriers instead of liquefaction to transport H_2, in a case where e-fuels are produced in Europe with hydrogen coming from MENA.

Figure 5: Comparison of GHG emissions from Fischer-Tropsch kerosene production from different CO_2 sources and different production locations in 2050

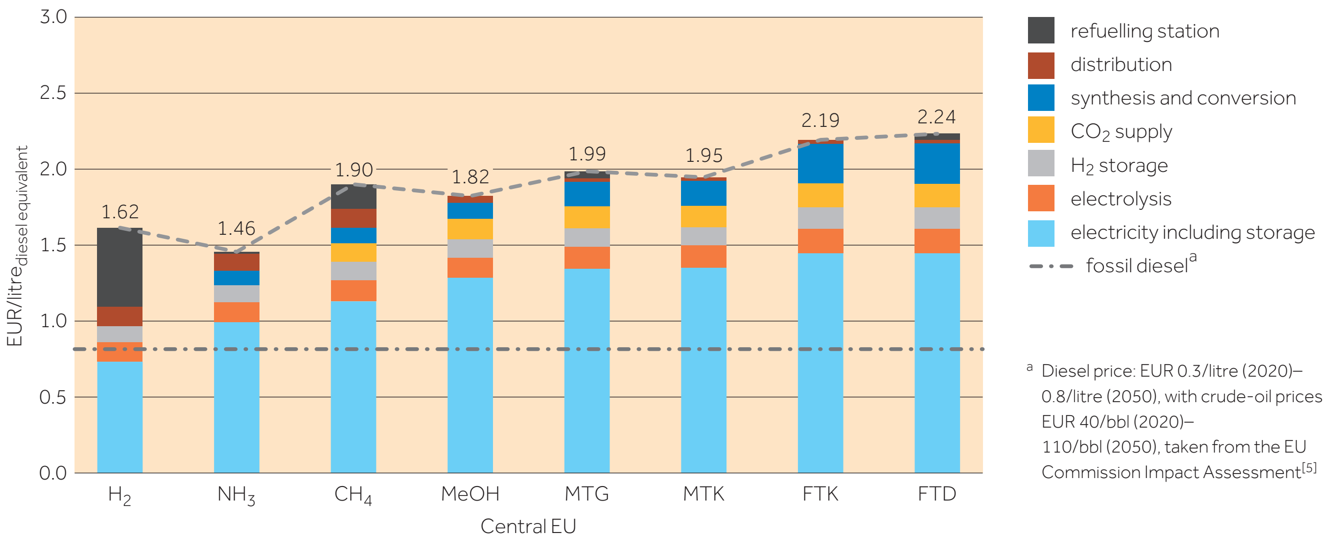


Economic assessment

Part 2 of the study[1] presents a detailed analysis of the costs of e-fuel supply for nine e fuels for four geographies (northern, central and southern EU and MENA) and for three time frames (2020, 2030 and 2050), plus a series of key sensitivities have been taken into account, leading to more than 100 assessments.

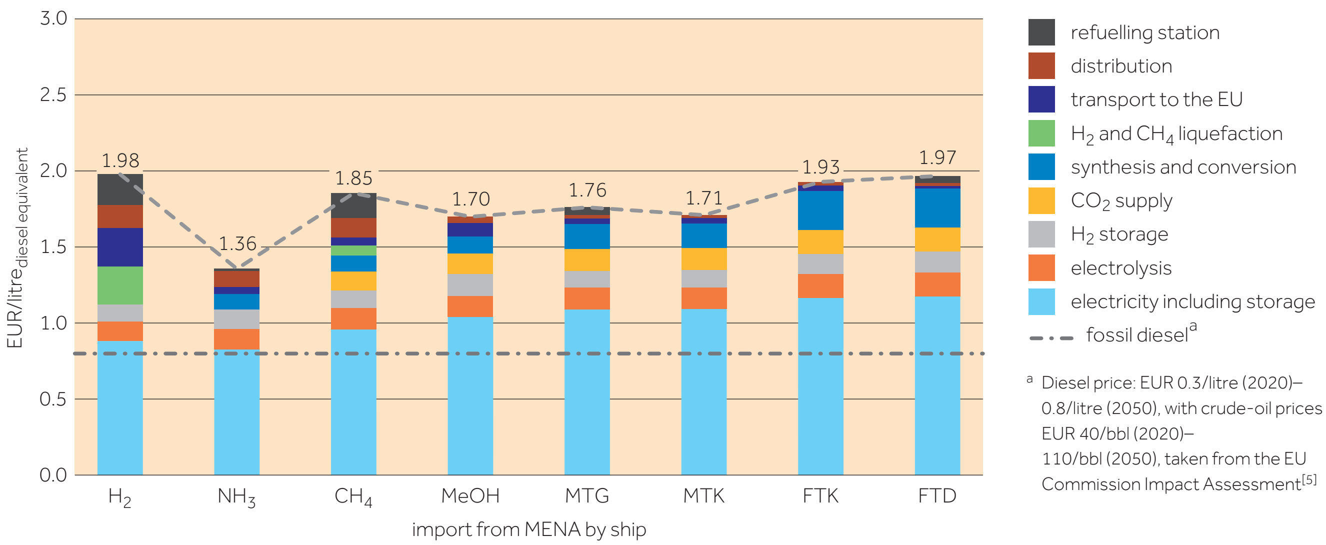
Figure 6 shows the costs of e-fuels produced in central Europe, and Figure 7 shows the costs of e-fuels produced in MENA and transported to the EU in 2050, as examples (the other regions and time frames are presented in the full report[1]). The figures show that between 40% and 80% of the cost including electricity storage comes from the renewable electricity cost.

Figure 6: Costs of e-fuels produced in central Europe in 2050



[a] Diesel price: EUR 0.3/litre (2020)–0.8/litre (2050), with crude-oil prices EUR 40/bbl (2020)–110/bbl (2050), taken from the EU Commission Impact Assessment[5]

Figure7: Costs of e-fuels produced in MENA and transported to the EU in 2050



[a] Diesel price: EUR 0.3/litre (2020)–0.8/litre (2050), with crude-oil prices EUR 40/bbl (2020)–110/bbl (2050), taken from the EU Commission Impact Assessment[5]

The figures show the strong correlation between energy requirements for e-fuel production and associated costs. E-fuels that are less energy-intensive to produce generally lead to lower costs of fuel production, such as e-hydrogen and e-methane. However, subject to transport distance and mode, e-hydrogen and e-methane need to be liquefied, thus increasing the transportation effort.

Based on the assumptions taken, this economic assessment of e-fuels towards 2050 shows that fuel supply costs across all regions range between EUR 1.7 and 4.6 per litre of diesel-equivalent in the short term, and between EUR 1.4 and 2.8 per litre in the long term if the outlier OME_x is excluded. For OME_x the fuel supply costs range between EUR 3.2 and 6.8 per litre of diesel equivalent in the short term, and between EUR 2.7 and 4.3 per litre of diesel equivalent in the long term.

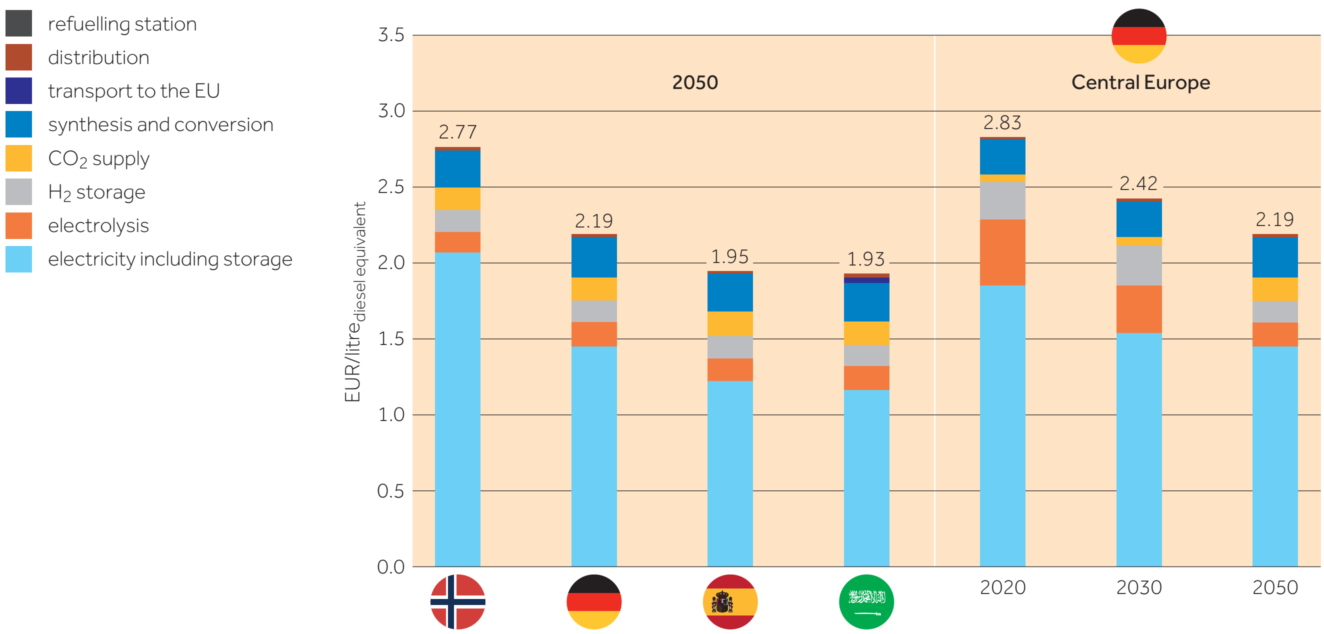
Figure 8 shows that FTK produced in MENA and southern Europe represent the lowest fuel costs, followed by central and northern Europe. This is directly linked to the full load hours and the renewable electricity cost.

Note that in this study for northern Europe, 100% offshore wind has been taken into account assuming that new additional e-fuels plants would rely on this source. If hydropower is used as the primary electricity source, the e-fuel production cost in northern Europe would be lower.

Figure 8 also shows that the cost of e-fuels produced in central Europe is reduced with time (20%) due to decreasing CAPEX for wind and PV plants, electrolysis, and improvement of electrolysis efficiency despite lower availability of concentrated CO_2 sources.

Figure 8: Costs of Fischer-Tropsch e-kerosene

The left part of the chart refers to 2050, and the right refers to central Europe (see the full report for details of the other regions and timelines[1])

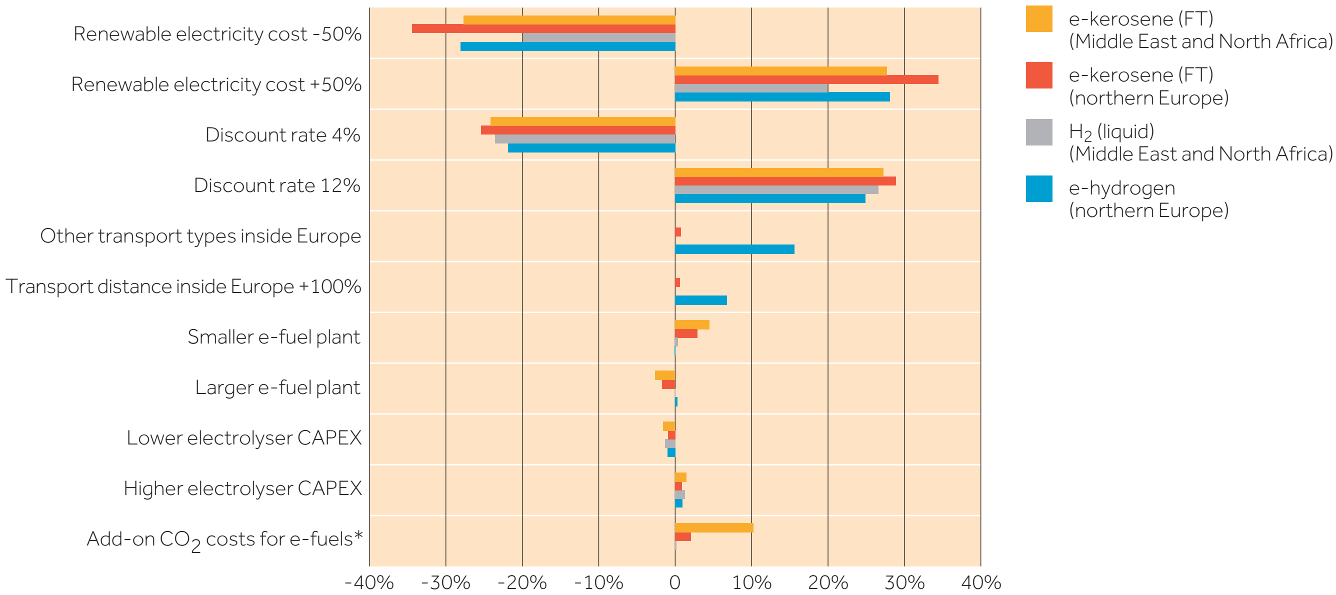


For this part of the assessment, the same H_2 and CO_2 buffer storage capacities have been assumed for all regions. An evaluation of the impact of the regional weather conditions on the size of the buffer capacities, and its cost, is conducted later in the intermittency and seasonality assessment.[1]

Sensitivities to key economic parameters

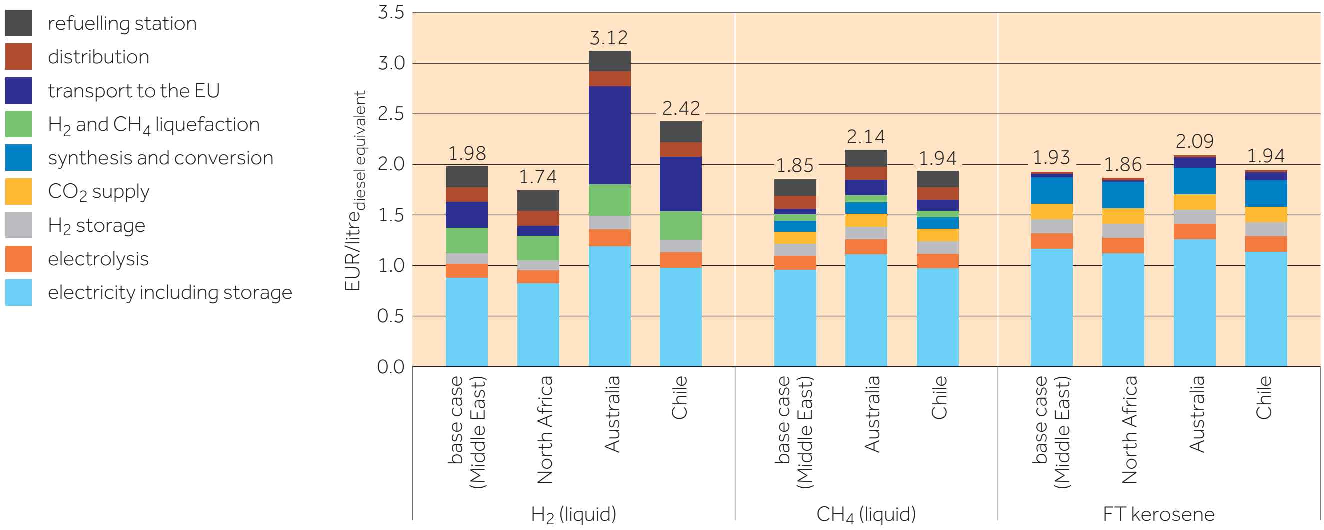
Figure 9 shows the sensitivities studied. Electricity costs and discount rates have a significant impact on overall fuel supply costs. A 50% change in electricity supply costs or discount rate assumptions resulted in a change of about 25% in the supply cost. Other factors investigated, such as transport type and distance inside or outside Europe, or e-fuel plant size, have only marginal impacts (single-digit percentage points). The cost impacts relative to the final production costs are similar for 2020 and 2050 except in the case of CO_2 add-on costs for CO_2 for e-fuels. In 2050 CO_2 from concentrated CO_2 sources with CO_2 add-on costs have been applied as sensitivity compared to CO_2 from direct air capture without CO_2 add-on costs in the base case.

Figure 9: Sensitivity—impact of the variation of selected parameters (2050 base case)



A deep dive into the e-fuels production cost when produced and imported to Europe from most distant regions of the world, such as Australia and Chile, has been conducted and is shown in Figure 10 on page 20. The results show that for liquid e-fuels, even very long transport distances lead to minor changes in e-fuel production costs, of similar ranges as for e-fuels produced domestically in southern Europe. For e-hydrogen, long distance transport over many thousands of kilometres significantly increases the production costs.

