Concawe
Environmental Science for European Refining

Review

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Foreword

The move towards climate neutrality is clearly on its way: last year, the European Commission launched its Green Deal; and Japan, the Republic of Korea and more than 100 other countries worldwide have made public commitments to reach net-zero emissions by 2050. These were followed by China which, in September last year, announced its plan for carbon neutrality by 2060. One of the first acts of President Biden was to recommit the USA to the Paris Agreement, and its administration has shown a desire for the USA to become a leader of the move. This evolution shows the pertinence of the Low Carbon Pathways (LCP) project, which Concawe launched a few years ago to identify the opportunities and challenges for the refining industry to contribute to the evolution towards climate neutrality.

This edition of the Concawe *Review* is composed of articles concerning recent studies from the LCP project. The first article summarises a literature review of commercial, near-term and emerging technologies for carbon capture and storage, which is key in every scenario to achieve climate neutrality. The second article investigates the feasibility and the impact on the European refining industry of three scenarios from *A Clean Planet for all*, the long-term strategy published by the European Commission. The third article gives the main findings of the *JEC Well-To-Wheels report v5* — the latest update of the in-depth study performed with the Joint Research Centre (JRC) and EUCAR — which provides details of the greenhouse gas emissions associated with numerous combinations of fuels and powertrains. Finally, the initial phase of a research project commissioned by Concawe and conducted by Ricardo Energy & Environment is summarised in the fourth article. The study describes the technological and operational measures identified for decarbonising the maritime sector, and investigates the potential for alternative fuels and energy carriers.

Jean-Marc Sohier
Concawe Director

Contents

In the EU Commission's document entitled *A Clean Planet for all*, published by the Directorate-General for Climate Action (DG CLIMA) in 2019 as part of its long-term strategic vision, the Commission explores different scenarios leading to a low-carbon EU economy by 2050. In all these scenarios, carbon capture and storage (CCS) has been identified as a key technology for achieving this ambitious target, playing a crucial role in reducing emission levels to limit global warming to 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase even further to 1.5°C.

A new study, conducted by FutureBridge at the request of Concawe, provides an overview of state-of-the-art carbon capture technologies in the industry, with a focus on commercial/near-term technologies (already in the market or likely to be commercialised in the 2025–2030 time frame) as well as new emerging technologies which are being developed worldwide.

This technology scouting exercise:

- Includes information from patents, scientific literature, published techno-commercial reports, white papers, annual reports and sustainability reports to assess the available carbon capture technologies worldwide. In addition, FutureBridge has analysed the published front-end engineering and design reports, integrated assessment models and a techno-economic analysis report for pilot and demonstration plants to assess the near-term commercial carbon capture technologies.
- Considers various techno-economic factors such as carbon capture efficiency/rates, purity, cost of CO_2 capture per tonne and levelised cost of electricity, as well as main risks and barriers assessing the potential of both near-term and emerging carbon capture technologies.

This article serves as a brief summary to provide the reader with an appetite for gathering more details by reading the full report.

Enquiries: alba.soler@concawe.eu

A Clean Planet for all, the long-term strategy published by the European Commission (DG CLIMA) in 2018, analyses different long-term scenarios that could lead to significant reductions in greenhouse gas emissions on the way towards a carbon-neutral and circular European economy by 2050.

Focusing on three of the scenarios defined in the European Commission's publication, Concawe has issued a report that examines the implications for the EU refining sector, assesses the CO_2 emission reductions that could be achieved through the whole value chain, and provides an estimate of the investments required both to develop new plants and adapt existing refinery infrastructure, while also exploring key barriers and enablers associated with realising these scenarios.

The Concawe report highlights the risks associated with these scenarios, which will add significant burdens to the EU refining system in 2050. As currently defined, there would be a significant risk of reaching a point where meeting the defined demand and fuel composition, as described in *A Clean Planet for all* could not be economically feasible for the refining system in Europe, and could lead to refinery closures, with supply being met mainly by imports of fossil jet fuel into Europe from other regions of the world, with no benefit for climate change globally.

This article provides a brief summary of the Concawe report, and guides the reader through the same path that Concawe walked while understanding the future role for the refining industry based on the data in *A Clean Planet for all*. It highlights the main takeaways of the report, and aims to provide the reader with an appetite for gathering more details by reading the full text of the published report.

Enquiries: alba.soler@concawe.eu

The JEC consortium — a collaboration between the European Commission's Joint Research Centre (JRC), EUCAR (European Council for Automotive R&D) and Concawe — has conducted a major update of their joint Well-to-Wheels (WTW) study exploring the energy use and greenhouse gas (GHG) emissions associated with different combinations of fuels and powertrains in the European context. Looking at the 2030 time frame and following a three-step approach, the new JEC WTW v5 package includes a series of reports:

1. JEC Well-to-Tank (WTT) v5 which provides data on more than 250 modelled fuel production pathways, including their technology and commercial readiness levels, and incorporates a section devoted to biofuels' production costs.
2. JEC Tank-to-Wheels (TTW) v5 which explores the use of fuels in different powertrains, and assesses the fuel (energy) consumption and tailpipe emissions. This version of the TTW report extends the analysis beyond passenger cars for the first time, and now includes data on regional (group 4, mid-distance distribution traffic) and long-haul heavy-duty (group 5) vehicles.
3. JEC Well-to-Wheels (WTW) v5 builds on the above reports, and integrates a selection of feedstock/fuel production pathways (i.e. WTT), describing their use in different powertrains (i.e. TTW) and presenting the results in terms of MJ or g CO_2eq per km travelled.

Concawe's thanks go to the members of the JRC, EUCAR and Concawe task forces for their involvement and contribution to the project, as well as to the many external stakeholders who have contributed to it and expressed their interest during the whole process.

Enquiries: marta.yugo@concawe.eu

The main challenge for the maritime transport sector over the next decade is to develop a decarbonisation pathway to achieve the current 2050 ambition. The complexity of the sector requires the involvement of all of the industry's stakeholders in preparing a quantified and practical review of options to decarbonise the maritime sector by 2050.

Efforts are under way to achieve the IMO's ambition of reducing carbon emissions from international shipping by at least 50% in 2050 compared to 2008 levels. This ambition also aims to reduce the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 (again compared to a 2008 base year).

Concawe is funding a research project entitled 'Assessing technological, operational and energy pathways for maritime transport to reduce emissions towards 2050', to be conducted by Ricardo Energy & Environment. The study will provide quantified, evidence-based and neutral analysis to support high level decision-making, in particular with regard to investment scale-up. The analysis will include the identification of barriers and enablers to climate change responses in the maritime sector, from a broad range of technical, economic and regulatory perspectives.

This article summarises Phase 1 of the project, which provides the context for the maritime transport sector and its drivers, and describes the technological and operational measures identified for decarbonising the sector, as well as the options for alternative fuels and energy carriers.

Enquiries: damien.valdenaire@concawe.eu

Technology scouting—carbon capture: from today's to novel technologies

Concawe has commissioned a new study to evaluate state-of-the-art carbon capture and storage (CCS) technologies, with a focus on commercial/near-term opportunities for CCS that are already in the market or expected to be available in the 2025–2030 time frame, as well as the various emerging CCS techologies that are being developed worldwide. This article provides an overview of the study, the full details of which can be found in Concawe report no. 18/20.[1]

Introduction

Carbon dioxide (CO_2) emissions are a global concern as they are primarily responsible for climate change and global warming. The industrial sector is responsible for around 20% of current greenhouse gas (GHG) emissions worldwide. Technologies for reducing CO_2 emissions already exist, and include swapping fossil fuels for renewable sources, boosting production and energy efficiency, implementing carbon capture and storage (CCS) technologies, and discouraging carbon emissions by putting a price on them. Over the past three decades, several CO_2 capture technologies have been developed in response to the increasing awareness of the importance of reducing carbon emissions. A few of these technologies, such as amine-based CO_2 capture, are already being implemented at the industrial level.

CCS technology involves capturing carbon dioxide at stationary point sources, such as fossil fuel power plants, refineries, industrial manufacturing plants and heavy industrial (iron and steel, cement) plants, as well as mobile sources such as automobiles, ships and aircraft, or directly from the air (direct air capture). The captured CO_2 is compressed and then transported, either for storage in geological formations, or for direct use (non-conversion of CO_2, e.g. for use in enhanced oil recovery, food and beverage manufacture, as a heat transfer fluid, etc.) and indirect use (conversion of CO_2 into chemicals, fuels and building materials), the latter being referred to as carbon capture and utilisation (CCU).

A new study, conducted by FutureBridge at the request of Concawe,[1] focuses on near-term opportunities for carbon capture technologies that are likely to be commercialised in the 2025–2030 time frame, and also on the various emerging carbon capture technologies for power plants and industrial process applications.

In their assessment of near-term and emerging carbon capture technologies, FutureBridge took into consideration various techno-economic factors such as carbon capture efficiency/rates, purity, the cost of CO_2 capture per tonne, the levelised cost of electricity, risks and barriers. They collated information from a wide range of sources, including patents, scientific literature, published techno-commercial reports, white papers, annual reports and sustainability reports to support their assessment of both near-term and emerging carbon capture technologies. In addition, to gauge the potential for near-term commercial carbon capture technologies FutureBridge analysed published front-end engineering and design reports, integrated assessment models, and a techno-economic analysis report for pilot and demonstration plants.

1 See Concawe report no. 18/20.
https://www.concawe.eu/publication/technology-scouting-carbon-capture-from-todays-to-novel-technologies

Carbon capture technologies

Carbon capture is a process that involves capturing CO_2 at its point source or from the air, and either storing it underground to avoid its release into the atmosphere (CCS) or using it in a number of direct or indirect applications (CCU). The CCS process includes the following five steps:

- **Source characterisation:** this involves identification of the source location, CO_2 output flow rate, CO_2 purity, and the type of output stream. The Centre for Low Carbon Futures has classified CO_2 sources into four categories, based on the impact of CO_2 concentration on the energy requirements for capture, and the corresponding cost of separating the CO_2 from the gas stream. These categories are: high (>90%); secondary highest (50–90%); moderate (20–50%); and low (<20%).[2]
- **Capture/separation:** CO_2 is separated from the output stream using appropriate technology (chemical solvents, membranes, etc.) based on the type of stream. It is also separated from other gases or air (direct air capture) or from a concentrated source (e.g. industrial flue gases). It should be noted that the different sources have distinct characteristics in the way that CO_2 is produced, and can be further categorised into:
  a) high-purity CO_2 streams (e.g. from production of bioethanol, beer, hydrogen, etc.) with 96–100% CO_2 purity;
  b) medium-purity CO_2 streams (e.g. from production of iron and steel, cement, etc.) with 20–50% purity, and CO_2 streams from hydrogen production (e.g. syngas production, refinery processes) which are considered to be within the 30–45% purity range; and
  c) low-purity CO_2 streams (e.g. from production of paper and pulp, glass, etc.) that directly produce an output stream of <20%. In refineries, process heating and fluid catalytic cracker (FCC) units produce low purity (3–20%) streams of CO_2.
- **Purification:** depending on the source of the carbon emissions, and the type of fuel and capture method used, the CO_2 stream will contain various impurities, such as SO_x, NO_x, O_2, N_2, Ar, H_2, CH_4, CO, H_2S, H_2O and mercaptans, some of which may have a negative impact (e.g. corrosion and formation of liquid slugs in the pipeline) during transportation. The purification requirements of the captured CO_2 vary depending on the final use of the CO_2 stream. Impurities such as O_2 are largely removed by using cryogenic distillation and catalytic oxidation techniques, while H_2O is removed via refrigeration and condensation, and by adsorption using silica gel. Scrubbing and drying techniques are also used to remove impurities from the captured CO_2. A minimum of 96% CO_2 purity is required for pipeline transportation because CO_2 pipelines are susceptible to the propagation of ductile fractures.[3]
- **Transportation:** captured CO_2 is compressed to a pressure ranging from 8–17 MPa at ambient temperature (286 K to 316 K) to reach supercritical form, and the compressed CO_2 is then transported via pipelines, road tankers, railroad tankers (inland transportation) and ships. Each transportation system has its advantages and disadvantages, although pipelines are considered to be the most attractive mode of transportation because they can handle large flow rates effectively. On the other hand, road and rail tankers are more useful for transporting small quantities.

[2] https://www.ctc-n.org/resources/supporting-early-carbon-capture-utilisation-and-storage-development-non-power-industrial

[3] http://pdf.wri.org/ccs_guidelines.pdf

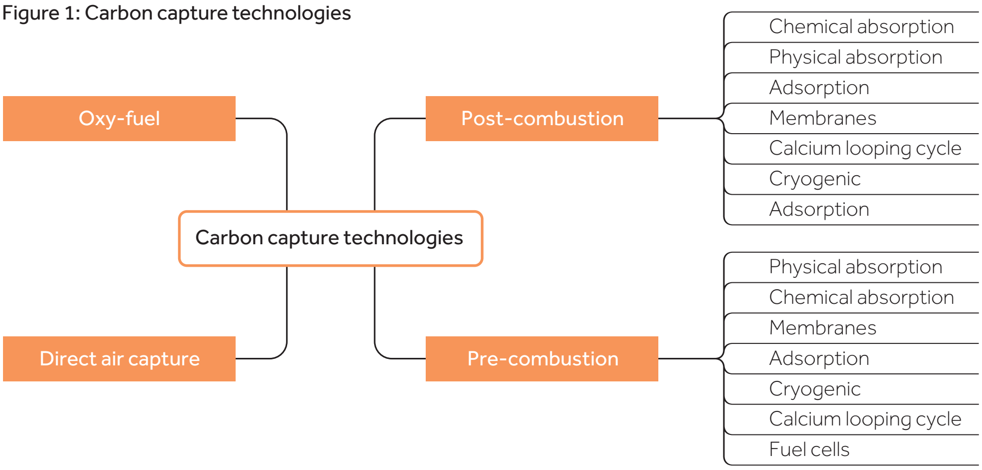
- **Storage:** captured CO_2 is stored by injecting it deep underground where it remains stored permanently. The CO_2 is stored in reservoirs, through the geological storage and oceanic storage routes, whereby CO_2 is directly injected deep into the saline formations of aquifers and depleted oil/gas wells. Three types of geological formations are eligible for storing CO_2: depleted oil and gas reservoirs; deep saline formations; and unminable coal beds.

The most technologically challenging and costly step in the process is the capture step (the main focus of this article). The purification, transportation and storage components of CCS are not nearly as technology-dependent as the capture component.

Currently, the technical approaches available for capturing CO_2 are as follows (see also Figure 1):

- **Post-combustion capture:** involves the removal of CO_2 from flue gas produced after the combustion of fossil fuels or other carbonaceous materials (such as biomass).[4]
- **Pre-combustion capture:** refers to the near-complete capture of CO_2 before fuel combustion or before venting out the exhaust gas or flue gases, and is usually implemented in conjunction with the gasification of coal, coke, waste biomass and/or residual oil or steam reforming/partial oxidation of natural gas to produce syngas.[5]
- **Oxy-fuel combustion:** although not technically a carbon capture technology, this is a process in which combustion occurs in an oxygen-enriched environment, hence producing a flue gas comprised mainly of CO_2 (~89% by volume) and water. [6]
- **Direct air capture:** a technology in which CO_2 is removed directly from the atmosphere as opposed to the capture at point source itself.[7] (Note that the concentration of CO_2 in the air is relatively low, at ~400 ppm.)

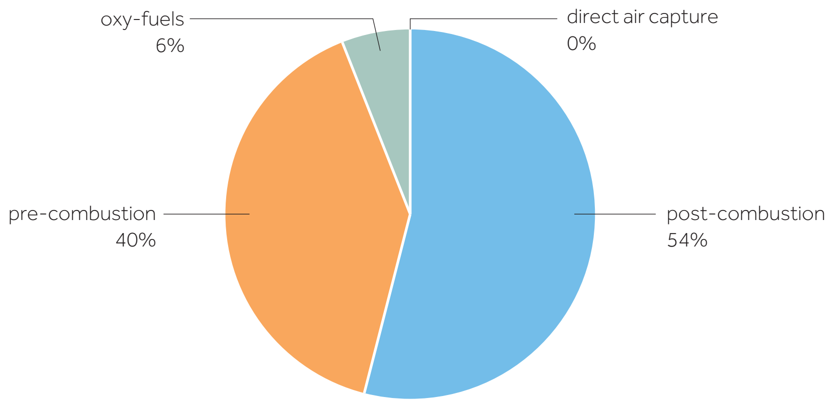
Figure 1: Carbon capture technologies



4 http://www.zeroco2.no/introduction/AminesNyhetsgrafikk.jpg
5 http://www.zeroco2.no/introduction/PrecombustionVattenfall.jpg
6 https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion
7 https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf

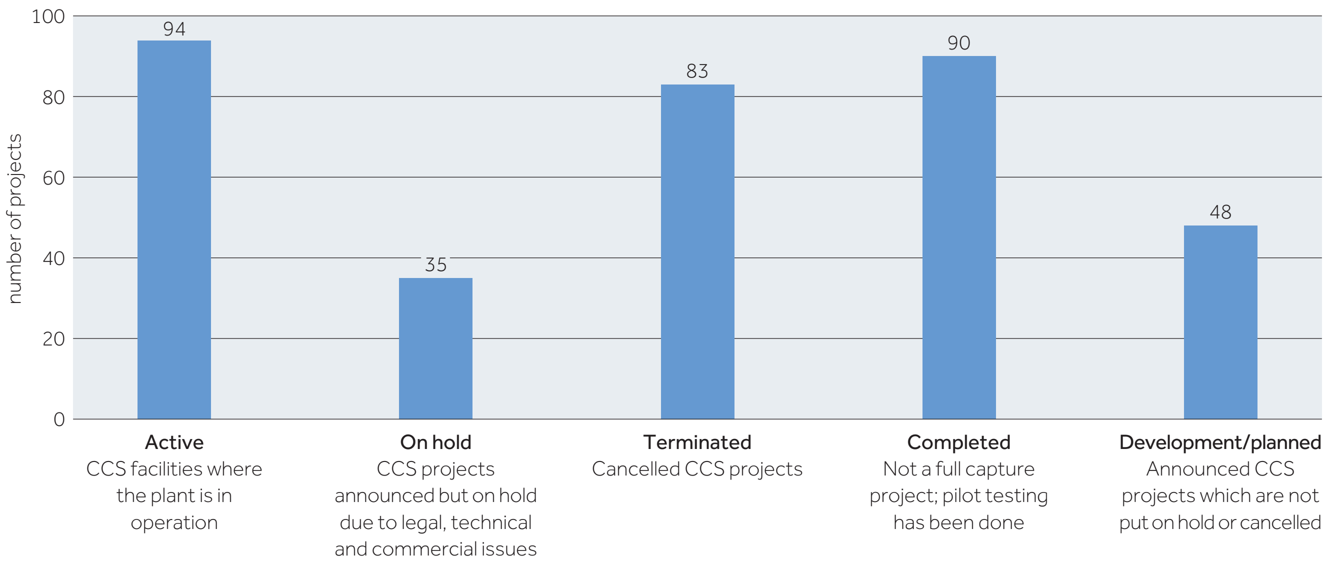
Currently, both pre- and post-combustion capture technologies have been commercialised, and are being used extensively in a variety of CCS projects worldwide, as shown in Figure 2.