Figure 10: The impact of geography—imports of e-fuels into the EU from other regions (2050)



A further relevant sensitivity analysis looked at the use of alternative carriers for H_2 import to feed synthesis processes. The use of ammonia and methylcyclohexane as H_2 carriers to feed synthesis processes leads to higher e-fuels production costs (EUR 3.20 per litre of diesel equivalent for ammonia and EUR 4.52 per litre of diesel equivalent for methylcyclohexane, compared to EUR 3.14 per litre of diesel equivalent in the base case). The use of methanol as an H_2 carrier, however, compares favourably at EUR 2.93 per litre of diesel equivalent.

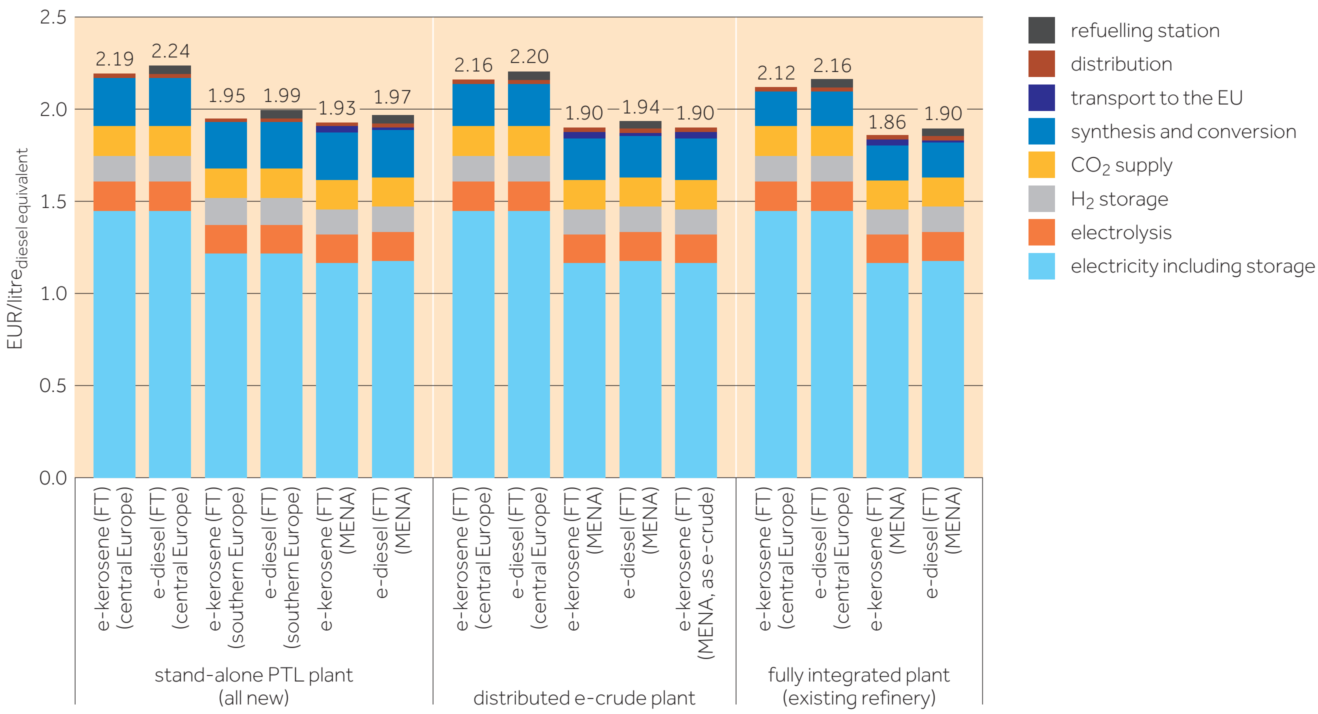
Stand-alone plants versus distributed e-crude plants versus fully integrated plants

The comparison between a stand-alone e-fuel plant (all-new integrated plant for hydrogen production, synthesis to e-crude, and final upgrading), a distributed e-fuel plant (new hydrogen production and synthesis to e-crude units, and e-crude upgraded in existing refineries) and a fully integrated e-fuel plant (the hydrogen production, synthesis to e-crude, and final upgrading is all fully integrated into an existing refinery) was also studied.

Existing refineries can play a facilitating role in the energy transition to e-fuels. They have been bulk consumers of hydrogen for decades and offer valuable knowledge in many aspects of hydrogen infrastructure, storage and end use. Switching natural gas-based hydrogen production at refineries to hydrogen from on-site electrolysis and/or supply via pipeline allows for an accelerated cost reduction path of electrolyser CAPEX and/or deployment of H_2 pipelines. The additional costs for deploying several hundreds of megawatts of electrolyser capacity per average refinery site are amortised over a product output of many gigawatts, resulting in marginal additional final product costs in the order of EUR 0.005 per litre of diesel equivalent.[6] Furthermore, the existing refining assets can, in part, be used to upgrade FT syncrude, allowing an efficient use of existing investments. Since refineries are complex, have diverse configurations, and differ in terms of supply infrastructure and product mix, refinery-specific feasibility studies are recommended to assess the opportunities in the field.

The difference between a stand-alone plant and a fully integrated plant in a refinery is that, in the case of the fully integrated plant, there are no capital costs for hydrocracking, fractionation (upgrading), utilities and logistics. Only OPEX is taken into account for these processes. However, these capital cost elements have a low contribution (~3%) to the total e-fuel production costs. In 2050 the e-fuel production costs range between EUR 1.93 and 2.24 per litre of diesel equivalent for stand-alone e-fuel plants, and between EUR 1.86 and 2.16 per litre of diesel equivalent for e-fuel plants that are fully integrated into an existing refinery.

Figure 11: Comparison of e-fuels production costs in a stand-alone, distributed and fully integrated plant (2050)



In the short to medium term there may be advantages in utilising existing refineries to minimise capital expenditure. There is a potential advantage of co-processing in the early e-fuel development. The lower the CAPEX, the higher the probability that a company will invest, aiming to have a return on investment in a shorter time.

In 2050, the CAPEX for the stand-alone FT plant without H_2 and CO_2 supply amounts to about EUR 1,800–2,000 million including indirect costs. The CAPEX for the distributed FT e-crude plant without H_2 and CO_2 supply amounts to about EUR 1,400–1,500 million. The CAPEX of the FT plant fully integrated into an existing refinery without H_2 and CO_2 supply amounts to about EUR 1,000–1,100 million. (Note that no learning curve has been applied to FT plant as the technology can be considered mature. However, the capacity of the plants changes between 2030 and 2050 due to an increase in the flexibility of the FT plant leading to a higher CAPEX of the FT plants in 2050 than in 2020 and 2030).

Comparison of e-fuel production costs versus fossil fuels, fuels produced from nuclear electricity, and biofuels

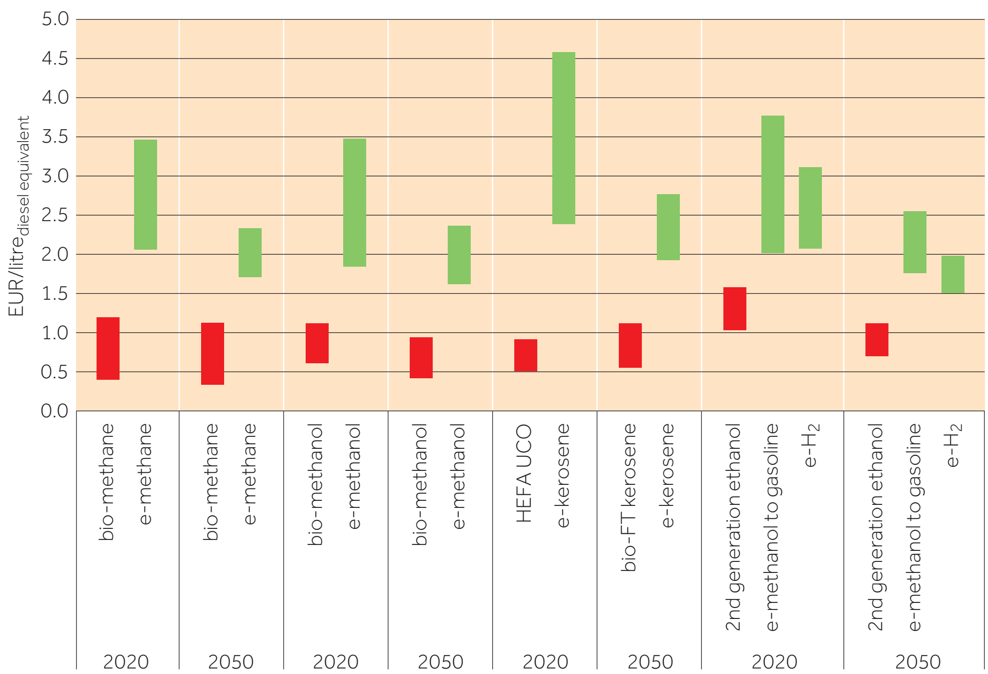
Based on the assumptions made, the costs of e-fuel supply are higher than those for fossil crude oil-based fuels, even in 2050 taking into account the improvement in technology and the decrease in electricity costs. In 2050 the costs of e-fuels supply ranges between EUR 1.5 per litre of diesel equivalent for e-hydrogen and EUR 2.8 per litre of diesel equivalent for FT kerosene. The costs of crude oil-based diesel amount to about EUR 0.8 per litre of diesel equivalent in 2050 (for a crude oil price of EUR 110 per barrel of oil equivalent).[5]

Based on the assumptions made,[7,8,9,10] nuclear electricity would result in higher e-fuels production costs in 2020 versus PV or on-shore wind electricity if new nuclear plants have to be built (except off-shore wind).

Based on biofuel cost data,[11] the production costs and GHG abatement costs for biofuels are lower than those for e-fuels. In 2050, the production costs of biofuels are expected to range between EUR 0.3 per litre of diesel equivalent (lower limit for bio-methane) and EUR 1.1 per litre of diesel equivalent (upper limit for bio-methane, bio-FT kerosene, and second-generation ethanol). The higher cost for e-fuels is attributable primarily to the cost of green hydrogen production as compared with biomass gasification. The FT process step is broadly the same for the e-fuel and biofuel cases while the cost of producing green hydrogen is high owing to high input electricity costs and, to a lesser extent, high CAPEX (electrolysis). By contrast, the CAPEX of gasification plant is high while the input feedstock costs are relatively low.

Fuel costs
Fossil fuel comparator (diesel~kerosine):
2050: 0.80 EUR/litre$_{\text{diesel equivalent}}$
Today: 0.30 EUR/litre$_{\text{diesel equivalent}}$

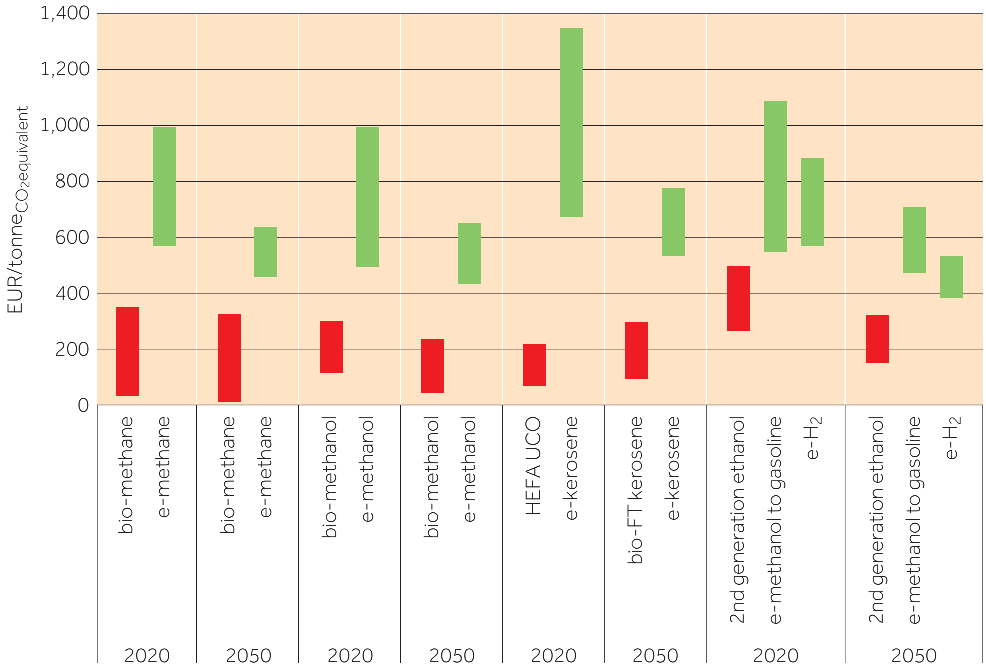
Figure 12: Production costs for e-fuels versus biofuels



Over time electrolyser CAPEX is likely to fall (perhaps more quickly than gasification plant CAPEX), but while the cost of renewable electricity will also fall it is not expected to match the lower costs of biofuel feedstock. However, while this study[1] provides a high-level cost comparison between e-fuels and biofuels based on acknowledged literature sources, it is neither designed to assess their cost differentials nor differentials between costs and prices.

The GHG abatement costs for e-fuels are expected to decrease from about EUR 480–1,350 in 2020 to some EUR 390–780 per tonne of avoided CO_2-equivalent in 2050. The GHG abatement costs for biofuels are expected to decrease from EUR 30–500 per tonne of avoided CO_2 equivalent in 2020 to some EUR 10–320 per tonne of avoided CO_2-equivalent in 2050.

Figure 13: GHG abatement costs for e-fuels versus biofuels



It should be noted that these abatement costs refer only to fuel supply (including embedded carbon), without accounting for use-case efficiencies. For example, fuel cell electric vehicles (FCEVs) have a higher efficiency than internal combustion engine (ICE) vehicles leading to lower abatement costs for hydrogen fuel. The powertrain assessment was not included in the scope in this study.

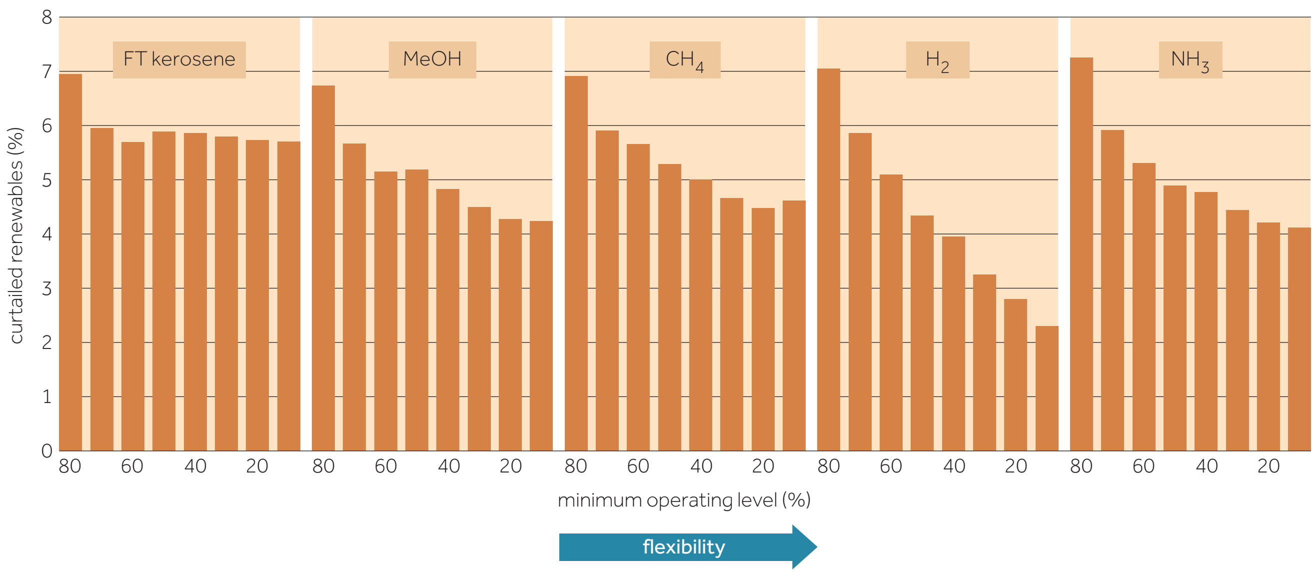
Intermittency and seasonality of renewable energy supply

The intermittency of renewable electricity sources and the operational flexibility of fuel production processes have a direct impact on the costs of e-fuel production. In this study,[1] the degree of variability in renewable power supplies was explored with a focus on wind and solar power. The results of this analysis provided inputs for the broad assumptions used in the rest of the study including the mix of PV and wind, the amount of renewable curtailment, and the size of storage elements. These include electricity storage based on battery systems, hydrogen storage, and CO_2 storage necessary for e-fuels production along with the cost impacts of production flexibility.

PV and wind are intermittent, but complementary to a large extent. Site-specific co-optimisation allows smoothing of the the electricity supply. The PV/wind ratio for least-cost production is driven by the combination of multiple parameters, including CAPEX for the different system facilities (PV and wind power plants, buffer storage of electricity, H_2 and CO_2, electrolysis plants and synthesis processes) and the equivalent full load hours. The CAPEX values for renewable electricity and for various components of the e-fuel plant change over time, leading to different PV/wind ratios also evolving over time.

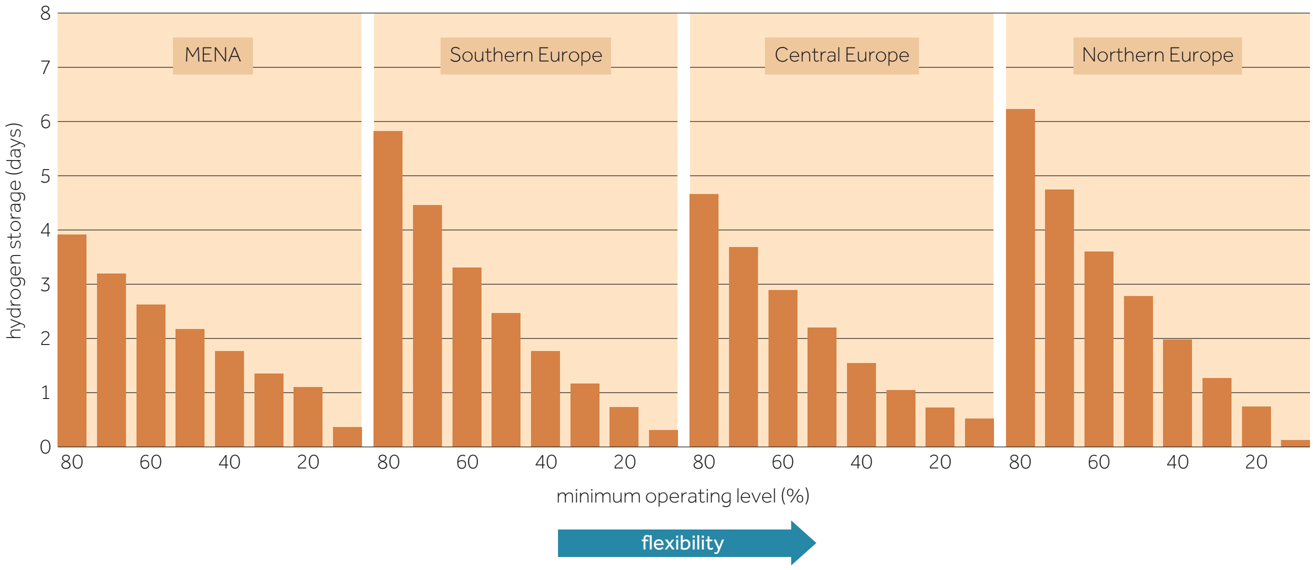
Figure 14 shows, for central Europe, the average amount of curtailed electricity across all operational points and fuels, which is about 5.8%. The level of curtailment decreases when the operational flexibility of the synthesis units increases. The study also shows that in northern Europe the curtailment amounts to only 2.6% on average across the range of fuel and conditions modelled. In MENA, the average electricity curtailment across all fuels and all operational conditions is around 6.6%. In southern Europe the inflexible cases see a much higher degree of curtailment due to the impacts of periods with low wind speed and low solar irradiation in renewable production, leading to overbuilding of assets, with an average of around 6.7% electricity curtailed across all fuels below a minimum part load of 60%.

Figure 14: Electricity curtailment in central Europe in 2050



As shown in Figure 15, the hydrogen storage capacity required depends on the flexibility of the downstream synthesis processes, such as the maximum change rate in hourly production and the minimum part load. This is also valid for the CO_2 storage capacity. The higher the flexibility of the downstream synthesis process, the lower the hydrogen and CO_2 storage requirements. Furthermore, the characteristics of renewable electricity supply over time also influence the H_2 and CO_2 storage requirements. The study shows that a higher PV share is related to higher H_2 and CO_2 storage requirements, except in regions with regular daily irradiation (batteries for day/night balancing). In most regions, increasing flexibility by 30% reduces the storage capacity requirements by more than half.

Figure 15: H_2 storage requirements (Fischer-Tropsch kerosene, 2050)



The study shows that, in general, as operational constraints become more flexible, the capacity of the synthesis plant increases with its load factor correspondingly decreasing. This is because the plants need to be oversized to allow higher production in times of high renewable energy availability, and compensate for lower production in times of lower renewable energy production in order to achieve the targeted annual production volume. The final capacity of the plant is a result of the balance between costs and load factors on all the different components in the system.

The study also demonstrates that a significant cost reduction in fuel production can be achieved with moderate flexibility of synthesis technologies. In the case of central Europe, 70–85% of the cost reduction potential can be achieved by moving the minimum part load from 80% down to 40%.

Context of e-fuels in the future of Europe — potential demand and feasibility

Technical potentials for renewable power production in Europe of more than 22,000 TWh/year as estimated in this study[1] is a factor of seven of today's electricity demand of approximately 3,000 TWh/year, and thus exceeds the foreseeable energy demand for all energy uses in a carbon-neutral future in principle. However, this is subject to social acceptance of the significant infrastructure that would need to be built. The technical potential in other regions of the world such as MENA is even greater but brings with it geopolitical and energy dependency risks.

High and low explorative scenarios for e-fuels developed for this study suggest that the demand for e-fuels in Europe could be in the range of 63 to 115 million tonnes of oil-equivalents (or 733 and 1,337 $TWh_{fuel,LHV}$, respectively). The low case is in line with the IEA World Energy Outlook (WEO) 2022[12] estimates for e-fuels, while the high case assumes that the remaining fossil fuels and biofuels in the IEA WEO scenario are also replaced with e-fuels. This would require the deployment of 278 to 1,531 GW of newly installed renewable generation capacity depending on the geographic distribution, generation mix and demand scenario chosen. Gross land use requirement for this is significant, around 0.1 million km^2, but it represents only around 2% of the total usable European land area (a little over 4 million km^2). The CAPEX required to deliver this amount of e-fuels process plant and associated renewables would lie in the range EUR 1–2.3 trillion or the equivalent of an annual investment of between 0.2 and 0.6% of EU GDP. This level of expenditure is consistent with other estimates (such as McKinsey, 2020[13]) of the investment required to achieve net zero.

The challenges involved in meeting e-fuels demand in both the high and low explorative scenarios are significant. Vast amounts of investment are required, and sizable amounts of resources will need to be mobilised, but it seems to be technically feasible. For example, the low and high explorative scenarios evaluated in this study, derived from IEA (2022).[12] result in a renewable electricity demand of 1,319 TWh (low scenario) to 2,805 TWh, respectively, which compares to a technical renewable electricity production potential of some 22,000 TWh/year in Europe. The main limitation to exploit the significant renewable electricity potentials in Europe may be social acceptance of mass deployment of wind and solar power plants, but not the technical renewable power production potentials.

In addition, suitable sources of CO_2 are needed as feedstock for electricity-derived synthesised hydrocarbon fuels. Use of concentrated CO_2 sources lead to lower overall fuel costs and higher e-fuel production efficiency, making it an interesting option until technologies for DAC are available at scale and while the availability of unavoidable CO_2 sources is foreseen.[14] However, the availability of industrial CO_2 sources, such as from steel production or cement industries, is set to decline in line with ETS[1] requirements, increased recycling efforts, and a general move towards a more circular economy towards 2050. Further industrial CO_2 sources will only be allowed for e-fuels production before 2041.[15] Beyond this date, only DAC and biogenic CO_2 sources will be allowed.

[1] Emissions Trading System — https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en

The demand for water required specifically for the production of electricity-based fuels is negligible compared to water demand for energy crops (a few litres versus several thousand litres of water per litre of energy-equivalent.[16] The use of dry cooling towers and/or closed-loop water cycling is recommended (where needed) to minimise net water demand. Some DAC technologies also provide water that can further reduce the net water demand from e-fuels plants. For regions that are prone to, or already face, water-supply stress, such as the MENA region, the net water demand of an e-fuel plant needs to be supplied by seawater desalination plants (less than 1% of e-fuel total costs). Despite the low specific water footprint, e-fuels production plants at scale are significant point water consumers. Diligent assessment of water supply, demand and reservoir characteristics is highly relevant in the preparation of environmental and social impact assessments accompanying plant approval processes.

A deep dive into the safety and environmental considerations, societal acceptance, barriers to deployment, regulation and new technologies is also included as part of the study.[1]

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HDV CO_2 Comparator — a life-cycle assessment tool for heavy-duty vehicles in real-world conditions

Introduction

This article summarises a study to create an interactive life-cycle assessment tool for heavy-duty vehicles. The tool enables users to compare the CO_2 emissions intensity of various heavy-duty transport technology options in order to determine the best options for decarbonisation for a range of vehicle categories and use cases. The tool can be accessed via the Concawe website.

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The Concawe HDV CO_2 comparator is an interactive life-cycle assessment (LCA) tool for heavy-duty vehicles (HDVs), developed by IFP Energies nouvelles (IFPEN) and commissioned by Concawe. It was first published on the Concawe website in July 2023, and some data source and interface updates are scheduled for early 2025. Users are provided with an easy-to-use interactive tool to compare the CO_2 intensity of various heavy-duty transport technology options.

Understanding the benefits and drawbacks of each solution from a life-cycle perspective for a given use case is difficult. The LCA tool described in this article aims to improve this understanding and assist in decision-making.

HDVs have numerous vehicle categories and use cases, and have access to many powertrains and energy carrier combinations. The tool combines the following parameters to define specific use cases:

- Six powertrains and their efficiencies: ICEV, fuelled by diesel or diesel-like fuels, gas (compressed natural gas (CNG) or liquefied natural gas (LNG), or hydrogen; HEV; PHEV; FCEV; and BEV (and CEV).
- Five vehicle categories: long-haul truck (Class 5); delivery truck (Class 2); city bus; coach; and refuse truck (for waste collection).
- Five categories of energy carriers: diesel (petroleum-based diesel and partially renewable blends such as B7, B30, B7+25%HVO[1]); renewable diesel-like fuels (including HVO, B100 (100% FAME[2]), e-diesel, biomass-to-liquid, etc.); hydrogen (grey, blue or green); CNG and LNG (fossil-based, bio-based, e-fuel based); and electricity (with variations in carbon intensity).
- Sensitivities around battery, fuel cell capacity and hydrogen tank production emissions.
- Number of battery packs used in the lifetime of the vehicle.
- Use cases (payload, trip profile, charging frequency).

All of this provides the user with a comprehensive yet simple tool to make direct comparisons on the same free-to-use platform via the Concawe website.

Context

Transport-related greenhouse gas (GHG) emissions represent approximately one quarter of European Union (EU) GHG emissions, of which commercial road transport represents approximately one third of this. In the context of aiming to reach carbon neutrality in 2050, reducing heavy-duty transport-related GHG emissions is important. Technology neutrality is an important consideration for achieving carbon neutrality whilst simultaneously retaining functionality within the diverse range of heavy-duty transport needs.

1 Hydrotreated vegetable oil

2 Fatty acid methyl ester

HDV CO_2 Comparator — a life-cycle assessment tool for heavy-duty vehicles in real-world conditions

When looking at each vehicle individually, there are several ways to consider their GHG emissions:

- The tank-to-wheel (TTW) approach, which only accounts for the tailpipe emissions.
- The well-to-wheel (WTW) approach, which is more comprehensive and takes into account the GHG emissions related to the production of the energy carriers.
- The LCA approach, which is holistic and also takes into account the GHG emissions related to the production of capital goods that are necessary for the transport system.

The LCA approach is the most relevant to climate-related issues. However, it is also challenging and dependent on the scenarios and use cases studied (i.e. combined assumptions). In this context, the passenger cars LCA tool[1] commissioned by Concawe in 2022 proved itself to be very useful as it allowed a complex set of options to be combined in a simple way, following the user's own approach.

Concawe received feedback from numerous external users of the passenger car LCA tool, who requested a similar tool to evaluate the life-cycle emissions of heavy-duty vehicles. This led to the development of the HDV CO_2 Comparator described in this article.

Scope and objectives

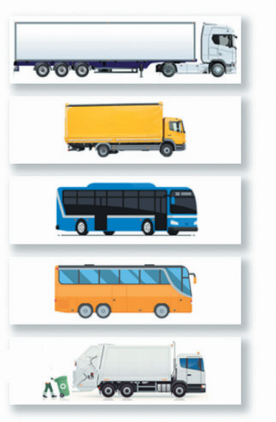
The objective of this study was to develop a life-cycle assessment online interactive tool for heavy-duty vehicles in real-world conditions, similar to the one previously developed for passenger cars. This includes:

- LCA CO_2-equivalent emissions (g/km) segregated by stage of life (vehicle manufacture, electricity, fuel production (well to tank, or WTT), TTW emissions, and absorbed CO_2 during the production of the fuel);
- overall energy consumption: fuel consumption TTW (l/100 km or kg/100 km), and electrical consumption (kWh/100 km); and
- the facility to specify the following conditions:
  - powertrains used and their efficiencies;
  - vehicle categories;
  - sensitivities around battery, fuel cell and hydrogen tank capacity and emissions during their production;
  - number of battery packs used in the lifetime of the vehicle;
  - use cases (payload, trip profile, charging frequency);
  - fuels used; and
  - carbon intensity of the electricity mix.

Overview of the tool functionality

As powertrains diversify in their electrification levels, energy carriers and fuel production pathways, the carbon footprint over their life cycle depends on their use cases. This interactive tool is user centric, allowing scenarios where multiple parameters can be combined to compare their environmental performance. The tool consists of a welcome page where the vehicle category can be selected by clicking on the corresponding picture for long-haul truck, delivery truck, city bus, coach or refuse truck (see Figure 1).

Figure 1: Vehicle categories available for selection



Long haul — Class 5

Delivery truck — Class 2

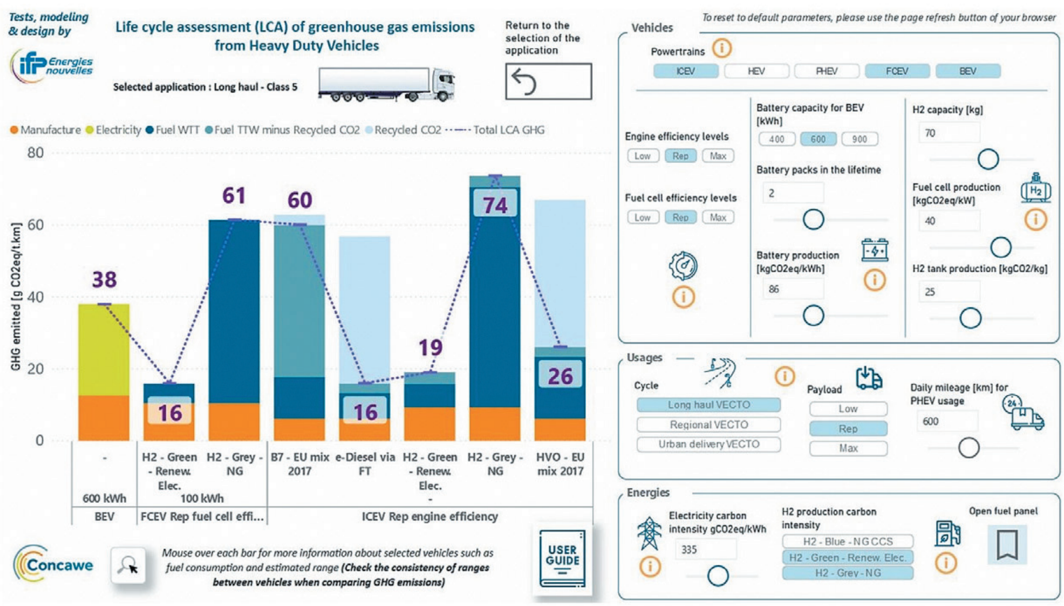
City bus

Interregional coach

Refuse truck

Once a selection is made, this is followed by a page composed of two main panels: the results panel (on the left-hand side) and the configuration panel (on the right-hand side), as shown in Figure 2.