Figure 2: Distribution of CCS projects worldwide



In April 2018, there were approximately 150 planned or active CCS facilities worldwide.[8] A total of 118 CCS projects were either on hold or had been terminated, and 90 pilot projects had been realised. The overall status of these CCS facilities is presented in Figure 3.

Figure 3: CCS facilities worldwide as of April 2018



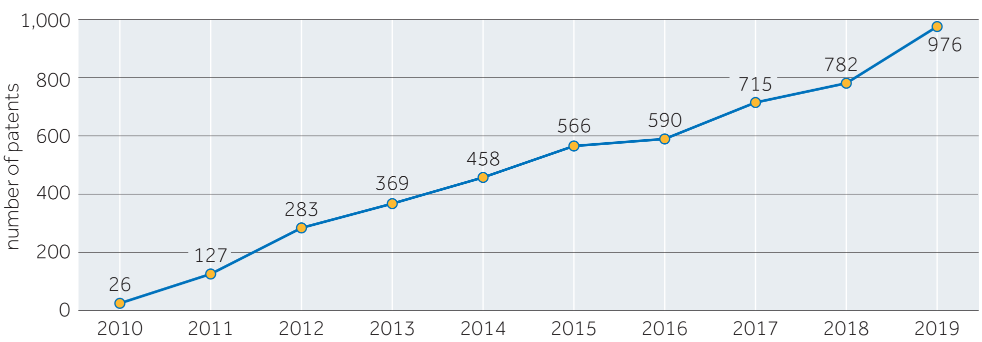
[8] https://www.netl.doe.gov/node/7633

Technology scouting—carbon capture:
from today's to novel technologies

Technology scouting: a deep dive into patent analysis

As part of their scouting assessment, FutureBridge conducted an analysis of patent publications issued since 2010. They identified an increasing trend in the publication of patents relating to carbon capture between 2010 and 2019, as shown in Figure 4.

Figure 4: Worldwide patent publication trend (2010–2019)



Analysing the trend per country (Figure 5) shows that, as of 2019, China was leading the most active countries in terms of the number of patents on the subject. Currently, China is the world's largest carbon emitter, and a recent push for greener production of goods and energy solutions by the Chinese government and state-owned Chinese companies has propelled the filing of patents related to climate change technologies.

Figure 5: Top 10 countries and their patent filing trends (2010–2019)

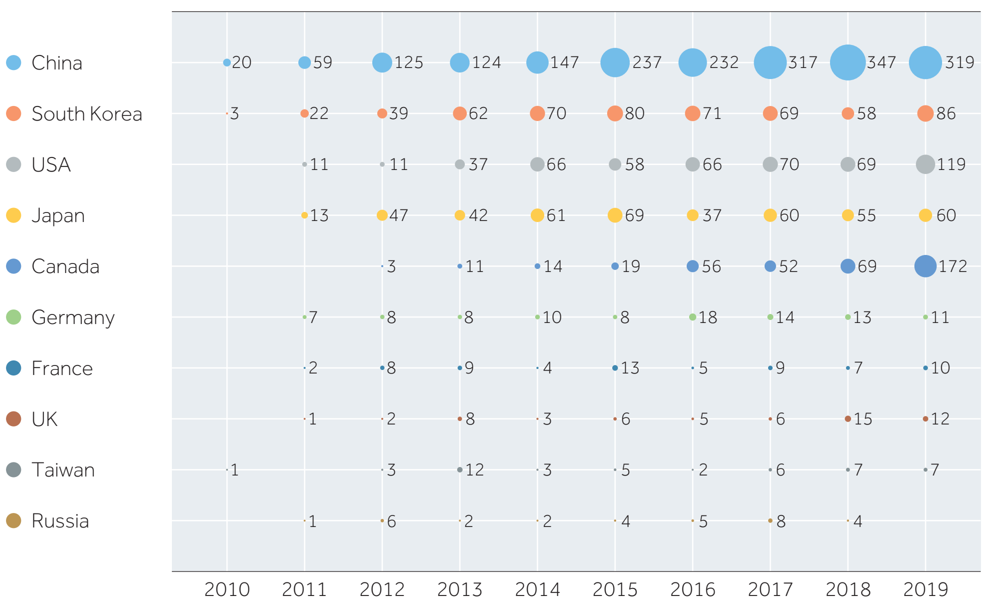
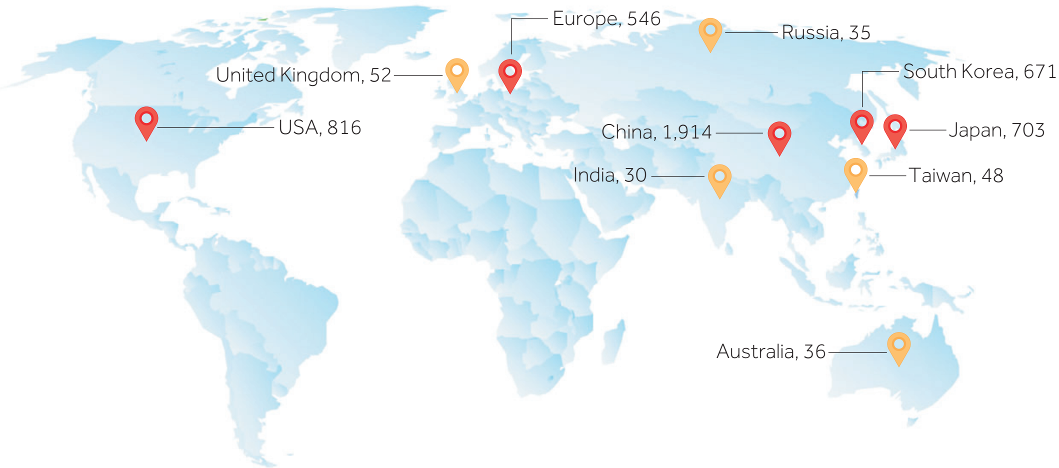


Figure 6: Geographic distribution of patents



A detailed analysis of patents per type of technology and the main players involved is presented in the full report.

Categorisation of carbon capture technologies

FutureBridge has defined three categories of carbon capture technologies according to their technology readiness level (TRL), i.e. commercial, near-term and emerging technologies (see Figure 7).

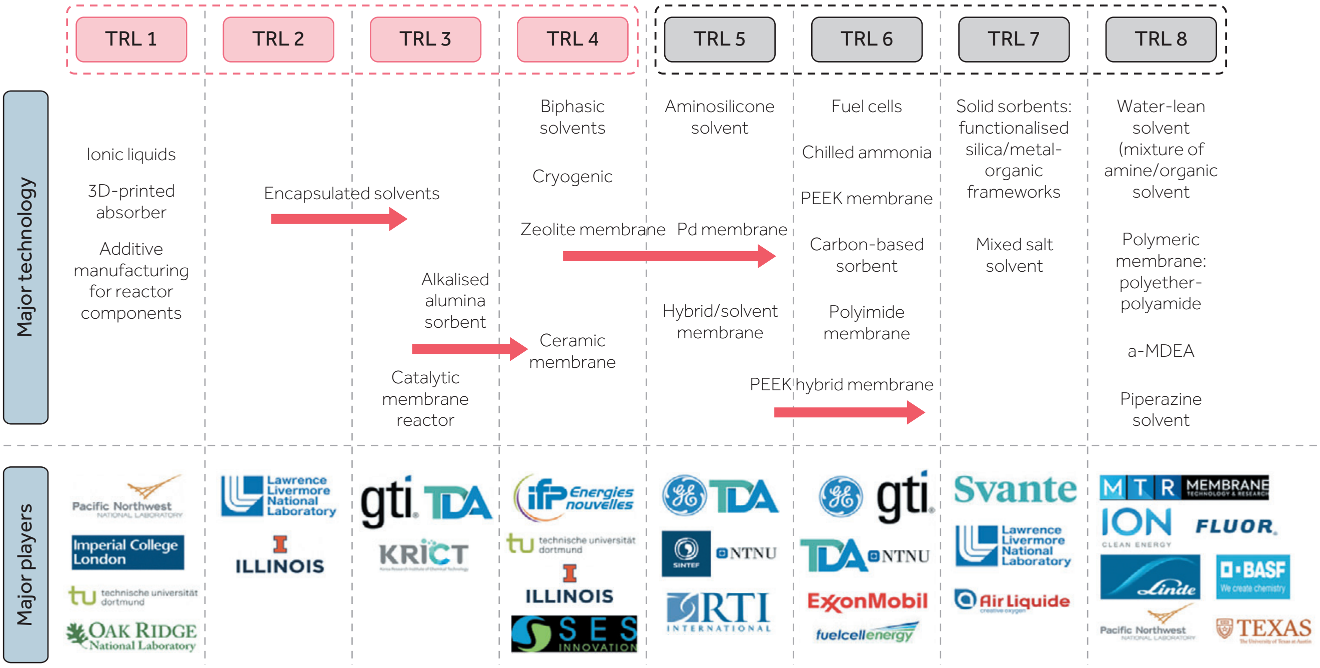
Figure 7: Carbon capture technology categorisation