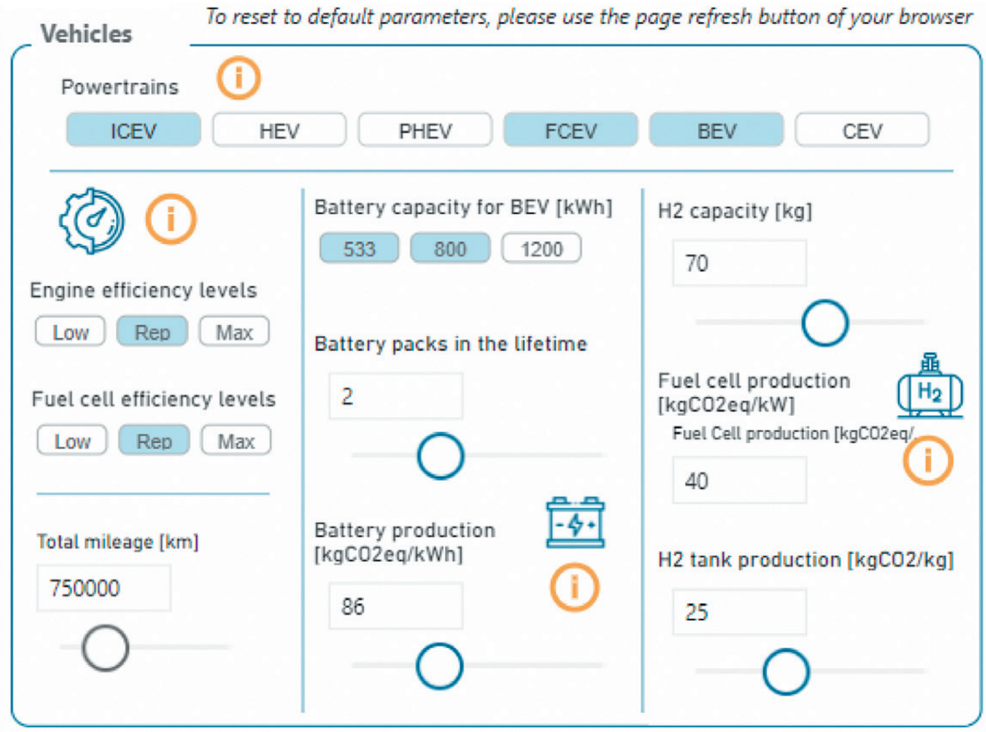
Figure 2: Main user interface of the tool



Vehicle configuration

On the configuration panel found on the right-hand side of the page, the user is presented with options to set up the desired comparison, starting with the vehicle itself (see Figure 3).

Figure 3: Details of the vehicle configuration user interface



Powertrains

Six powertrain options can be selected, and once selected their results appear as a bar chart in the results panel. The choice of powertrain options includes:

ICEV = internal combustion-engine vehicle
HEV = hybrid electric vehicle
PHEV = plug-in hybrid electric vehicle
FCEV = fuel cell electric vehicle
BEV = battery electric vehicle
CEV = catenary electric vehicle

The technical details of the powertrains modelled are shown in Table 1 on page 33. The user can select any number of these options and they will immediately appear on the results panel on the left-hand side.

Table 1: Powertrain sizing details and efficiencies

Powertrain	Energy carrier	Long-haul truck Class 5	Delivery truck Class 2	City bus 12 m	Coach/ interurban bus	Refuse truck
ICE	Diesel	12.8 litres / 400 kW / 46% / 2,700 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / 6 gears
	CNG/LNG	12.9 litres / 340 kW / 36.5% / 2,000 Nm / 12 gears	7.1 litres / 225 kW/ 36% / 1,150 Nm / 12 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears	7.1 litres / 225 kW / 36% / 1,150 Nm / 6 gears
	H_2	15.2 litres / 410 kW / 44.1% 1,950 Nm / 12 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 12 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears	9.3 litres / 220 kW / 44.1% / 1,100 Nm / 6 gears
HEV	Diesel	12.8 litres / 400 kW / 46% / 2,700 Nm / battery 20 kWh / e-motor 150 kW / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 30 kWh / e-motor 100 kW-280 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 20 kWh / e-motor 35 kW-250 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 25 kWh / e-motor 120 kW-800 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 25 kWh / e-motor 120 kW-8,000 Nm / 6 gears
PHEV	Diesel/ electricity	12.8 litres / 400 kW / 46% / 2,700 Nm / battery 130 kWh / e-motor 250 kW-1,100 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 100 kWh / e-motor 250 kW-1,100 Nm / 12 gears	7.1 litres / 225 kW / 42.4% / 1,130 Nm / battery 100 kWh / e-motor 160 kW-400 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears	7.7 litres* / 250 kW / 46% / 1,400 Nm / battery 100 kWh / e-motor 250 kW-1,100Nm / 6 gears
BEV	Electricity	Battery 533 kWh / e-motor 350 kW-2,000 Nm-5 krpm / 2 gears	Battery 400 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Battery 533 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Battery 667 kWh / e-motor 300 kW-1,500 Nm / 2 gears	Battery 400 kWh / e-motor 300 kW-1,500 Nm / 2 gears
FCEV	H_2	Fuel cell 225 kW / 65% / H_2 50 kg / battery 100 kWh / e-motor 350 kW-2,000 Nm-5 krpm / 2 gears	#1: Fuel cell 225 kW / 65% / H_2 30 kg / battery 20 kWh / e-motor 250 kW-1,100 Nm / 2 gears #2*: Fuel cell 75 kW / 65% / H_2 15 kg / battery 100 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Fuel cell 75 kW / 65% / H_2 35 kg / battery 75 kWh / e-motor 250 kW-1,100 Nm / 2 gears	Fuel cell 225 kW / 65% / H_2 35 kg / battery 75 kWh / e-motor 300 kW-1,500 Nm / 2 gears	Fuel cell 75 kW / 65% / H_2 25 kg / battery 75 kWh / e-motor 300 kW-1,500 Nm/ 2 gears
CEV	Electricity	Battery 130 kWh / e-motor 250 kW-1,100 Nm / 12 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 12 gears	Battery 100 kWh / e-motor 160 kW-400 Nm / 6 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears	Battery 100 kWh / e-motor 250 kW-1,100 Nm / 6 gears

Engine and fuel cell efficiency levels

Engine and fuel cell efficiency data are sourced either from the IFPEN engine database or the generic engine database within the EU VECTO tool (a simulator for HDVs developed by the European Commission).[2] The default setting is 'Representative' which corresponds to the efficiencies in Table 1.

For diesel, gas and H_2 engines, 'Low' and 'Max' correspond to peak efficiencies of 40% and 50%, respectively. For the fuel cell, 'Low' and 'Max' correspond to peak efficiencies of 55% and 70%, respectively.

Battery production (kgCO_2eq/kWh)

Battery production GHG intensity is mostly related to the material extraction and production process. In the tool, the user can set the GHG intensity for the production of 1 kWh of battery capacity. The value can be adjusted here as a user input with the following guideline from literature (users can view the explanation by clicking on the information icon near each parameter):

Given the dynamic nature of the sector, it is relevant to consider technological, geographical and environmental developments in battery production, which may reduce the emission factor over time for this key component. Xu *et al.*[3] built a prospective life-cycle assessment model for lithium-ion battery cell production for various chemistries, production regions and time frames. This work provides emission factor values for current and future battery production in different contexts. A value of 86 kgCO_2/kWh was ultimately set as the default value since current solutions are largely produced in China.

Fuel cell and H_2 tank production (kgCO_2eq/kWh)

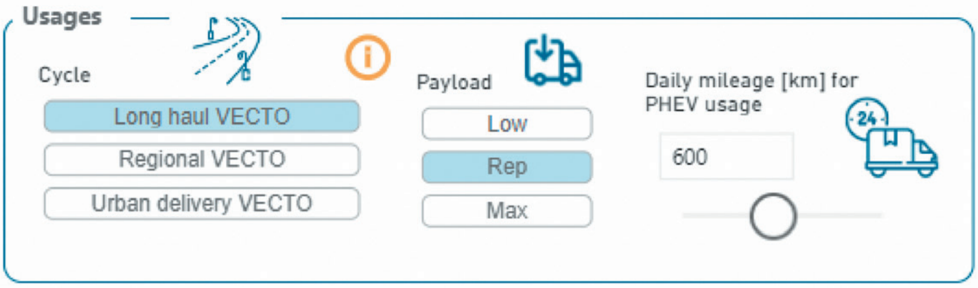
For the fuel cell, a power of 225 W/cell was considered (IFPEN assumption). The fuel cell modelling is based on the studies of Evangelisti[4] and Miotti[5] for bipolar plates. Regarding fuel cell auxiliary equipment, the study by Stropnik[6] was used. For platinum, an Ecoinvent emission factor of 69,500 kgCO_2eq/kg is considered. This leads to an estimated emission factor of 40 kgCO_2eq/kW_fuel_cell for the fuel cell as a whole, which is set as a default value for the corresponding input field.

The amount of H_2 carried in vehicles can be modified. This parameter has an impact on the vehicle's estimated range (visible by hovering the mouse over the results bar chart). It also has an impact on the emissions associated with the carbon fibre tank, whose emission factor can also be modified using a slider (25 kgCO_2eg/kg_tank is set as a default value according to IFPEN LCA modelling). It was assumed that to store 1 kg of H_2, a 26.3 kg tank is needed.

Usage configuration

Once the vehicle parameters are set, the next step is to set the usage parameters with the following options.

Figure 4: Details of the usage configuration user interface



Cycle

VECTO is a new simulation tool developed by the European Commission to determine CO_2 emissions and fuel consumption from HDVs, and the cycles used in VECTO are considered to be the most representative for the purposes of this comparator. For the long haul and delivery truck, three cycles are considered coming from the VECTO database[2]: a 'long-haul' cycle representative of highway driving conditions; a 'regional delivery' cycle including a mix of highway and intercity driving conditions at lower speed; and an 'urban delivery' cycle at a lower average speed for deliveries in cities.

For the city bus two cycles are considered: a medium average speed cycle, 'Urban' from VECTO, as well as a lower average speed cycle representative of very dense urban usage, the 'TfL UIP cycle', proposed by Concawe and courtesy of Transport for London.

For the interurban bus, a medium average speed cycle, 'InterUrban', as well as a higher average speed cycle including highway driving portions, 'Coach', both from the VECTO database, are considered.

Finally, for the refuse truck, a specific cycle including driving displacement and power take-off (PTO) work called 'Municipal Utility PTO' is considered. This cycle is an urban driving cycle with several standstill phases using a PTO cycle consistent with a refuse collecting phase.

Payload

Alongside driving cycles, variations in payload are considered for the vehicle from low to maximum payload. Payload is the weight of goods transported for Class 5 and Class 2 trucks and the refuse truck. For the city bus and interurban coach it corresponds to the number of passengers. Maximum payload is adjusted to stay within the maximum vehicle weight according to the vehicle type. The maximum payload is defined for a conventional ICE configuration, but can be adjusted for other powertrain configurations considering the vehicle curb mass effect of the powertrain (e.g. the battery mass impact for BEVs). 'Low' and 'representative' payloads are taken from the VECTO definitions.

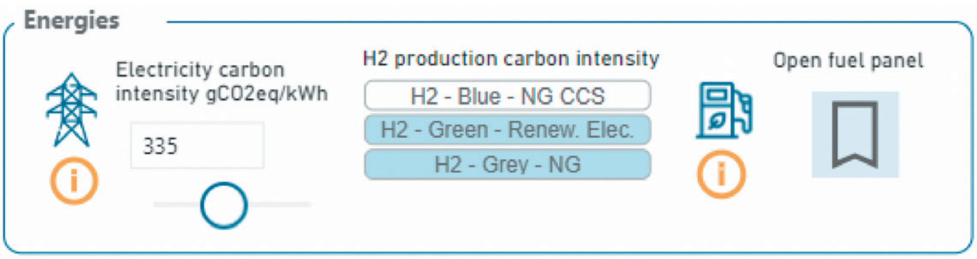
PHEVs fuel calculation

For PHEV consumption, a weighting of 'charge depleting' and 'charge sustaining' consumption is used. The weighting coefficient is called the 'utility factor' and is defined as the ratio between the all-electric range and the vehicle's daily distance (which can be directly selected by the user), assuming that drivers will recharge their PHEV every night between two driving days.

Energy configuration

The remaining panel is used to select energy parameters (see Figure 5).

Figure 5: Details of the energy configuration user interface

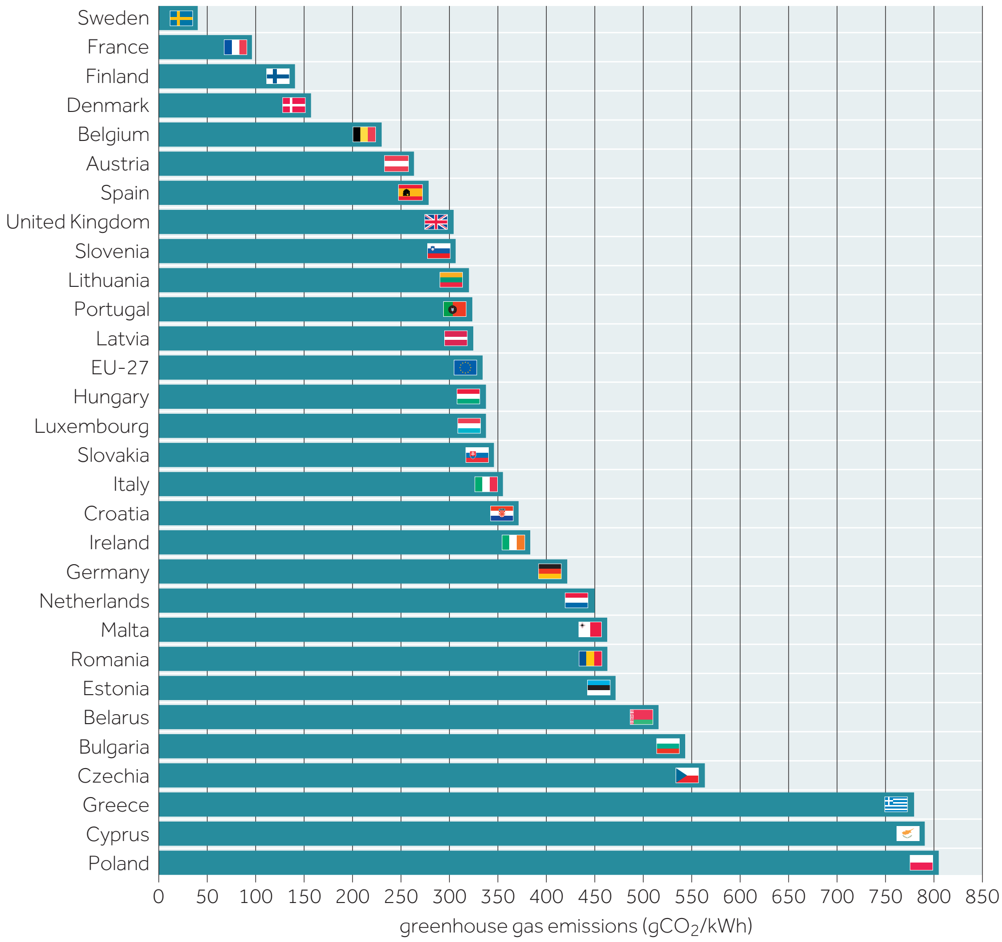


Electricity carbon intensity (gCO_2/kWh)

The user needs to input a value based on where the electricity will be coming from. The GHG intensity of electricity for European countries can be used as a guideline to help users set this value. This key parameter is used to calculate CO_2-equivalent emissions related to the vehicle electricity consumption.

These values are extracted from Scarlat *et al.*,[7] which presents an LCA-based methodology to quantify the produced and the consumed electricity carbon intensities of European countries. The default value chosen for used electricity carbon intensity is the EU-27 average for 2019, which is 334 gCO_2eq/kWh (see Figure 6 on page 37). This is down from approximatively 650 gCO_2/kWh in 1990, and is expected to decrease further in the coming decades. As newer sources become available this will be updated, so users should refer to the orange information icon to see the source used in the current version.

Figure 6: Greenhouse gas emissions intensity of used electricity for 2019 (gCO_2/kWh)



H_2 production carbon intensity

Where hydrogen is considered, the user can choose between three different hydrogen production sources:

- H_2-blue (natural gas reforming coupled with carbon capture and storage (CCS));
- H_2-green (electrolysis using renewable electricity); and
- H_2-grey (natural gas/methane reforming with no CCS).

Fuels

A variety of diesel- and CNG-like fuels can be selected. Fuels selected here are displayed in the results panel.

Table 2: Fuels available for selection in the tool

Diesel-like fuels	CNG-like fuels
B100—EU mix 2017	CNG[g]—fossil EU mix 2017
B100—rapeseed	Compressed biomethane—EU mix 2
B100—UCO[a]	Compressed biomethane—manure
B30—EU mix 2017	Compressed biomethane—municipal
B7—EU mix 2017	Compressed e-methane
B7—EU mix 2017 with 25% HVO[b]	Liquefied biomethane—EU mix 2017
BtL[c] via FT[d]	Liquefied biomethane—manure
BtL via FT and BECCS[e]	Liquefied biomethane—municipal waste
BtL via HTL[f]	Liquefied biomethane—waste wood
e-diesel via FT	Liquefied e-methane
HVO—EU mix 2017	LNG[h]—fossil EU mix 2017
HVO—UCO	

[a] UCO = used cooking oil [b] HVO = hydrotreated vegetable oil [c] BtL = biomass to liquid
[d] FT = Fischer Tropsch [e] BECCS = bioenergy with carbon capture and storage [f] HTL = hydrothermal liquefaction
[g] CNG = compressed natural gas [h] LNG = liquefied natural gas

The primary properties of the fuels considered for the vehicle simulations are provided in Table 3. These properties are specifically related to parameters that have an impact on the energy analysis, including density, lower heating value (LHV) and the air/fuel ratio (AFR). Additional attributes such as carbon content and carbon intensity, pertaining to the production of petroleum fuels, derivatives and renewable fuels, are described in the section on *Life-cycle assessment* on pages 41–46.

Table 3: Primary fuels properties

Fuel	Density (kg/m^3)	LHV (kJ/kg)	AFR
B7	835	42,580	14.39
Gas	0.66	42,700	17.24
H_2	0.08	120,000	34.2

Vehicle simulation methodology

In the vehicle simulation phase of the study, typical figures for the energy consumption of current and future propulsion systems for HDVs were assessed. This part of the study is related to the TTW analysis providing the vehicle energy consumption, a technical definition of the selected HDV and the associated powertrain as the input for the LCA. This focuses on energy consumption and GHG emissions, therefore pollutant emissions were not included in the vehicle simulations. However, GHG contributions from CH_4 and N_2O emissions were factored in. These additional GHG emission contributions were added to the other emissions based on data collected in the literature.

Vehicle simulations aim to estimate the overall energy consumption (kWh/100 km) of HDV vehicles as well as the fuel consumption (l/100 km for liquid fuels and kg/100 km for gaseous fuels) or electrical consumption (kWh/100 km) depending on the considered powertrains.

Five typical categories of HDVs, representative of the European HDV market, were identified in the scope of the study by Concawe members:

- An HDV, also referred to as a long-haul vehicle, with a maximum weight of around 44 tonnes.
- A medium-duty vehicle (MDV), also referred as a delivery truck, with a maximum weight of around 19 tonnes.
- A 12-metre non-articulated city bus.
- An interregional coach (bus).
- A 26-tonne utility truck, also referred to as a refuse truck.

For each of these vehicles, five categories of powertrains were evaluated:

- Conventional powertrain for ICEVs.
- Hybrid electric powertrain for HEVs.
- Plug-in hybrid electric powertrain for PHEVs.
- Hydrogen fuel cell powertrain for FCEVs.
- Battery electric powertrain for BEVs.
- Catenary electric power for CEVs.

Furthermore, four categories of energy carriers were considered:

- Diesel-type fuels (for ICEVs, HEVs and PHEVs): petroleum-based with renewable blend components such as B7, B30 or B7+25% HVO, and renewable diesel-like fuels such as HVO, B100 (100% FAME), e-diesel, BtL, etc.
- Hydrogen (for ICEVs and FCEVs): grey, blue or green.
- Gas (for ICEVs): CNG and LNG, fossil-based, bio-based or e-fuel-based.
- Electricity (for PHEVs and BEVs), with variations in carbon intensity.

Energy consumption figures of the vehicles were evaluated considering vehicle representative cycles depending on vehicle category:

- For the HDV long-haul truck:
  - 'High speed' cycles corresponding to national and international travel.
  - Local/urban trips for last-mile delivery.
- For the MDV delivery truck:
  - 'High speed' cycles corresponding to national and international travel.
  - Local/urban trip for last-mile delivery.
- For the city bus:
  - Urban transport including medium- and low-speed travel.
- For the interregional bus:
  - 'High speed' cycles corresponding to national and international travel.
- For the refuse truck:
  - Local/urban low- and medium-speed trip including garbage collection phases.

A nominal simulation matrix including vehicle categories, powertrain architectures, and the selected energy carrier was considered as a nominal simulation set. In addition, a sensitivity analysis was considered around nominal configurations (default vehicle and powertrain sizing). For the sensitivity analysis, the following parameters were investigated:

- Vehicle payload.
- Vehicle driving cycle.
- ICE peak efficiency (for ICEVs, HEVs and PHEVs).
- Battery capacity (for BEVs).
- Fuel cell efficiency (for FCEVs).
- Charging frequency (for PHEVs).

Note: all the simulations were operated at nominal temperature (20°C) with an ambient start.

Vehicle simulations were developed using Simcenter Amesim™ sketches. First, the simulations were calibrated using the VECTO tool[2] on the 'mainstream' ICEV configurations; this showed a good fit, with a less than 2% difference in fuel consumption on typical driving cycles.

The simulations were then expanded to alternative powertrains (HEV, PHEV, FCEV, BEV). The vehicle configurations (powertrain characteristics, weight, efficiencies, battery capacity, etc.) and their conditions of use (driving cycles, payload) were selected based on a literature review of existing vehicles. The simulation results (energy consumption) were cross-checked with data found in the literature and showed a fairly good consistency considering that the driving cycles used in the literature may vary and are not always described. The vehicle simulations provided an energy consumption (expressed in l/100 km, kg/100 km or kWh/100 km) for each vehicle configuration featuring the combined parameters mentioned above.

This energy consumption is converted to CO_2eq emissions using the emission factors (TTW, WTT and recycled CO_2 contributions) of the different energy carriers (liquids, gases and electricity). Added to that are the non-CO_2 exhaust emissions (i.e. CH_4 and N_2O contributions — powerful GHGs even when emitted in small quantities) and the emissions from manufacturing the vehicle (powertrain, chassis, battery, tank, tyres), giving the life-cycle emissions of the vehicles expressed in gCO_2eq/t.km (where 't' represents tonnes of goods transported).

An in-depth Concawe report on the vehicle simulation details and LCA methodology was published in March 2024.[8]

Life-cycle assessment

The GHG emission factors used in the simulator are summarised below. Three categories of emission factors are considered: fuel emission factors; carbon intensity of the electricity mix; and emission factors associated with vehicle production and recycling (for chassis, tyres and battery).

These emission factors were obtained using LCA methodology. The LCA was performed in accordance with ISO 14040 and 14044 standards. The functional unit is gCO_2eq/t.km, where 't' refers to the payload of the vehicle, not to the total mass of the vehicle.

Fuel emission factors

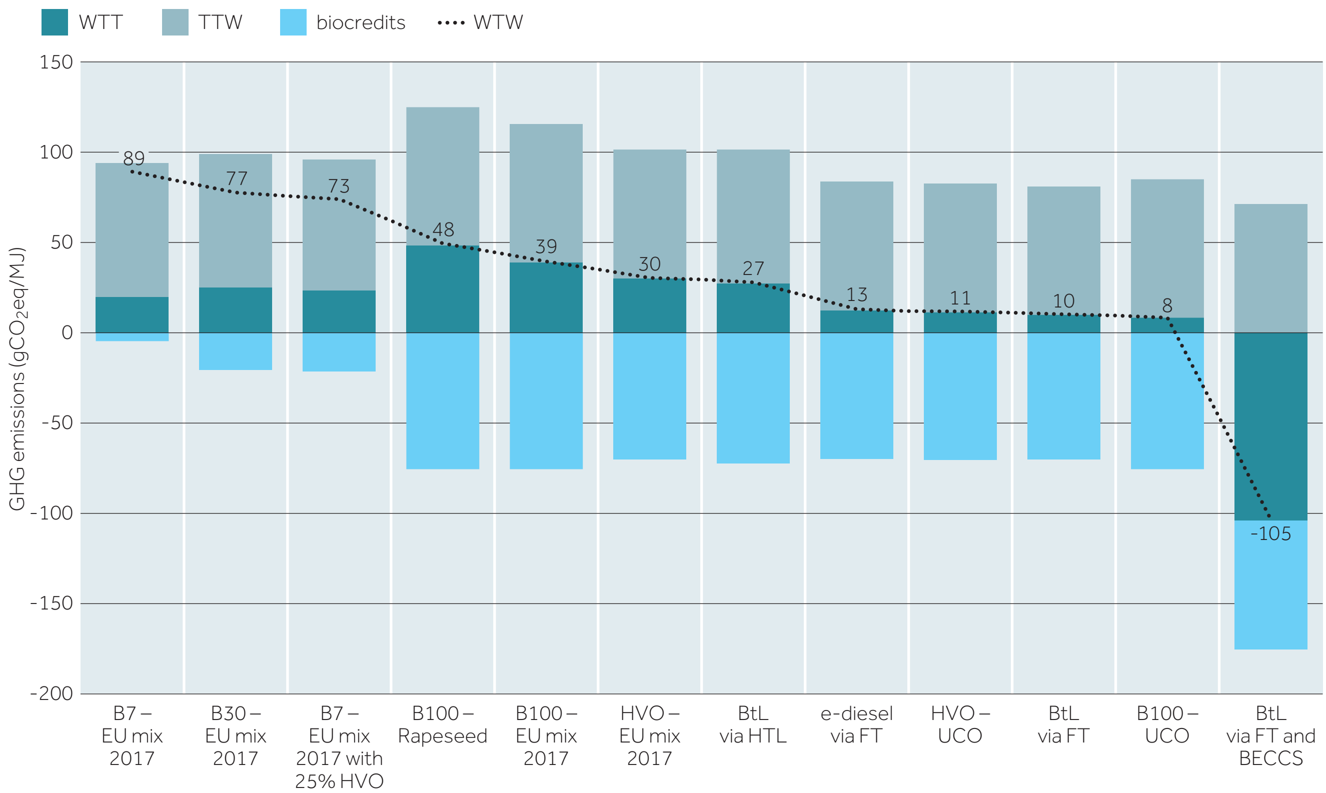
The combustion of fuel generates GHG emissions. However, to assess the life-cycle impact of fuel use, it is also necessary to consider the production and supply phases of the fuel. Therefore, fuel emission factors are generally subdivided in two categories: WTT for the production and supply phases, and TTW for the use phase. The sum of these contributions is the emission factor of the fuel over its entire life cycle, and is usually denoted as WTW.

For some fuels, such as biofuels or e-fuels, CO_2 is captured from the atmosphere to make the fuel. This CO_2 consumption is either absorbed by the plants grown for the biomass used to produce the fuel, or captured directedly from the air (direct air capture, or DAC) or taken from industrial flue gas stacks which would otherwise emit the CO_2 to the atmosphere. This means that some credit (called recycled CO_2) can be applied to the emission factors of these fuels.

Finally, it is sometimes possible to blend different fuels, for example petroleum diesel blended with biodiesel in B7 or B30. Emission factors of such blends can be calculated from the known composition.

Figure 7: Fuel emissions considered in the LCA GHG estimation (gCO_2eg/MJ)

(Shown here for diesel-like fuels. Hydrogen and gaseous fuels are also available in the tool.)



Well-to-tank GHG emitted

'Well to tank' refers to the production, transport, manufacture and distribution of the fuels. This is the scope considered for petroleum-based fuels and biofuels. For further details, please consult the JEC Tank-To-Wheels report v5.[9] For e-fuels (green H_2, e-diesel, e-methane), the emission scope is extended with upstream emissions from infrastructure needed to produce them (mainly solar panels and wind turbines). See the Concawe e-fuels study[10] for further details. It was observed that infrastructure requirements (per unit of energy produced) are significantly higher for e-fuels than for petroleum fuels and biofuels, and could not reasonably be neglected for e-fuels.

Tank-to-wheels GHG emitted

'Tank to wheels' refers to the combustion process within the engine that converts fuel energy into CO_2 emissions. N_2O and CH_4 were added to the total TTW part of the overall LCA GHG results. Based on a literature review, the contribution of N_2O and CH_4 in terms of CO_2-equivalent emissions represents around 6.6% of CO_2 exhaust emissions for diesel fuelled-trucks (essentially from N_2O emissions which are approximately 50 CO_2eq/km[11]) and 2.5% of CO_2 exhaust emissions for CNG fuelled-trucks (essentially from CH_4 emissions which are approximately 500 mg/kWh).[12] For ICE-H_2 fuelled-trucks, it is assumed that the after-treatment system and the N_2O emissions are the same as for diesel-fuelled trucks.

Recycled CO_2

This is the amount of credit related to the CO_2 offset that occurs if CO_2 is consumed during the production of the fuel, resulting in a closed-loop carbon cycle. For example, for biofuels this would be the CO_2 captured by biomass from the air when it grows, or for e-fuels the CO_2 captured from the air via DAC.

Carbon intensity of the electricity mix

BEVs use electricity as the primary energy carrier. Therefore, the GHG emissions per kWh of electricity consumed must be computed to obtain a realistic life-cycle impact of the energy consumption of BEVs. In this study, the carbon intensity of the electricity is set by the user of the web application. Guidelines are given in the tool overview, as shown in Figure 6.

Emission factors due to vehicle production

The GHG emission factors of the various vehicle components: chassis, tyres, battery, fuel cell, electric motor, ICE and tanks are considered and are built into the tool. These emission factors were obtained using the LCA methodology performed in accordance with ISO 14040 and 14044 standards using the commercial LCA software SimaPro®. The database used is Ecoinvent v.3.8. LCA results were obtained using the EF3.0 characterisation method (environmental footprint).

Chassis

For the emission factors related to the production of ICEV (and HEV) chassis, the Ecoinvent data 'Bus production {RER}| producing' has been used and adapted (depending on the types of vehicles). For the interurban bus, the modelling of the chassis is derived from that of the bus (mass difference). Some differences in interior composition were also accounted for, namely the additional steel seats. For the emission factors of the EV and FCEV chassis, a material percentage adjusted in relation to the chassis of ICEVs was considered.

The end-of-life scenario for chassis is modelled from the PE International and Gingko21 report produced for ADEME. Most of the rates provided concerning the proportion of recycling, incineration and landfilling by type of material have been reused. The 2000/53/EC directive of the European Parliament and of the Council relating to end-of-life vehicles (ELVs) has also been followed. An ELV collection rate of 69% was used. The distances from the holder to the demolisher, and then from the demolisher to the crusher, have also been taken into account.

Table 4: Emission factors used for chassis CO_2eq emissions

Application	Chassis emission factor (tCO_2eq/kg)
Class 5	40.1
Class 2	24.4
City bus	33.9
Interurban bus	37.8
Refuse truck	24.4

Tyres

The weight and composition of coach and truck tyres are based on the JRC[3] report, *Environmental Improvement of Passengers Cars (IMPRO-car)*. Tyre life is assumed to be 40,000 km.

The end-of-life scenario for tyres is based in part on a study carried out for ADEME entitled 'Transport and logistics of waste' published in October 2014.

Table 5: Emission factors used for tyre CO_2eq emissions

Application	Chassis emission factor (tCO_2eq/kg)
Class 5	34.0
Class 2	8.4
City bus	10.9
Interurban bus	10.9
Refuse truck	8.4

Powertrain

For the emission factors of thermal and electric motors, the Ecoinvent 'Internal combustion engine, passenger car {GLO}' and 'Electric motor, electric passenger car {GLO}' data were used.

For the fuel cell, a power of 225 W/cell was considered (IFPEN assumption). The fuel cell modelling is based on the studies of Evangelisti[4] and Miotti[5] for bipolar plates. Regarding fuel cell auxiliary equipment, the study by Stropnik[6] was used. For platinum, an emission factor of 69,500 kg CO_2eq/kg is considered ('Ecoinvent: Platinum {GLO}| market for'). This leads to an estimated emission factor of 40.9 kgCO_2eq/kW_fuel_cell for the fuel cell as a whole, that is set a default value for the corresponding slider.

Table 6: Emission factors used for powertrain components CO_2eq emissions

Powertrain	Emission factor (kgCO_2eq/kg)
Internal combustion engine	26.6
Electric motor	5.0
Fuel cell	40.9

[3] The European Commission's Joint Research Centre: https://commission.europa.eu/about/departments-and-executive-agencies/joint-research-centre_en

Tank

For diesel tank modelling, 50% steel, low alloy and 50% aluminum, cast alloy was considered.

For hydrogen Type IV tanks, 45% epoxy resin, 55% carbon fibre was considered. This tank can contain a maximum of 5.1 kgH_2 at 700 bar.

Table 7: Emission factors used for tank CO_2eq emissions

Tank type	Tank capacity (kg)	Tank mass, empty (kg)	Emission factor ($kgCO_2eq/kg\_tank$)
Type I — 200 bar	16	93	5.8
Type IV — 500 bar	8	210	22.8
LNG tank steel	115	320	10.0
Diesel steel tank	418	500	3.2

Battery

Battery production GHG intensity is mostly related to the material extraction and production process. In the tool, the user can set the GHG intensity for the production of 1 kWh of battery capacity. In the updated version of the comparator, the battery result is displayed separately and not added to the total vehicle manufacturing result.

Aichberger *et al.*,[13] who analysed 50 publications from the years 2005–2020 about the LCA of lithium-ion batteries, assessed the environmental effects of production, use and end of life for application in electric vehicles. For battery production emissions, the median value was 120 $kgCO_2eq/kWh$.