Technology	Technology readiness level	Characteristics
Commercial	1 2 3 4 5 6 7 8 9 (current: 9)	• First generation technology • 85–90% CO_2 capture rate with 95% CO_2 purity • Average cost of CO_2 capture is US$50–75 per tonne
Near-term commercial	1 2 3 4 5 6 7 8 9 (Today: 5–8; 2030: 9)	• Second generation technology • 90% CO_2 capture rate with 95% CO_2 purity • Reduce cost of electricity (COE) by 20–30% • Average cost of CO_2 capture is US$40 per tonne
Emerging	1 2 3 4 5 6 7 8 9 (Today: 1–4; 2040: 9)	• Early stages of research and development • 95% CO_2 capture rate with 99% CO_2 purity • Reduce COE by 30–40% • Average cost of CO_2 capture is US$30 per tonne

Technology scouting—carbon capture: from today's to novel technologies

The major near-term and emerging carbon capture technologies and the major players have been classified as shown in Figure 8.

Figure 8: Overview of the near-term (TRL 5–8) and emerging (TRL 1–4) carbon capture technologies and main players



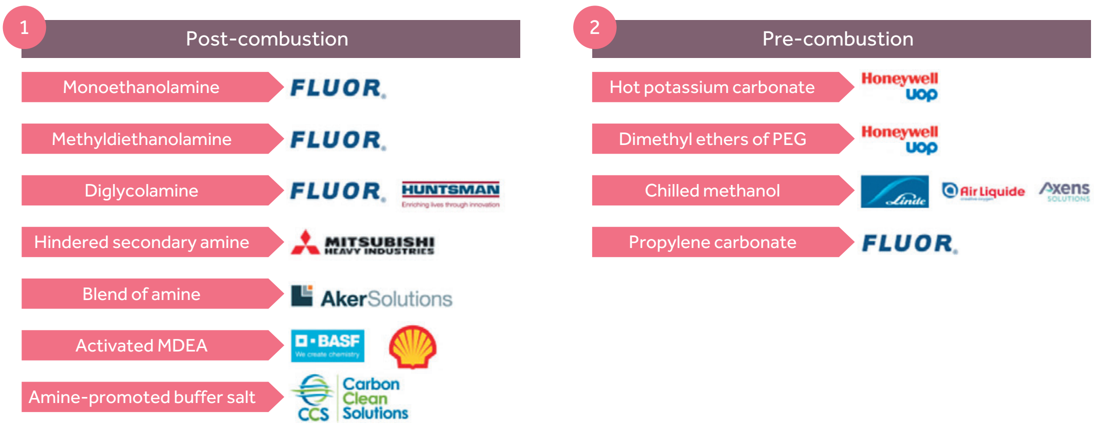
Commercial carbon capture technologies

Commercial technology: first generation technology (TRL 9) with 85–90% CO_2 capture and 95% CO_2 purity.

- Post-combustion capture with chemical absorption is the most proven technique for CO_2 removal from combustion flue gases, and is mostly based on chemical absorption/desorption with the use of liquid absorbent, such as monoethanolamine (MEA) at 30 wt% in water. Chemical absorption is commercialised and used in petroleum, natural gas, and coal-based power plants for separating acid gas (such as CO_2 or H_2S) from natural gas streams. This technique focuses on the reaction (largely exothermic) between the chemical absorbents and CO_2.
- Currently, pre-combustion physical solvent-based technology is used in industrial manufacturing processes, such as syngas, hydrogen, and natural gas production. A few facilities, such as the Enid Fertiliser CCS plant in northern Oklahoma, utilise a high-temperature, high-pressure chemical absorption process in which hot potassium carbonate is employed as a solvent to remove the CO_2 (Benfield process, Honeywell UOP).

Figure 9 summarises the key technologies and main players for both post- and pre-combustion commercial technologies.

Figure 9: Overview of the commercial carbon capture technologies and main players

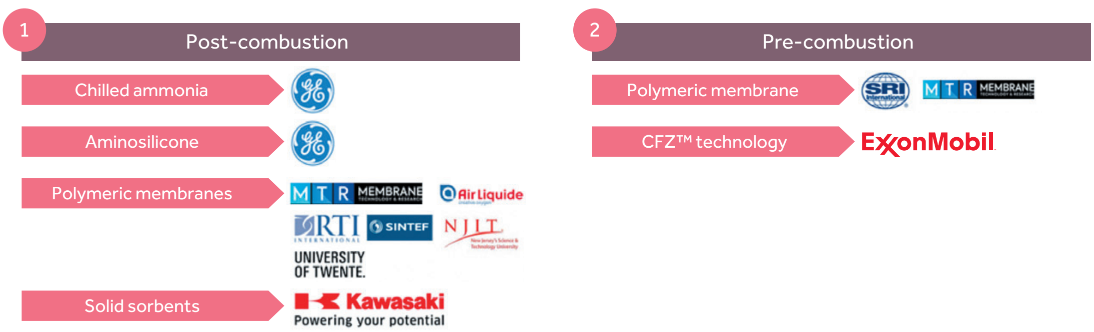


Near-term commercial carbon-capture technologies

> **Near-term commercial technology:** second generation technologies, currently in the advanced phase (>TRL 5) that are scheduled to become available for demonstration-scale testing around 2020–25 and expected to be available for commercial deployment in 2025–30. These technologies can offer a low overall cost of carbon capture (~US$40 per tonne of CO_2) and a 90% CO_2 capture rate with 95% CO_2 purity compared to currently available first-generation technologies.

Figure 10 lists some of the technologies that are likely to be commercialised for coal-fired and natural-gas-fired power plants, together with the main players.

Figure 10: Overview of near-term commercial carbon capture technologies and main players



- Research and development work has been ongoing to provide improvements in the membrane technology used for pre- and post-combustion CO_2 capture. Several groups are developing polymeric membrane technology for post-combustion carbon capture. For example, the Norwegian University of Science and Technology patented a polyvinylamine (PVAm) membrane[9] containing amine groups, which has been evaluated in pilot-scale testing at an EDP power plant in Portugal. In addition, Membrane Technology Research Inc. (MTR) has been testing its innovative Polaris™ membranes at various test centres since 2006. MTR is also evaluating a hybrid membrane-absorption process system based on a combination of Polaris™ membranes and an amine solvent-based capture system. Other organisations such as Air Liquide S.A., SRI International, SINTEF Norway, Twente University, Research Triangle Institute, and the New Jersey Institute of Technology are also active in this area.

Emerging carbon-capture technologies

Emerging technology: transformational technologies (<TRL 5) that are in the early stages of research and development and which offer the potential for game-changing improvements in cost and performance (30–40% reduction in the cost of electricity), and have an overall carbon capture cost of ~US$30 per tonne of CO_2, and a 95% CO_2 capture rate with 99% CO_2 purity. These technologies will be available for demonstration-scale testing around 2030–35, and for commercial deployment in the 2035–40 time frame.

These emerging technologies will outperform current technologies for both pre- and post-combustion carbon capture in power plants and refineries, including H_2 generation.

Figure 11: Overview of emerging carbon capture technologies and main players

[9] https://patents.google.com/patent/US8764881B2/en

The potential for CO_2 storage

The following types of geological structures are available for storing CO_2:

- **Underground sedimentary formation:** CO_2 is stored in porous geological formations underground. These geological formations are located at depths of several kilometres, and have pressure and temperature conditions that allow carbon dioxide to be stored either in the supercritical or liquid state. This is one of the most mature technologies for the storage of carbon dioxide and has been in use for more than two decades.
- **Saline aquifers:** saline aquifers are porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains. They are found at depths greater than aquifers that contain potable water. Water contained in a saline aquifer cannot be technically and economically exploited for surface uses due to its depth and high saline content. The scientific literature related to carbon dioxide storage states that saline aquifers have enormous potential for carbon dioxide storage. A large proportion of European storage capacity exists in offshore saline aquifers, especially in the North Sea region, around Britain and Ireland, to some extent in the Barents Sea and likely in the Baltic Sea.
- **Depleted oil and gas fields:** these are suitable candidates for geological sequestration of carbon dioxide, although the CO_2 storage capacity is less than that of other structures. This is because of the need to avoid exceeding pressures that can damage the caprock, and because of the significant threat of leakage posed by abandoned wells. The major advantage of this type of storage is its known geology and proven capability to store oil and gas in the formation.
- **Oil and gas wells:** the process of injecting CO_2 into oil and gas wells to enhance recovery has been used for many years. With the right reservoir conditions, the injection of CO_2 can result in permanent storage of the CO_2 in the geological formation. Enhanced oil recovery (EOR) techniques can also involve the use of other gases (e.g. natural gas or nitrogen) as well as thermal or chemical injection; the IEA's new global database of enhanced oil recovery projects shows that around 500,000 barrels of oil are produced daily using CO_2-EOR, representing around 20% of total oil production using EOR techniques.
- **Coal beds/seams:** injecting CO_2 into coal beds/seams allows the CO_2 to be stored in the coal seam while simultaneously enhancing the recovery of coal bed methane. Research into this process—known as enhanced coal bed methane (ECBM) recovery—has been ongoing for the past two decades. The major technical challenges for carbon dioxide storage in coal beds are the low injectivity of coal seams and loss of injectivity as more CO_2 is injected. These challenges significantly limit the opportunity for CO_2 storage.
- **Carbon mineralisation in mafic and ultramafic rock formations:** this is an emerging storage technology and involves storing CO_2 in mafic and ultramafic rocks through mineralisation via carbonation reaction. CO_2 mineralisation can be used in different settings and include the in-situ CO_2 mineralisation of basalts or ultramafic rocks, ex-situ mineralisation of alkaline mine tailings, and reactions that produce other materials that have the potential to be used as mineral resources. Basalt rock has high porosity and permeability which increases its reactivity with CO_2, making it an ideal medium for CO_2 injection and storage.

Technology scouting—carbon capture: from today's to novel technologies

The global CO_2 storage capacity and storage projects across the world are shown in Figures 11 and 12, respectively. A detailed list is provided in the full report.

Figure 12: Global storage capacity ($GtCO_2$)[10]

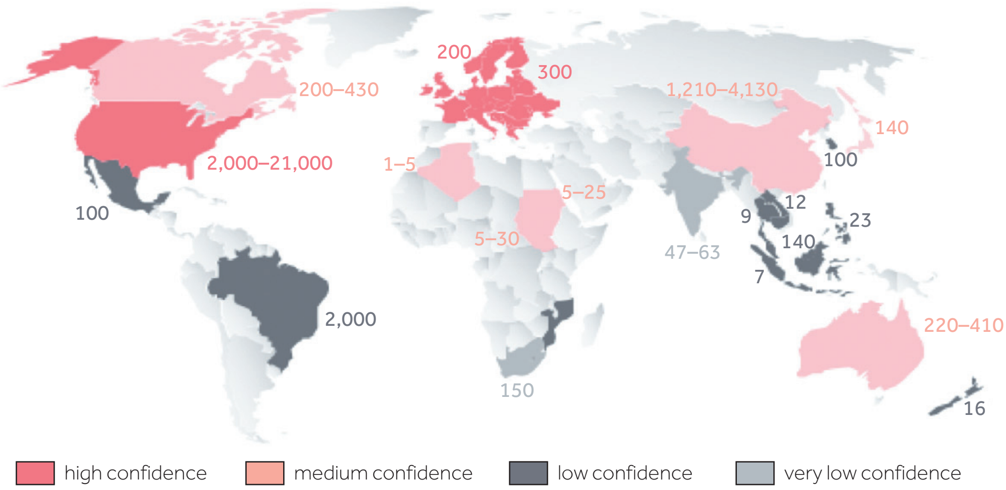


Figure 13: Storage projects across the world[11]

[10] https://www.globalccsinstitute.com/resources/global-status-report/

[11] https://link.springer.com/article/10.1007/s12182-019-0340-8

A Clean Planet for all: an impact assessment of the potential implications for the refining system and the link with 'Refinery 2050'

Objective

The European Commission's long-term strategy, *A Clean Planet for all*[1,2] published by DG CLIMA in 2018, analyses different long-term scenarios that could lead to significant reductions in greenhouse gas (GHG) emissions on the way towards a carbon-neutral and circular European economy by 2050.

Concawe has published a report that analyses three of the scenarios presented in the DG CLIMA publication. It examines the implications for the EU refining sector, assesses the CO_2 emission reductions that could be achieved through the whole value chain, and provides an estimate of the investments required to develop new plants and adapt existing refinery infrastructure, while also exploring key barriers and enablers associated with realising these scenarios.

Focusing on three of the scenarios defined in the European Commission's long-term strategy, *A Clean Planet for all*, Concawe has published a report that assesses the potential reductions in CO_2 emissions, together with the implications for the EU refining sector in terms of the required investments, and the barriers, enablers and associated risks. This article provides a brief summary of the Concawe report.


EUROPEAN COMMISSION

Brussels, 28 November 2018

IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773

A Clean Planet for all
A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

Concawe's new report focuses on three scenarios defined in the European Commission's long-term strategy, *A Clean Planet for all*, published in November 2018.

The Concawe report focuses on the following three EU scenarios (each compared to 1990):

- Baseline, with current policies to 2030[1] which achieve GHG emission reductions of 45% by 2030 and 60% by 2050;
- P2X (power-to-fuels/e-fuels), achieving an 80% reduction in GHG emissions across the whole EU economy; and
- 1.5TECH (climate neutral scenario), achieving a 100% net reduction in GHG emissions (including sinks).

Concawe's report also aims to answer the following key questions:

- What are the implications for the European refining system in 2050?
- What are the results in terms of GHG emission reductions that could be achieved across the whole value chain?
- What are the external requirements, as well as the key barriers and enablers, for the realisation of such scenarios?
- How will the domestic production/import/export balance be impacted?

[1] 45% reduction in GHG emissions by 2030, and 60% reduction by 2050.

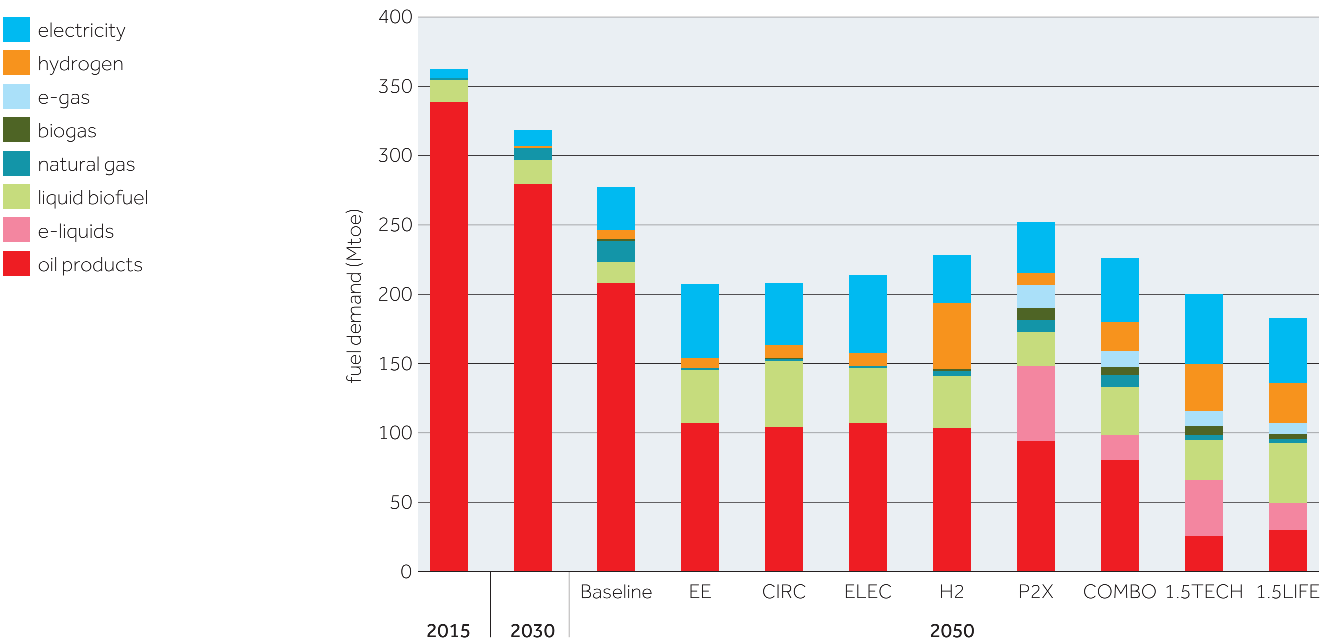
Product demand

Transport fuels

All scenarios rely on a combination of energy sources and carriers to satisfy the demand for transport, and on the substitution of fossil fuels increasing with the GHG reduction ambition (see Figure 1).

- Domestic demand for oil-based products decreases steeply towards 2050 — by up to 90% in the 1.5TECH scenario compared to the current level. Aviation fuel becomes dominant in the total transport fuel demand, and retains the largest proportion of fossil material.
- Although the contribution of total liquid fuels (oil products, e-liquids, liquid biofuel) to transport is reduced, they retain a significant share with 50% of the 2050 domestic demand in the most ambitious (1.5TECH) scenario.
- The baseline case still shows a large fossil contribution in all liquid product pools. The fossil contribution is significantly reduced in the P2X scenario (45%) and even further in the 1.5TECH scenario (10%).
- Electrification becomes a main feature for transport through both the direct use of electric road vehicles and the use of so-called e-fuels derived from captured CO_2 and hydrogen produced mostly from renewable electricity. The P2X scenario is particularly ambitious for e-fuels in road transport (up to 60%).
- Biomass also plays an increasingly significant role.