Given the dynamic nature of the sector, it is relevant to consider technological, geographical and environmental developments in battery production, which may reduce the emission factor over time of this key component. Xu *et al.*[3] built a prospective life cycle assessment model for lithium-ion battery cell production for various chemistries, production regions and time frames. This work provides emission factor values for current and future battery production in different contexts. A value of 86 $kgCO_2/kWh$ was ultimately set as the default value since current solutions are largely produced in China.

Table 8: Emission factors for battery production for different chemistries and regions ($kgCO_2eq$)

	Lithium iron phosphate (LFP)-graphite			Nickel-manganese-cobalt (NMC)-graphite / nickel-cobalt-aluminium (NCA)-graphite		
	China	United States	European Union	China	United States	European Union
2020	69	49.5	39.5	86	65	52
2030	56	40	34	70	52	45
2040	45	32	28	58	42	37
2050	34	24	19.5	44	32	27

(86 $kgCO_2/kWh$ is set as the default value in the interactive tool for current solutions.)

The energy density chosen for the batteries in the LCA tool to calculate the weight of the battery pack system is 200 Wh/kg.[13] It is assumed that the operational battery depth of discharge is 85%. This value is used to calculate the vehicle range shown in the toolbox when hovering the mouse over the bar graph.

The following aspects are not considered in this study:

- Battery production capacity.
- Raw materials availability.
- Externalities generated by mining activities.

Fuel cell and hydrogen tank

The fuel cell is composed of modular packs of 75 kW. From 1 to 3 packs are considered depending on the vehicle category. Three levels of efficiency are considered for the fuel cell: a nominal peak efficiency of 55% (state of the art for the HDV vehicle), a maximum 65% peak efficiency (current state of the art for the LDV) as well as a future 70% peak efficiency (for maximum trend). For fuel cells a 600 W/kg system is considered for the mass estimation, derived from the US Department of Energy (DOE) *Hydrogen and Fuel Cells Program Record* (2020). Hydrogen tank mass impact on vehicle curb mass is also considered with a 60 gH_2/kg density, representative of a Type IV tank (350 or 750 bar).

Conclusion

The interactive digital tool developed from this study is powerful and can provide valuable insights if used correctly as per the guidelines and the deeper understanding outlined in this review.

The use of this LCA tool for HDVs shows that the optimal options for decarbonisation are highly dependent on the use case considered. The best technology and energy options may differ according to the use case, highlighting the importance of technology neutrality when selecting the best option for decarbonisation.

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Technologies and fuels for decarbonising global aviation — the opportunities and challenges

This article provides a summary of a recent study undertaken on behalf of Concawe to investigate the challenges faced by the aviation industry when trying to reduce CO_2 emissions. The study explored the options available to reduce emissions, including improvements in aircraft technology and the use of alternative aviation fuels, and a modelling approach was used to determine which options would be required to achieve future emissions targets under a range of scenarios.

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Introduction

In 2019, the global aviation industry consumed around 363 billion litres of jet fuel and was responsible for 914 $MtCO_2$ in direct emissions.[1,2] Passenger aviation, including aircraft carrying belly freight, accounted for 92% of these emissions, with the remaining 8% being attributable to freighter flights.[3] If future fuel use and emissions growth is only half the historical (1980–2019) rate of 2.8% per year, global aviation fuel demand and CO_2 emissions would increase by around 50% by 2050.

In 2009, the International Air Transport Association (IATA) — the aviation industry's trade body — set a sector target of reducing CO_2 emissions by 50% by 2050, compared to 2005 levels. Such drastic abatement requires a radical transformation of the entire aviation sector, affecting each determinant of CO_2 emissions. This article and the associated report illustrate how such strong reductions could be achieved, along with the implications for stakeholders of the aviation value chain, particularly the fuels industry.

Strong demand growth

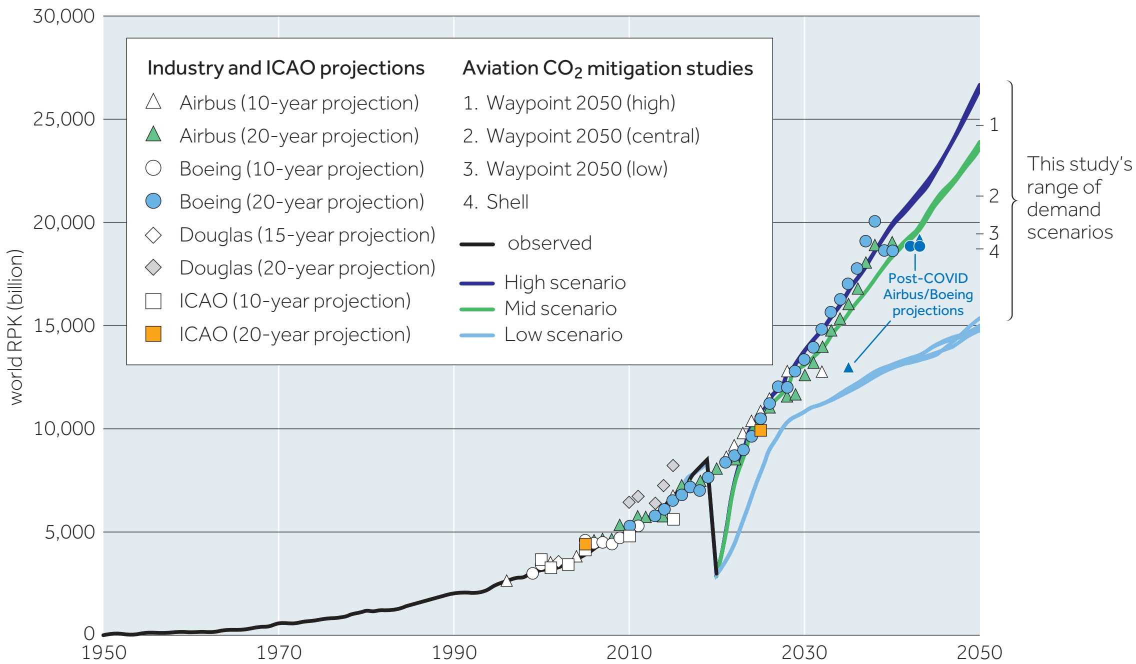
Historical aviation growth has mainly been the result of income growth, followed by declining airfares and the growing population.

Figure 1 on page 49 depicts the study's range of demand scenarios, which span a larger range compared to demand scenarios considered in the Waypoint 2050 study[4] and a study undertaken by Shell. Each utilises different global scenarios for income, population and energy prices, leading to a 'High' scenario (dark blue curve) which implies that demand growth will return to pre-COVID-19 growth rates, a 'Mid' scenario (green curve) where growth rates are close to post-COVID-19 industry projections, and a 'Low' scenario (light blue line) where growth rates diverge from historical trends.

These differences are driven mainly by differences in income growth between the scenarios, which are derived from the IPCC's[1] Shared Socioeconomic Pathways (SSP) scenarios;[5] for the Low scenario, demand growth is additionally assumed to decouple from income growth due to ongoing changes in attitudes to aviation.

Figure 1: World revenue passenger-kilometres travelled (RPK), observed (black continuous line), and projections by industry and ICAO[2] (symbols) and this study (coloured continuous lines).

Adapted from Schäfer and Waitz, 2014.[6]



Long time constants

Developing a new aircraft is a long (10–20 years) and capital-intensive (USD 20–30 billion) process. In light of the roughly 15 years development time for a new aircraft model, the four reference aircraft considered in this study, with entry-into-service dates between 2011 and 2017, are likely to represent two successive generations, one in 2030–35 and another one in 2045–50.

The average operating lifetime of today's commercial aircraft — the time span by which 50% of an aircraft cohort is retired — is about 30 years.[7,8] This implies that around half of those aircraft introduced today will still be operating in 2050. Combined, these long time constants mean that the time between identifying promising concept technology bundles and their significant market impact is around 40–50 years.

1 Intergovernmental Panel on Climate Change

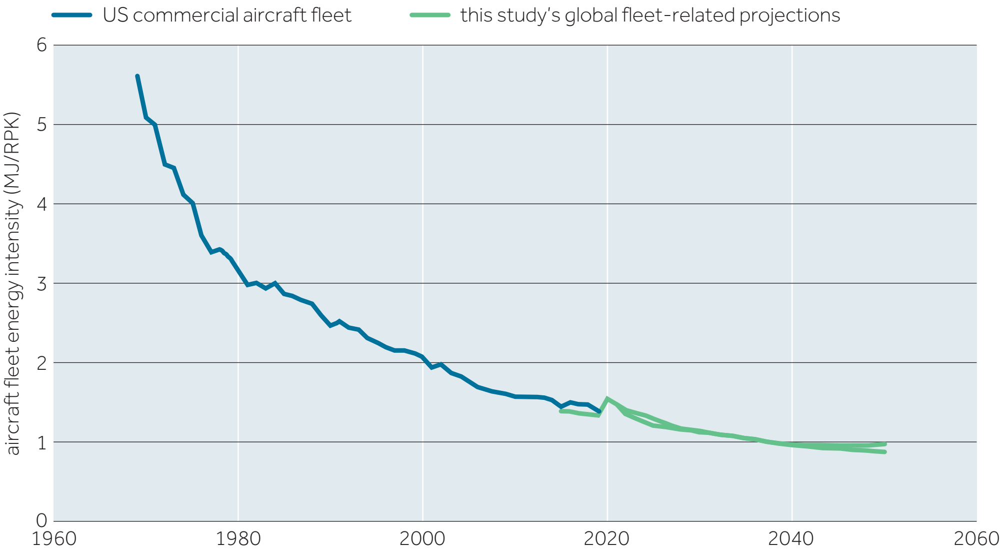
2 International Civil Aviation Organization

Fuel efficiency improvements

Overall, the energy intensity of the US aircraft fleet has declined from 5.6 MJ per RPK in 1969 to 1.4 MJ per RPK in 2019, a 75% reduction which translates into an average of 2.7% per year. As the life-cycle CO_2 intensity of jet fuel has historically remained largely unchanged, the depicted decline in aircraft fleet energy intensity corresponds with a decline in CO_2 intensity.

Figure 2: Historical trend in aircraft fleet energy intensity, US (1969–2019) and global projections (2020–2050)

Data source: Lee *et al.*, 2001 and US Form 41[9]



Technologies and fuels

Aircraft technologies

Three key factors affect aircraft range and energy use, and are captured in the Breguet range equation: the aircraft lift-to-drag ratio or aerodynamic efficiency; engine-specific fuel consumption or the amount of fuel burnt per unit of thrust; and the empty weight of the aircraft. The higher the lift-to-drag ratio, the lower the engine-specific fuel consumption, and the lower the empty weight of the aircraft, the lower the aircraft energy intensity.

The menu of options for reducing aircraft fuel burn consists of:

- airframe-related technologies, which directly address the lift-to-drag ratio, aircraft drag or aircraft empty weight;
- engine-related technologies, which aim to increase engine efficiency;
- fuel-related technologies that reduce aircraft CO_2 emissions directly;
- air traffic management-related technologies that improve flight procedures; and
- operational technologies and techniques, i.e. measures that the airlines themselves can apply when operating their fleet in the air and on the ground.

As shown in Table 1, this study uses four reference aircraft to assess technology characteristics, jointly covering all major market segments. Aircraft with year-2000 technology form the basis of this classification. The 2015 aircraft types were modelled based on available data about specific aircraft model performance and costs in each size class for this generation (e.g. Airbus A320neo; see the full study report for tables of assumptions for these aircraft).

Table 1: Reference aircraft and projected fuel burn reductions compared with year-2000 performance

Market segment	Representative aircraft for year 2000 (2015)	Seat count	Average stage length (nm)[a]	% fuel burn change compared with year-2000 technology, EIS[b]	
				2030–35	2045–50
Regional	E190-E2	98	500	-28.6	-35.5
Short haul	A320-200 (A320neo)	150	1,000	-30.4	-38.3
Medium hall	A330-300 (B787-9)	295	3,500	-23.6	-57.0
Long hall	B777-300ER (A350-1000)	368	4,500	-25.7	-52.5

[a] nm = nautical miles; 1 nm = 1,852 km

[b] EIS = entry into service

The fuel burn reductions for the next (2030–2035) aircraft generation are similar across all aircraft types, as they build upon similar technologies. In contrast, the generation after next (2045–2050) rely on different technologies particularly between the two smaller and the two larger aircraft size classes, which leads to marked differences in fuel burn reduction.

Alternative aviation fuels

These alternatives can be categorised as drop-in liquid fuels and non-drop-in fuels. Drop-in fuels have similar properties to fossil jet fuel, meaning that no significant modifications to existing infrastructure, aircraft and engines are required. On the other hand, uptake of non-drop-in fuels will require significant modifications and investment.

Drop-in fuels

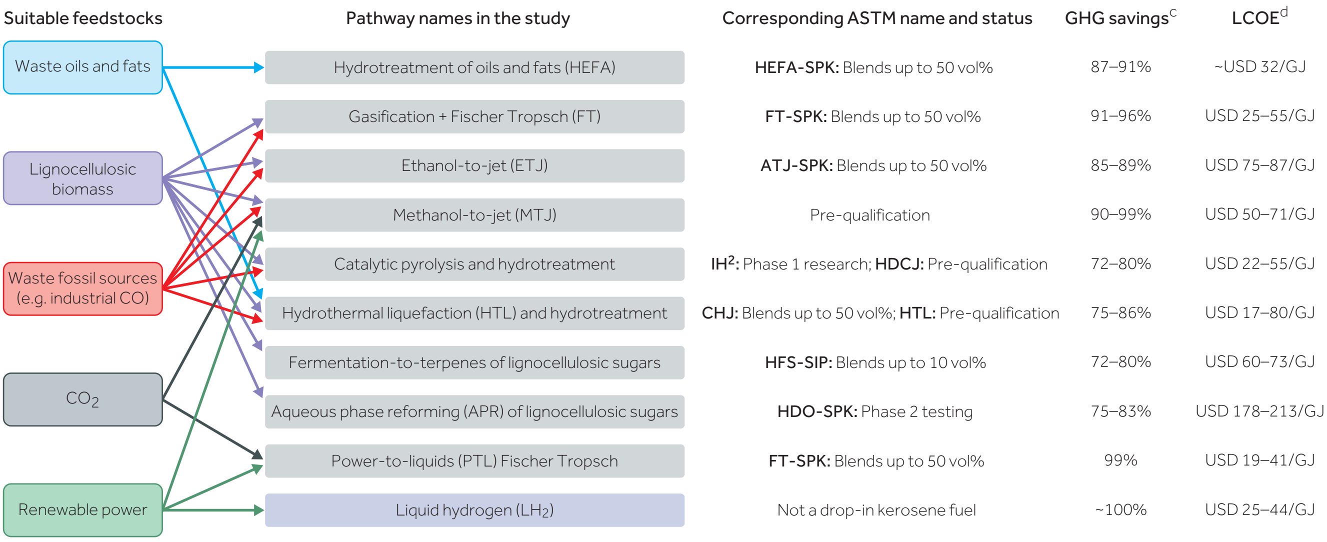
Drop-in sustainable aviation fuels (SAFs) are produced from renewable feedstocks, including biomass and renewable hydrogen, as well as recycled waste fossil carbon (if it leads to sufficient CO_2 emissions reduction), and have a similar composition and performance to that of fossil jet fuel.

Currently, most SAF technology pathways are at an early stage of development, with HEFA[3] the only commercialised route. Nonetheless, a number of routes are already certified under ASTM International's D7566 standard (D1655 for co-processed fuels), which are highlighted in Figure 3 on page 52.

[3] Hydroprocessed esters and fatty acids

Figure 3: Schematic of the alternative aviation fuels considered in this analysis

(GHG savings are given relative to the CORSIA[a] benchmark. LCOE[b] represents production costs, in 2020 USD)



[a] Carbon Offsetting and Reduction Scheme for International Aviation [b] Levelised cost of electricity

[c] Compared to the fossil jet benchmark of 89 g/CO_2eq/MJ [d] LCOE cost ranges between 2025–2050; some pathway variation based on feedstock used

Figure 3 provides an estimate of the range of levelised costs of production for the different fuel routes between 2025 and 2050.[10,11,12,13] Due to the early stage of development of these routes, the production costs of alternative aviation fuels are much higher than fossil jet prices. Over time, the production costs will decrease, owing to scale-up efficiencies and process improvements. Furthermore, routes which rely on renewable electricity — PTL-FT,[4] liquid hydrogen and e-methanol-to-jet — might see a dramatic reduction in feedstock cost as the availability of low-cost renewable power increases. Nonetheless, some routes will remain expensive in 2050, and will likely require policies that support the uptake of alternative aviation fuels in order to effectively penetrate into the fuel mix.