Figure 1: Fuel demand in the transport sector according to *A Clean Planet for all* [1]



Other products

The demand for petrochemicals (olefins, aromatics), LPG, bitumen, lubes and waxes are not specifically mentioned in *A Clean Planet for all*. The Concawe study builds on figures previously considered in Concawe's 'Refinery 2050' study.[3]

Modelling

The three scenarios were simulated on a pan-EU refinery system basis using Concawe's RafXL[2] model, with the objective of matching demand in terms of both tonnage and origin distribution (fossil/bio/e-fuels) for each main product pool. The feedstocks and processing schemes considered were:

- crude oil and conventional refinery processes;
- lipids (vegetable oils) hydrotreated to middle distillates;
- woody biomass to liquids via gasification and Fischer-Tropsch (FT) synthesis; and
- own (captured) and imported CO_2 plus electrolytic hydrogen to e-fuels.

A 'high jet' mode (validated with confidential proprietary data from different technology providers) was introduced for the FT product processing to support the high demand for jet fuels. As an assumption, it was considered that components from different origins would mostly be produced in separate plants (or even sites) so that they could be routed independently to the appropriate product pool. Given the existing infrastructure and facilities already available at refineries, some of which would be underutilised, and the potential synergies with the new conversion technologies, it is reasonable to assume that existing refining sites will attract a good number of these new plants which could be integrated into the existing systems (for additional details see Concawe report no. 9/19, *Refinery 2050: Conceptual Assessment*.[3])

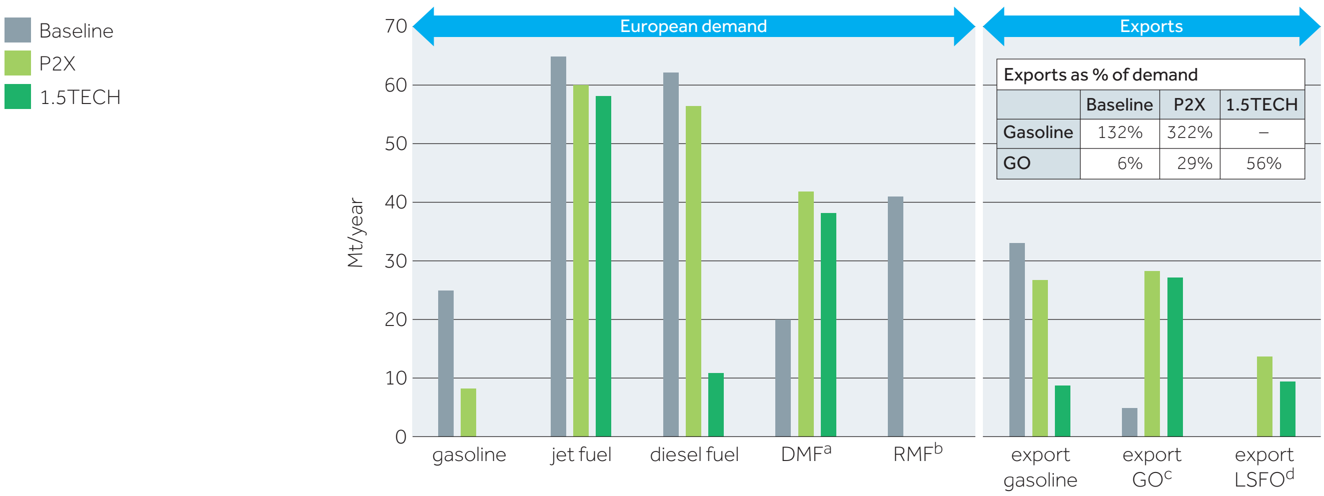
Results

Demand

With the level of flexibility afforded by the segregation of fossil, bio and e-streams, and the availability of a 'max jet' hydrocracking mode, the RafXL model demonstrates that it would be possible to meet the 2050 demand for the main products in all three of the selected scenarios described in *A Clean Planet for all*, both in terms of tonnage and origin (feedstock) distribution, as well as meeting the demand for the other products, but only with some non-negligible burdens described below.

[2] As described in Concawe report no. 9/19,[3] Concawe's RafXl simulation tool was used with the objective to best match both the EU domestic demand and origin distribution for all three transport fuel pools, while also meeting the demand for other products and minimising surpluses (exports out of Europe). The modelling exercise was done for the whole of the EU refining industry notionally operating as a single refinery, with the total European refinery plant capacities.

Figure 2: European demand and exports



[a] diesel marine fuel
[b] residual marine fuel
[c] GO refers to exported gas oil, all the middle distillates left over
[d] low-sulphur fuel oil (RMF or other grades)

The main implications of the three selected scenarios are as follows:

- The large quantities of middle distillates required, and particularly jet fuel with a significant fossil component, coupled with weak gasoline and diesel demand and the disappearance of marine fuel oil in the most advanced scenarios, results in significant surpluses of gasoline, gas oils and heavy fuel oil (exports out of Europe, overwhelmingly comprised of fossil components).
- Surpluses can be reduced, but not totally eliminated, by relaxing the origin distribution constraints defined in the European Commission's report.
- Technologies that address the gasoline/distillate balance (such as oligomerization) or modifications of existing hydrocrackers would only have a limited impact.

The main challenges

The fossil fuels consumption mix anticipated in the European Commission's report is so weighted towards jet fuel that, as an outcome of Concawe's analysis, it was identified that it would not be feasible to achieve these yields in the average EU refinery without the consequent surplus of different types of fuels (mainly fossil with a percentage of renewables), which would need to be exported out of the EU. The percentage of fuels of renewable origin exported would potentially be transported to countries that could not valorise their renewable nature, adding an additional cost of production versus fossil. This is envisaged to be highly uneconomical for the EU system.

In addition to the export issue, and although the surplus volumes of gasoline, gas oil and heavy fuel oil (mostly fossil based) are of a similar order of magnitude to historical EU trading figures, it is questionable whether the estimated levels of 'fossil' exports required to meet the analysed scenarios could be considered sustainable in a low-carbon 2050 world. Eventually, this could mean that the EU would be reducing emissions domestically at the cost of increasing them somewhere else.

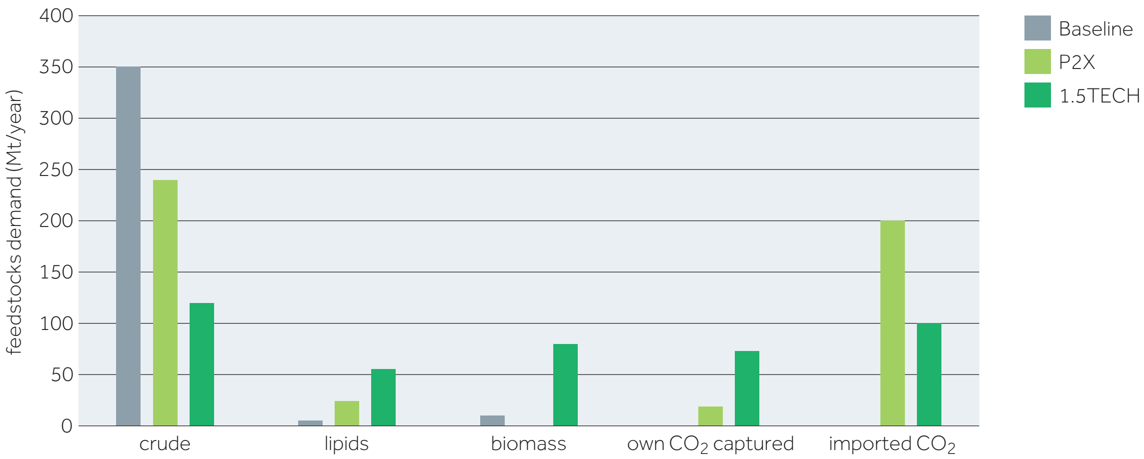
Implications for the refining industry

Feedstock requirements

In all cases, the crude oil volume required to meet the total demand for transport fuels (with the share of fossil components as defined in *A Clean Planet for all*) was higher than the minimum of about 65 Mt/year set by the demand for bitumen.

The estimated demand for lipids and biomass were within the maximum availability forecast for 2050.[4]

Figure 3: Demand for feedstocks



The main challenges

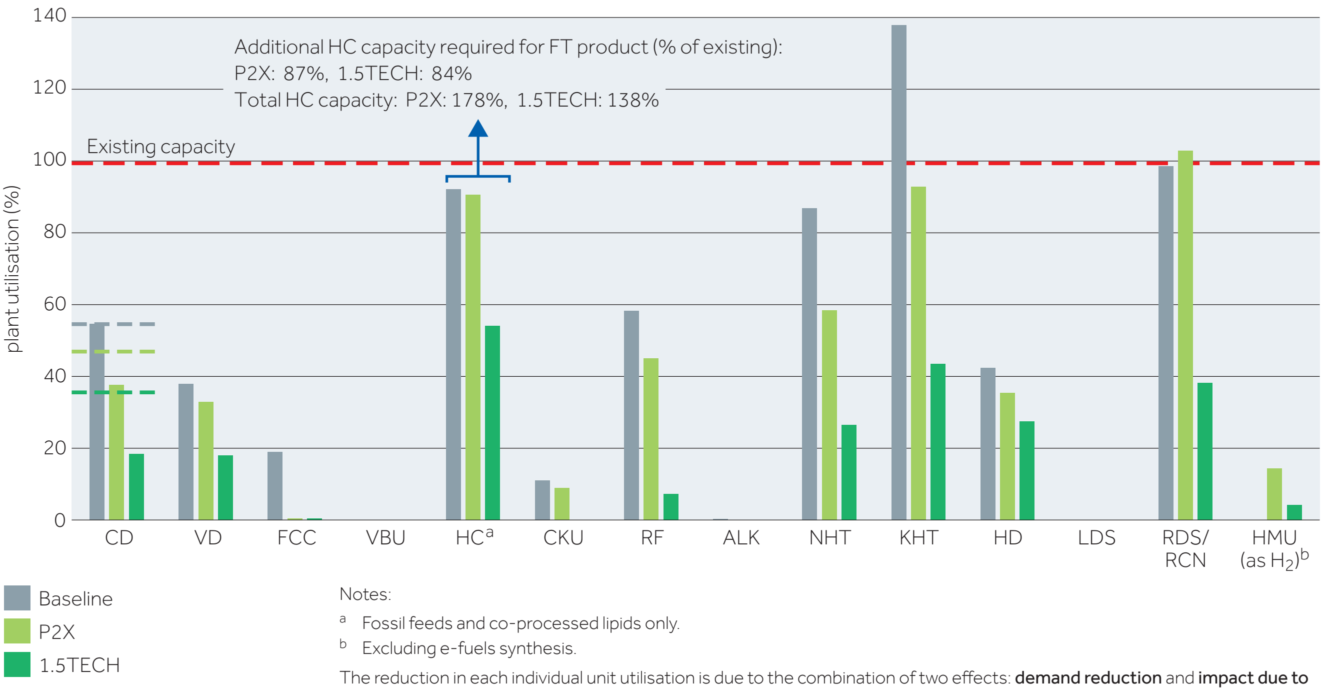
The emphasis on e-fuels (domestically produced in Europe in this assessment) sets a very high target for CO_2 'imports', as production within the EU refining system only meets a fraction of the total CO_2 requirement (9% in the P2X scenario and 42% in the 1.5TECH scenario). This requirement of CO_2 as a feedstock for the refinery system could foster the creation of industrial hubs (where the CO_2 comes from other industrial sites) or the development of technologies such as direct air capture.

Key issues such as the mobilisation of high volumes of sustainable feedstocks at the European level are also major caveats with regard to the 2050 demand scenarios.

Refinery plant utilization and new capacities

Conventional refinery plants are heavily underutilised, with the exception of hydrocrackers, kerosene hydrotreaters and residue converters. Processing the raw synthesis material will require up to a twofold increase in existing EU hydrocracking capacity, or the repurposing of some existing hydrotreaters.

Figure 4: Refinery plant utilisation



CD: Crude distillation

VD: Vacuum distillation

FCC: Fluid catalytic cracking

VB: Visbreaking

HC: Hydrocracking

CKU: Coking

RF: Catalytic reforming

ALK: Alkylation

NHT: Naphtha hydrotreating

KHT: Kerosene hydrotreating

HD: Gasoil hydrodesulphurisation

LDS: Atmospheric residue desulphurisation

RDS/RCN: Vacuum residue desulphurisation/conversion

HMU: Hydrogen manufacturing (SMR)

Notes:

[a] Fossil feeds and co-processed lipids only.

[b] Excluding e-fuels synthesis.

The reduction in each individual unit utilisation is due to the combination of two effects: **demand reduction** and **impact due to the alternative feedstocks** fed into the refinery, replacing crude oil (in some cases, the alternative feedstocks will be fed directly into HC or FCC units, minimizing CD/VD utilisation). As a visualisation of the impact of these combined effects, the dotted lines on the figure indicate the current capacity and general level of demand reduction in each scenario, applied to the crude processing capacity.

New plants would be required to process lipids into marketable diesel, and biomass and CO_2 into liquid fuels. Based on today's commercial practice, up to some 40 plants/trains would be required to process lipids. Although biomass-to-liquids (BTL) technology has not yet reached commercial scale, single train capacities of 200 kt/year of liquid product are considered feasible, which would suggest a requirement for up to 50 plants/trains across Europe. E-fuels plants are very much unchartered territory in terms of hydrogen production at scale and CO_2 conversion. The FT stage would be very similar to proposed BTL plants, and small sizes could potentially be envisaged in Europe (~0.2 Mt/year of liquid product). However, there is considerable uncertainty with regard to the future capacity of these plants, and larger ones — such as gas-to-liquids (GTL) plants — could also be deployed in certain favourable areas with capacities of up to 1 Mt/year of liquid product. As a reference, they will require about 3 Mt/year CO_2 and 3 GW of electricity generation capacity for 1 Mt/year of liquid product.

The main challenges

Major challenges would lie ahead for the scaling up of biomass-to-liquids plants, and the development of large e-fuels plants in terms of CO_2 availability and distribution/transport systems, electricity generation capacity and supporting infrastructure, and very large electrolyser banks.

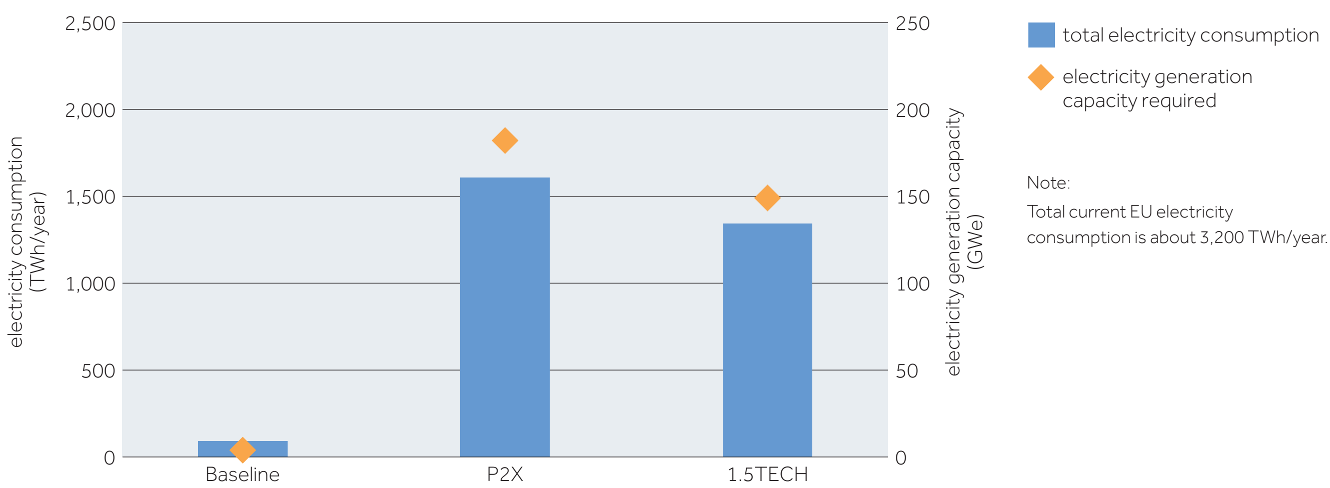
Energy consumption

Energy consumption is dominated by electricity required to produce hydrogen for the refinery and, overwhelmingly, for e-fuels manufacture. Electricity consumption for conventional refining, as in the Baseline case, is dwarfed by the demand for electricity required for e-fuels production in the other scenarios.

With low crude intake and the use of CO_2 capture, fossil site emissions are very low in the P2X scenario (about 5% of current emissions) and virtually eliminated in the 1.5TECH scenario. At the same time, potential emissions from fuel products are reduced as a result of the decreasing proportion of fossil material in their make-up.

As imported grid electricity is not assumed to be fully renewable, there is still a fossil component in the imported utilities.

Figure 5: Electricity consumption



Note:
Total current EU electricity consumption is about 3,200 TWh/year.

The main challenge

In the P2X scenario, electricity consumption would account for about half of today's total demand for electricity in the EU.

CO_2 emissions

Table 1 shows the breakdown of CO_2 emissions according to the refinery modelling conducted.

Table 1: CO_2 emissions breakdown (Mt/year)

	Baseline	PSX	1.5TECH
Total net from site Total (fossil + non-fossil) CO_2 emitted on site; can be negative where CO_2 is absorbed by e-fuels	60	-192	-69
Total from fuel products Total (fossil + non-fossil) potential CO_2 from all carbon in fuel products combustion (including exports)	842	784	506
Fossil from site Fossil CO_2 emitted on site: the fossil content of the actual emissions	46	5	1
Fossil from fuel products Potential CO_2 from fossil carbon in fuel products combustion (including exports)	825	552	222
Fossil from utility imports Fossil CO_2 emitted when generating imported electricity and gas	6	30	7
Percent reduction in direct CO_2 emissions vs 1990	62%	96%	99%

With low crude intake and the use of CO_2 capture, fossil site emissions are very low in the P2X scenario and virtually eliminated in the 1.5TECH scenario. At the same time, potential emissions from fuel products are reduced as a result of the decreasing proportion of fossil material in their make-up.

The direct (fossil from site) CO_2 emissions reduction (compared to 1990) in the EU refining system ranges from 62% in the Baseline to 96% (P2X) and 99% (1.5TECH). The P2X case achieves a greater reduction in CO_2 emissions from EU refineries (96%) than the claimed reduction across the whole EU economy (80%). The 1.5TECH case almost achieves net zero emissions in EU refineries, while a 100% reduction is claimed for the whole EU economy.