Non-drop-in fuels

There is scope for the use of liquid hydrogen as an aviation fuel (in contrast to liquefied natural gas (LNG) and electrification). Although significant infrastructure and aircraft modifications would be required, many industries are investigating hydrogen supply chains and technologies, which could accelerate development. Hydrogen production costs from renewable energy are projected to decrease from ~28–63 USD/GJ in 2019 to ~10–28 USD/GJ in 2050.[14]

[4] Power-to-liquids via Fischer Tropsch synthesis

Hydrogen can be produced with minimal emissions through the electrolysis of water using a renewable power source. Importantly, hydrogen combustion does not directly generate CO or CO_2 emissions. In addition, although the combustion of hydrogen produces NO_x, it is unclear to what extent it does so relative to burning kerosene.

Technology packages

Table 2 summarises the selected technology and fuel combinations explored in this study. Building upon four reference aircraft and using the most promising technologies from Table 1, two distinct aircraft families are considered: a drop-in fuel family that can use either fossil kerosene or SAF, and a liquid hydrogen (LH_2) family. The characteristics of both aircraft families are projected for two future generations, being 15 years apart.

Whereas the entry-into-service date of the next evolutionary aircraft generation is expected to be 2030, liquid hydrogen aircraft are unlikely to be available before 2035. It is assumed that LH_2 would be introduced first on less complex, smaller aircraft and then progress to larger aircraft later.

Airlines are interested in new aircraft designs that offer significant reductions in operating costs compared to those vehicles already in their fleet. Of particular interest are the direct operating costs (DOCs), which consist of crew, fuel, maintenance, ownership or depreciation, and other expenditures.

Table 2: Chosen aircraft technologies for the drop-in fuel and LH_2 aircraft families

Technology	2030	2035	2040	2045	2050	2055
	Generation N+1			Generation N+2		
Drop-in fuel family	Regional, short haul	Medium and long haul		Regional, short haul	Medium and long haul	
Hydrogen family		Regional, short haul	Medium and long haul		Regional, short haul	Medium and long haul
Wing	15 AR[a]			20 AR[a]	BWB[b] (drop-in) 20 AR[a] (LH_2)	BWB[b] (LH_2)
Engines	UHBR[c]			UHBR[c] and flying slower		
Composite materials	Apply to 50% of components by weight			Apply to 100% of components by weight		

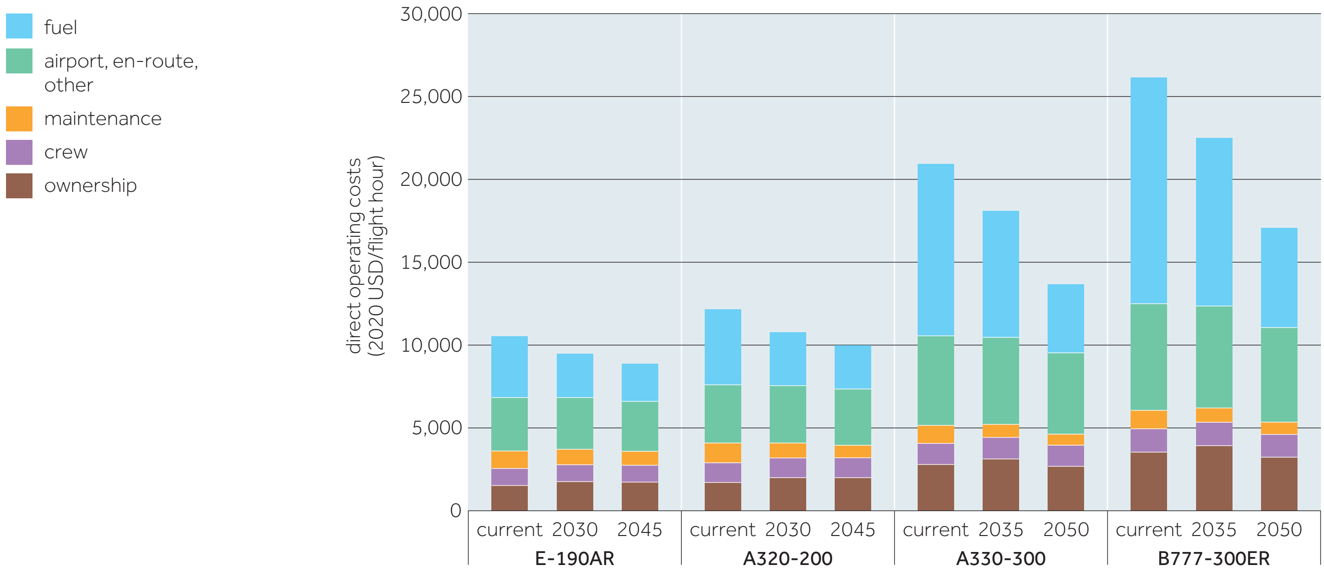
[a] Wing aspect ratio [b] Blended wing body aircraft [c] Ultra-high bypass ratio engines

Figure 4 depicts the resulting DOCs in USD (2020) per flight hour by DOC category for the four aircraft size classes using (synthetic) liquid fuels for today's conditions, for Generation N+1 (2030–2035) and for Generation N+2 (2045–2050). Fuel costs are based on a fuel price of USD 5 per gallon. Although capital costs of the Generation N+1 aircraft are projected to increase above those of the current generation of aircraft, the savings in all other expenditure items are anticipated to increase more strongly (particularly for fuel costs), thus leading to a decline in total DOC.

Because of the projected strong reduction in aircraft energy intensity, the share of fuel costs to total DOC declines from one generation to the next. For example, for the medium-haul A330 type of aircraft, fuel costs account for around 50% in the reference case, around 42% in the Generation N+1 aircraft, and only around 30% in Generation N+2. See the full study report for the estimated DOCs of hydrogen aircraft.

Figure 4: Estimated DOCs (2020 USD) per flight hour for the four aircraft size classes using synthetic liquid fuels for today's generation, Generation N+1 (2030–2035) and Generation N+2 (2045–2050)

(The underlying jet fuel price is USD 5 per gallon)



Modelling results

Methodology and scenarios

The Aviation Integrated Model (AIM)[5] was used to project the potential global impact of the uptake of the various technologies and fuels. Six different scenarios for combinations of demand, fuel supply, policy and aircraft technology were explored using AIM.

These scenarios are intended to be aspirational, highlighting the effort that will be required to meet different aviation emissions targets: as such, they are not projections. Each scenario consists of a set of technology roll-outs defined by the technology analysis; a demand case, including policy ambitions, various demand drivers and trends; and a SAF supply case aimed at meeting the projected demand.

- Technology roll-out
  - **'Drop-in'** technology: New aircraft generations enter service on the expected industry schedule and drop-in SAF is part of the fuel supply, with uptake stimulated by blending mandates.
  - **'H_2'** technology: New aircraft launches are delayed by five years with the first hydrogen-fuelled aircraft entering service in 2035. Both drop-in SAF and liquid hydrogen are part of the fuel supply, with uptake stimulated by blending mandates (for SAF) and aircraft design/purchase standards (for hydrogen aircraft).
- Demand cases
  - **High demand:** assumes high income growth, low oil prices, and limited long-term impact of the COVID-19 pandemic.
  - **Mid demand:** assumes that population and income follow central-case trends, leading to aviation demand growth that is close to the post-COVID-19 industry projections.
  - **Low demand:** assumes that economic growth is on the low end of the projections and, additionally, that aviation passenger demand growth is suppressed by changes in attitudes to aviation arising from societal changes in the wake of the COVID-19 pandemic and/or from increased environmental concerns about flying.
- Supply cases
  - **Low supply:** results in a SAF supply of 10.8 EJ (~250 Mt) in 2050, increasing from ~1 EJ (~25 Mt) in 2030. Both biofuels and PTL routes make up this supply but biofuels are relied upon up to 2030, accounting for 92% of the total SAF supply. Post-2030, as PTL pathways reach commercialisation, biofuels account for 67% of the SAF supply.
  - **Mid supply:** results in a SAF supply of 17.5 EJ (~400 Mt) in 2050, with a supply of 1.2 EJ (~27 Mt) in 2030. Roughly 90% of the 2030 supply is from biofuels, decreasing to 56% in 2050.
  - **High supply:** results in a SAF supply of 30.6 EJ (~700 Mt) in 2050, from a supply of 1.2 EJ (~27 Mt) in 2030. The ramp-up phase to 2030 remains the same as for the mid supply case, with reduced project development timelines, where biofuels account for 90% of SAF in the first decade. However, market expansion after commercialisation occurs at a much faster rate, mostly due to the rapid scale-up of PTL-FT, which accounts for roughly 63% of SAF in 2050.

[5] The Aviation Integrated Model (AIM) is a global aviation systems model which simulates interactions between passengers, airlines, airports and other system actors into the future, with the goal of providing insight into how policy levers and other projected system changes will affect aviation's externalities and economic impacts.

Figure 5: Sustainable aviation fuel (SAF) supply comparison

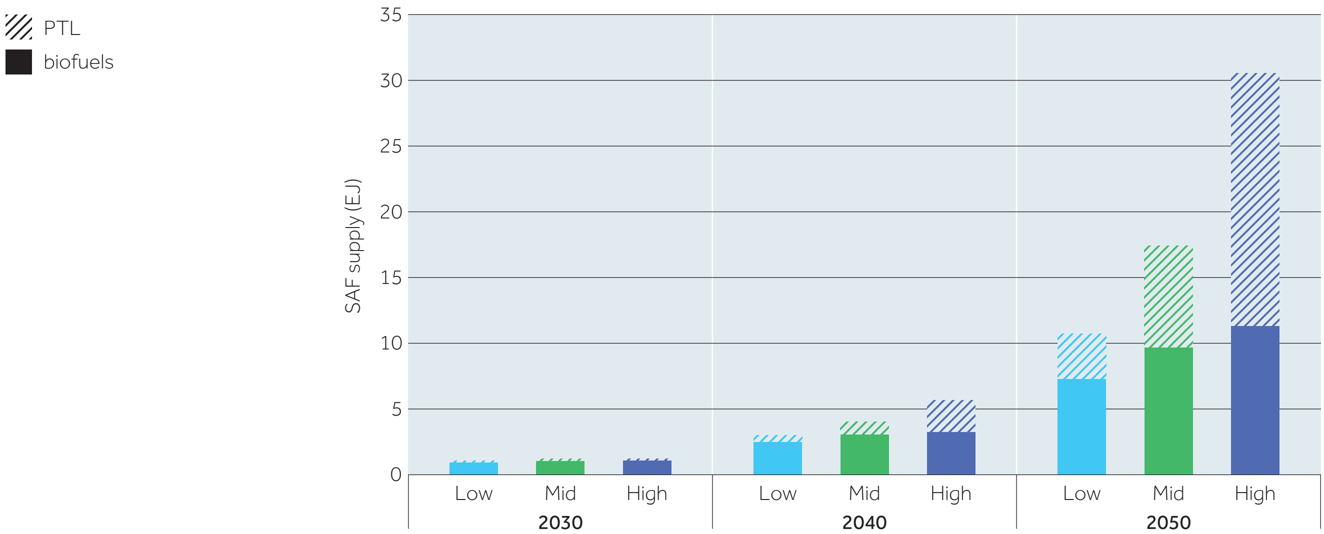


Table 3: Summary of the modelled scenarios

Scenario	Technology roll-out	Technology roll-out	Supply case
Low (drop-in)	New aircraft, drop-in SAF, and operational measures	Long-term economic growth and demand growth is suppressed. High oil prices, ReFuelEU[a] SAF mandate applied globally.	Standard project development timelines during ramp-up phase. 15% CAGR[c] for biofuels, 21% CAGR for PTL fuels during market expansion phase.
Low (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		
Mid (drop-in)	New aircraft, drop-in SAF, and operational measures	Economic growth follows central-case trends, aviation demand trends follow post-COVID-19 industry projections. Low oil prices, following IEA SDS[b] scenario. ReFuelEU[a] SAF mandate applied globally.	Accelerated project development timelines during ramp-up phase. 15% CAGRc for biofuels, 23% CAGR for PTL fuels during market expansion phase.
Mid (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		
High (drop-in)	New aircraft, drop-in SAF, and operational measures	High economic growth: high income growth, aviation demand trends follow pre-COVID-19 industry projections. Low oil prices, following IEA SDS scenario. Ambitious global SAF mandate, rising to 100% in 2050.	Accelerated project development timelines during ramp-up phase. 16% CAGRc for biofuels, 36% market growth CAGR between 2030–2040, 23% CAGR between 2040–2050 during market expansion phase.
High (H_2)	New aircraft, drop-in SAF, hydrogen and operational measures. Hydrogen aircraft mandates introduced as part of the demand case.		

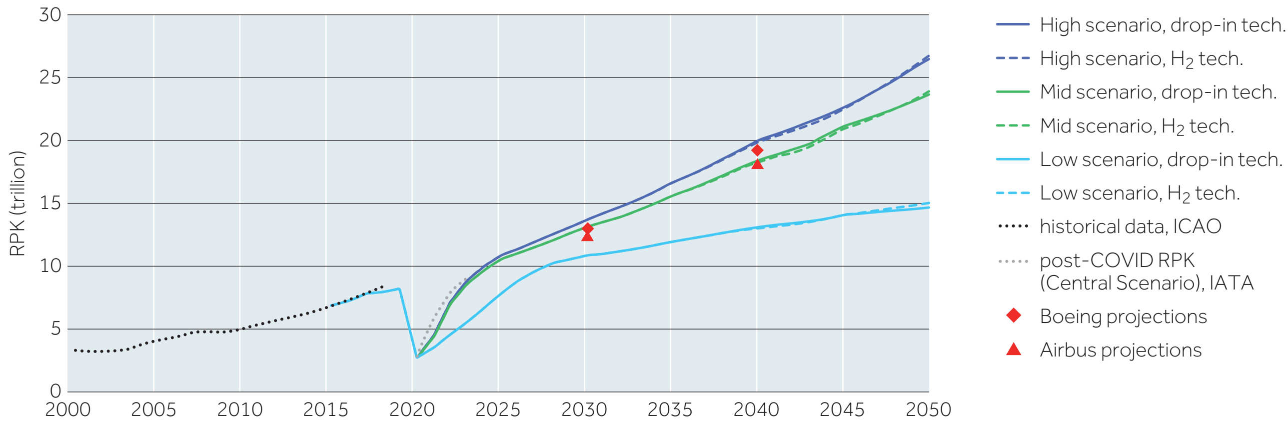
[a] ReFuelEU is a European Commission initiative that aims to boost the supply and demand for sustainable aviation fuels in the EU.

[b] International Energy Agency (IEA) Sustainable Development Scenario (SDS). [c] Compound annual growth rate.

- **Demand and fleet evolution**

  Figure 6 shows the demand for aviation, from 2000 to 2050, under the various scenarios considered in the study, together with projections from Airbus and Boeing.

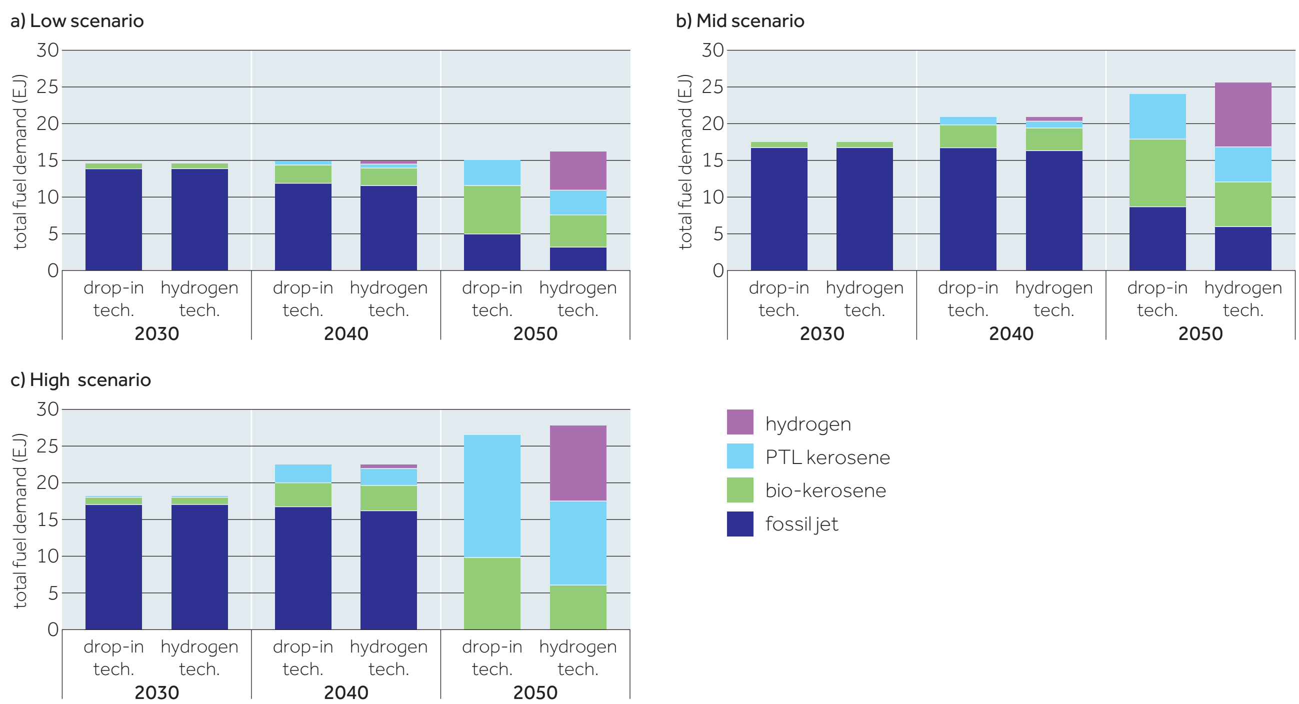
Figure 6: Demand for aviation expressed in revenue passenger-kilometres (RPK)



- **Fuel supply composition**

  Figure 7 presents the overall composition of fuel supply, showing the ramping up of SAF (biofuels and PTL fuels) and liquid hydrogen through to 2050.

Figure 7: Total fuel demand (energy basis) in each scenario



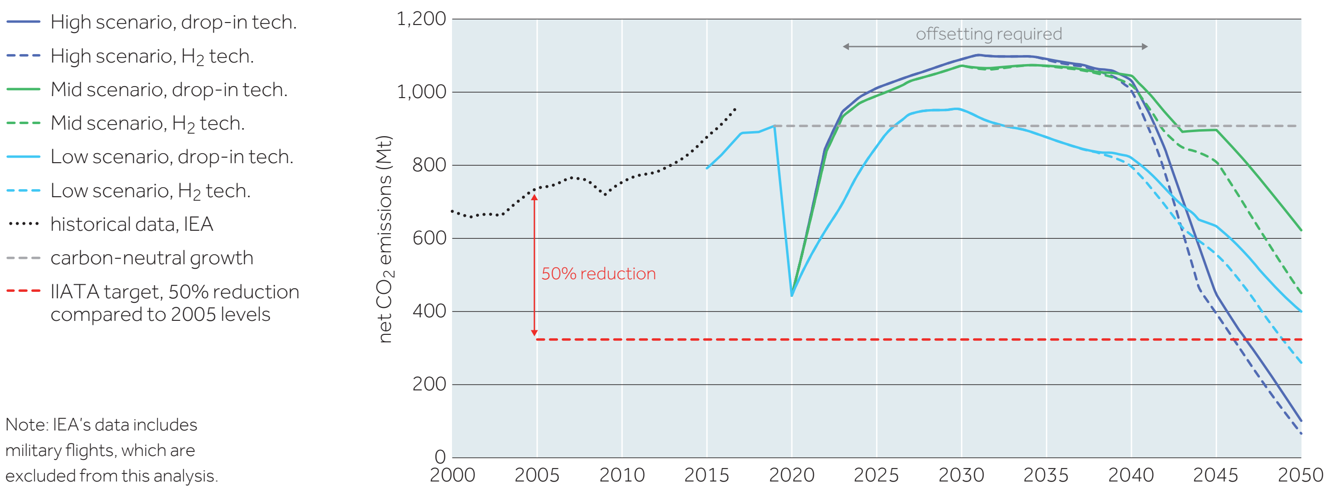
- **CO_2 savings**

  The decarbonisation ambition level for the aviation sector has been evolving towards a net zero target by 2050:

  - Since 2009, IATA has had an ambition to achieve a 50% reduction, compared with 2005 levels, by 2050.
  - In 2016, ICAO adopted CORSIA, with the (current) ambition of stabilising aviation's net CO_2 emissions at 2019 levels, from 2021 (carbon neutral growth).
  - However, in October 2021, IATA approved a revamped goal of achieving net-zero carbon emissions by 2050, in alignment with the Paris Agreement.

Figure 8 indicates the net CO_2 emissions from the aviation sector under a range of scenarios from 2000 to 2050.

Figure 8: Net CO_2 emissions from the aviation sector

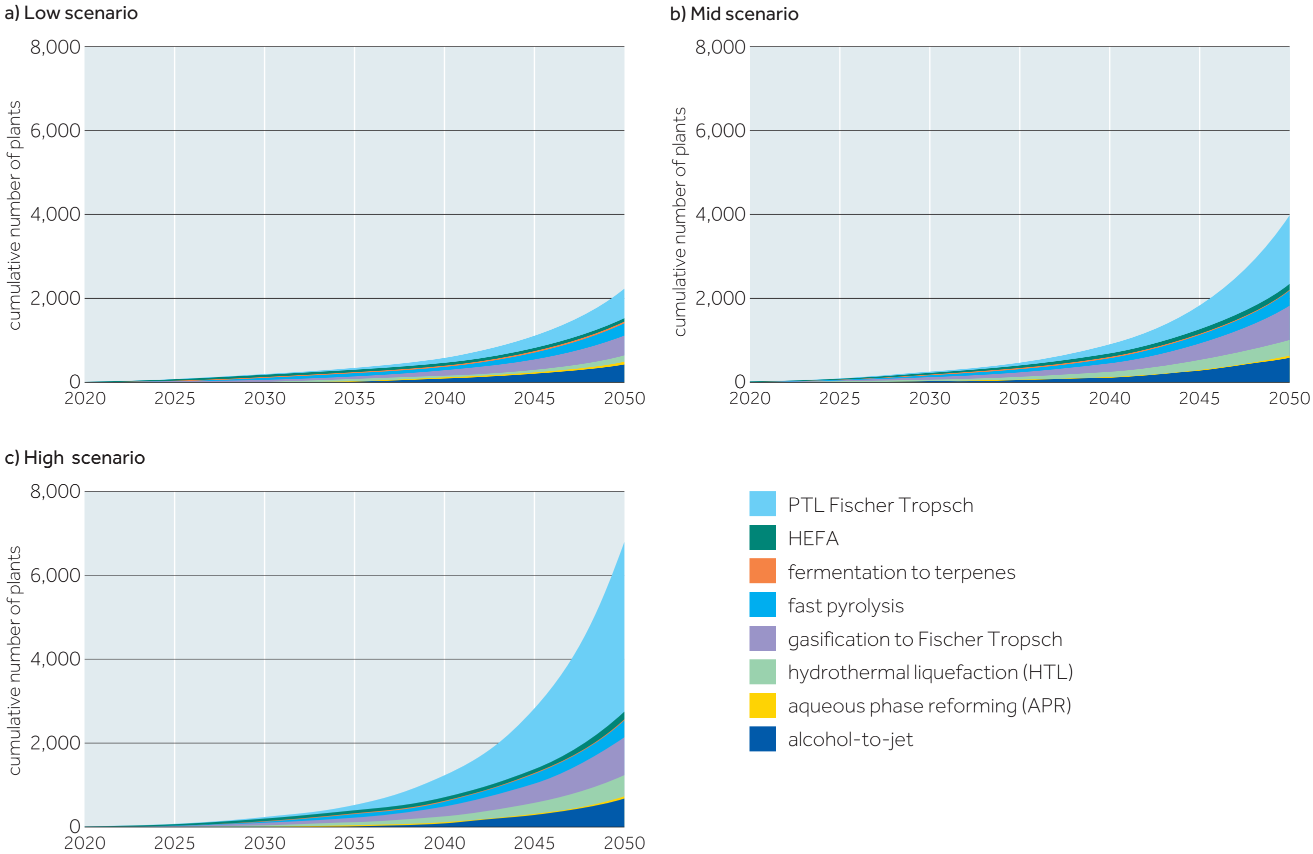


Note: IEA's data includes military flights, which are excluded from this analysis.

The hydrogen scenarios result in slightly reduced emissions compared with their corresponding SAF-only counterparts. However, limited additional mitigation occurs until 2040, due to uptake constraints. From 2040 onwards, significant numbers of hydrogen aircraft enter the fleet: this reduces the amount of drop-in fuels required, and hence drives sectoral emissions down.

The number of operational plants under each of the three main scenarios studied are shown in Figure 9. Based on nameplate plant capacities and 'nth plant' specific capital investment costs taken from literature, a high-level estimate of the required capital investment costs can be calculated.

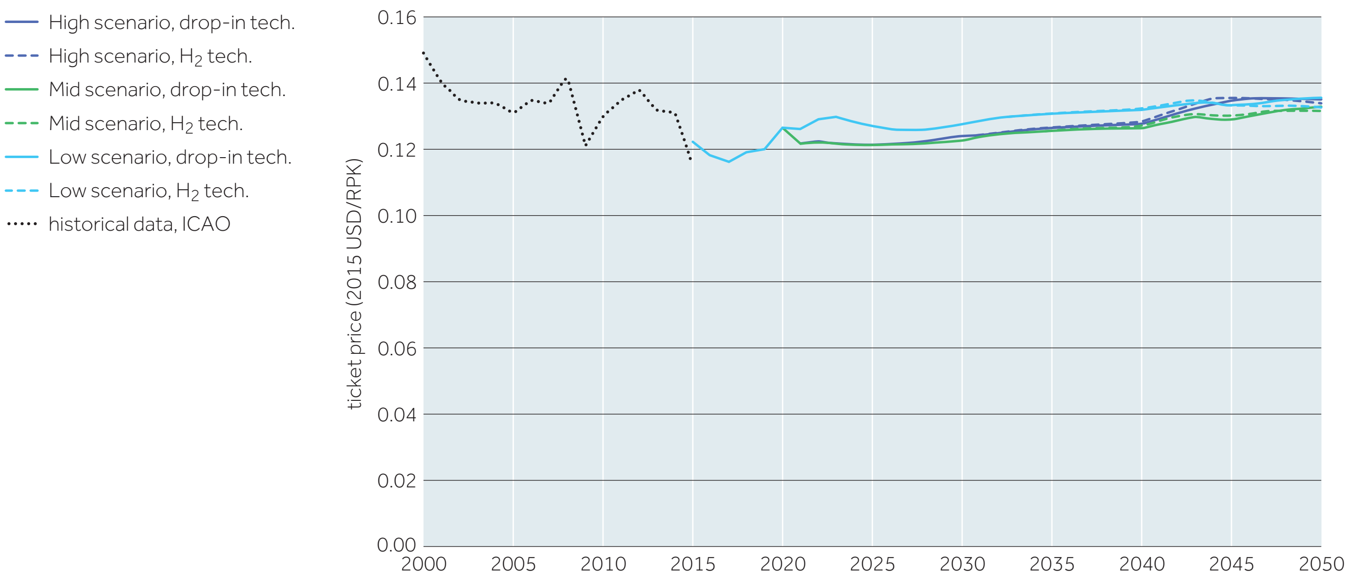
Figure 9: Number of operational plants in each scenario
(typical plant capacity ranges from 30 kta to 250 kta for current developments)



- **Ticket price**

  As shown in Figure 10 on page 60, the model analysis suggests that there will be minimal variation in ticket price across all scenarios between 2020 and 2050. The largest impact on ticket price arises from the variation in oil prices assumed across the 2020–2040 period. Due to all scenarios imposing a significant mandate (minimum 63% SAF by 2050), the uptake of SAF is high in each scenario, with SAF prices assumed to be broadly similar in each (USD 4–6/gallon). The uptake of SAF increases the airline operating cost. Historically, fuel costs have accounted for 10–30% of airline direct operating costs (ICAO, 2020). However, aircraft performance improvements are projected to drive down the proportion of operating costs attributable to fuel, while increases in the effective fuel price from SAF uptake are projected to increase it. The net result, at typical rates of cost passthrough which are close to 100%, is a modest increase in ticket price.

Figure 10: Ticket price from 2000 to 2050 in 2015 USD per RPK



Conclusion

- Technological improvements to aircraft alone will not be sufficient to reduce the aviation sector's CO_2 emissions, due to anticipated increases in demand.
- Bio-based kerosene can contribute substantially to aviation fuel, but supplying the aviation industry with 100% SAF would require vast quantities of biomass feedstock.
- Decarbonising the aviation sector strongly depends on the success of PTL technology and an abundance of low-cost renewable power.
- The speed of hydrogen aircraft fleet introduction will be constrained by technology development, fleet turnover, cost and production line capacity.
- Life-cycle CO_2 emissions still arise from the production of sustainable aviation fuel, therefore market-based measures and/or greenhouse gas removal technology will be needed in the long term to achieve net-zero targets.

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Abbreviations and terms

ADEME	French Agency for Ecological Transition
AFR	Air/Fuel Ratio
AIM	Aviation Integrated Model
APR	Aqueous Phase Reforming
AR	Aspect Ratio
ASTM	American Society for Testing and Materials
ATJ-SPK	Alcohol To Jet Synthetic Paraffinic Kerosene
B7	Diesel fuel blend containing 7% biodiesel
B30	Diesel fuel blend containing 30% biodiesel
B100	Pure biodiesel derived from vegetable oils
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BtL	Biomass to Liquid
BWB	Blended Wing Body (aircraft)
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CEV	Catenary Electric Vehicle
CH_4	Methane
CHJ	Catalytic Hydrothermolysis Jet
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CTG	Cradle To Grave
DAC	Direct Air Capture
DOC	Direct Operating Cost
e-OME_{3-5}	E-Polyoxymethylene Dimethyl Ethers produced from renewable electricity and CO_2
EIS	Entry Into Service
EJ	ExaJoule
ELV	End-of-Life Vehicle
ETJ	Ethanol To Jet
ETS	Emissions Trading System
EU	European Union
EU-27	The 27 member countries of the European Union
EU-27 + 3	The 27 member countries of the European Union plus Norway, Switzerland and the United Kingdom.
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
FEMG	Concawe's Fuels and Emissions Management Group
FT	Fischer Tropsch
FTD	Fischer Tropsch Diesel
FTK	Fischer Tropsch Kerosene
FT-SPK	Fischer Tropsch Synthetic Paraffinic Kerosene
GHG	Greenhouse Gas
GJ	GigaJoule
H_2	Hydrogen
HDCJ	Hydrotreated Depolymerised Cellulosic Jet
HDO-SPK	Hydro-Deoxygenated Synthetic Paraffinic Kerosene
HDV	Heavy-Duty Vehicle
HEFA	Hydroprocessed Esters and Fatty Acids
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HEV	Hybrid Electric Vehicle
HFS-SIP	Hydroprocessed Fermented Sugars to Synthetic Iso-Paraffins
HTL	HydroThermal Liquefaction
HVO	Hydrotreated Vegetable Oils
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEA SDS	International Energy Agency Sustainable Development Scenario
IFPEN	IFP Energies nouvelles
IH^2	Integrated Hydropyrolysis and Hydroconversion
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change

Abbreviations and terms

(continued)

JEC	Collaboration between the European Commission's Joint Research Centre, EUCAR and Concawe
JRC	Joint Research Centre of the European Commission
LCA	Life-Cycle Assessment
LCOE	Levelised Cost Of Electricity
LDV	Light-Duty Vehicle
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LP	Linear Programming
MDV	Medium-Duty Vehicle
MENA	Middle East and North Africa
MeOH	Methanol
MJ	MegaJoule
$MtCO_2$	Million Tonnes (Megatonnes) of Carbon Dioxide
MTG	Methanol To Gasoline
MTJ	Methanol To Jet
MTK	Methanol To Kerosene
N_2O	Nitrous Oxide
NCA	Nickel Cobalt Aluminium
NG	Natural Gas
NGPP	Natural Gas Power Plant
NH_3	Ammonia
nm	Nautical Mile
Nm	Newton Metre
NMC	Nickel Manganese Cobalt
NO_x	Nitrogen Oxides
O&M	Operation and Maintenance
OME_{3-5}	E-polyoxymethylene Dimethyl Ethers
OME_x	Oxymethylene Dimethyl Ethers
OPEX	Operational Expenditure
PHEV	Plug-In Hybrid Electric Vehicle
PTL	Power To Liquids
PTL-FT	Power To Liquids via Fischer Tropsch synthesis
PV	PhotoVoltaic
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
RPK	Revenue Passenger-Kilometres
SAF	Sustainable Aviation Fuel
SECA	Sulphur Emissions Control Area
SMR	Steam Methane Reforming
SSP	Shared Socioeconomic Pathway
STF-25	Concawe Special Task Force (Diesel)
TfL	Transport for London
TTW	Tank To Wheels
UCO	Used Cooking Oil
UHBR	Ultra-High Bypass Ratio (engine)
UIP	Urban Inter Peak (test cycle)
VECTO	Energy consumption calculation tool for HDVs (developed by the European Commission)
WEO	World Energy Outlook
WTT	Well To Tank
WTW	Well To wheels

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