Investment estimate

Investment in production sites, which are dominated by e-fuels production, could range between G€250 and 400 for the whole EU refining system in the P2X and 1.5TECH scenarios.

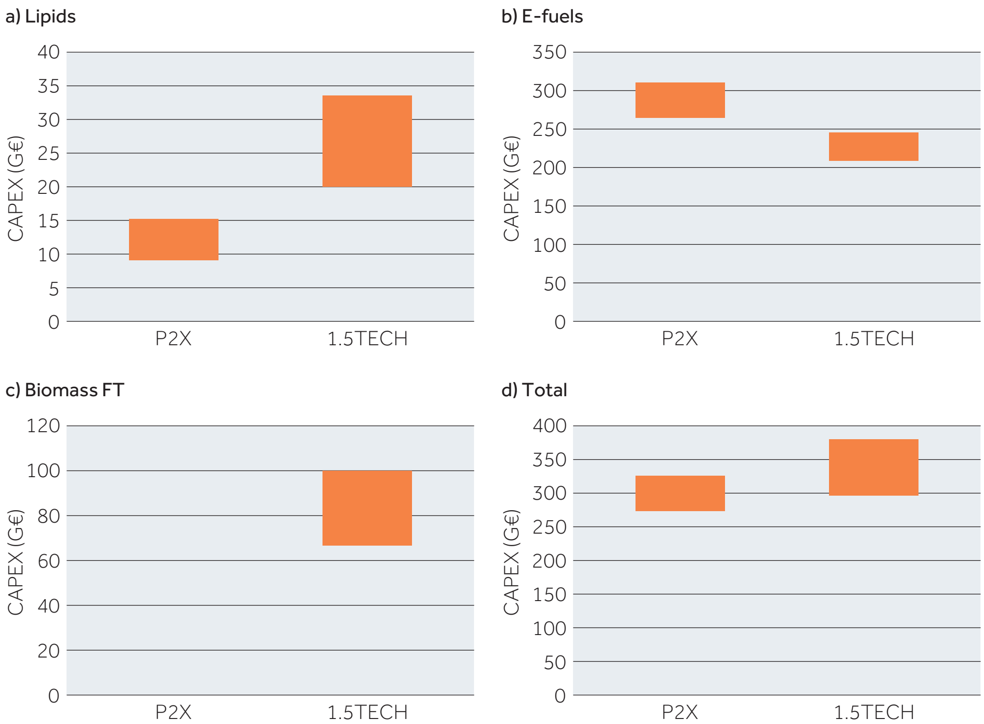
Introducing alternative feedstocks in the refinery environment at the scale discussed above would require investment in brand new plants for the front-end processing of these feedstocks, extensive modifications and revamping of existing plants for further processing and treating of the raw products, and extensive adaptation of ancillary facilities such as import terminals, tankage, etc.

An estimate of the CAPEX associated with the new processes has been undertaken, noting that the main investments required to implement the scenarios are related to the processing of lipids and biomass and, most importantly, to the massive production of e-fuels that is envisaged.

The CAPEX on electricity generation has not been included, nor has the CAPEX on the supply chain or additional investment derived from the repurposing/adaptation of existing refineries to accommodate the new technologies.

Based on the best estimate of the specific CAPEX ranges for such plants as discussed in Concawe's 'Refinery 2050' report,[3] Figure 6 shows the total investments that could be required.

Figure 6: Ranges of CAPEX associated with the development of new processes

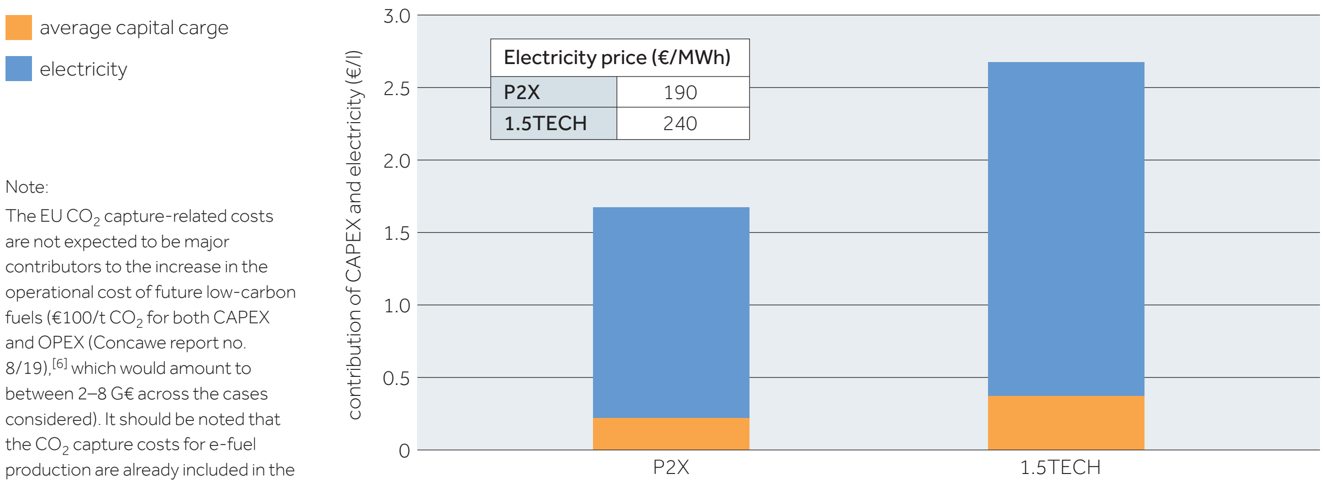


Basis	Capacity per unit (Mtoe/year)	CAPEX per plant (M€)	M€/kt/year product[a,b]
New HVO plants	0.5	275	0.55
Lignocellulosic	0.15	610–900	4.0–6.0
E-fuels	0.2	400–650	2.0–3.3[c]

[a] Capacities are expressed in terms of liquid product; toe/t factor=1 for liquid products.
[b] CAPEX data aligned with Concawe report no. 9/19.[3]
[c] Other new sources[5] are reporting lower CAPEX figures (below 3 M€/kt/year) than in Concawe report no. 9/19 (3.77–4.43 M€/kt/year).

CAPEX accounts for only a fraction of the costs involved. The main variable cost would be that of electricity. Figure 7 shows the contributions to the fuel unit cost in €/l, taking into account the annualised CAPEX (the average of the above figures plus a 15% capital charge) and electricity price in line with the EU Commission's forecast. The cost of the small amount of natural gas and other operating costs such as personnel, maintenance, etc. are not represented here, but they would be dwarfed by the very high cost of electricity.

Figure 7: Contribution of CAPEX (average capital charge) and electricity to fuel unit cost



Note:
The EU CO_2 capture-related costs are not expected to be major contributors to the increase in the operational cost of future low-carbon fuels (€100/t CO_2 for both CAPEX and OPEX (Concawe report no. 8/19),[6] which would amount to between 2–8 G€ across the cases considered). It should be noted that the CO_2 capture costs for e-fuel production are already included in the e-fuel related figures.

It is important to note that the Concawe study is a conceptual assessment and further implications in terms of the level of investment required across the whole refining system have not been assessed in detail.

Conclusions

This Concawe study highlights the risks associated with the selected scenarios defined in the EU Commission's report, *A Clean Planet for all*, which will add significant burdens to the EU refining system in 2050. Based on the information presented in this article, it can be seen that the materialisation of these scenarios could potentially lead the refining system to a point where meeting the defined demand (and fuel composition), as described in the EU Commission's report, would not be economically feasible for the refining system in Europe, and could lead to refinery closures, with supply being met mainly by imports of fossil jet fuel into Europe from other regions of the world, with no benefit for climate change globally.

Although the combination of the alternative feedstock pathways has been modelled to occur simultaneously in the same refinery, different combinations of routes may be followed by individual refineries (depending on factors such as the proximity to a specific resource, geographic location, initial refining configuration, etc). All of this is subject to individual strategic plans and is out of the scope of this Concawe study.

This study cannot therefore be considered as a roadmap for the whole European refining system but as an initial exploration of the potential consequences at macro-level to provide the basis for engagement in a more detailed technical debate on the subject with the European Commission.

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JEC Well-to-Wheels study version 5: a look into the carbon intensity of different fuel/powertrain combinations in 2030

Version 5 of the JEC evaluation of well-to-wheels energy use and greenhouse gas emissions for a range of potential future fuel and powertrain options has now been completed. Full details are available online via the JEC consortium website at https://ec.europa.eu/jrc/en/jec. This article provides an overview of the JEC study.

Introduction

The JEC consortium is a long-standing collaboration between the European Commission's Joint Research Centre (JRC), EUCAR (European Council for Automotive R&D) and Concawe.

The overall objective of this collaboration is to:

- evaluate the energy and greenhouse gas (GHG) emissions associated with powertrains and fuel quality, and the interaction between them;
- conduct coordinated research on the evaluation of the relative performance of future powertrains and fuels; and
- support the sustainability of European fuel- and vehicle-related industries, and to provide the European Union (EU) with scientific facts for policy support.

The consortium periodically updates their joint evaluation of well-to-wheels (WTW) energy use and (GHG) emissions, for a wide range of potential future powertrains and fuels options, within the European context. The JEC WTW reports and methodology have become a scientific basis for the European energy and transport research landscape. The objectives of the WTW study are to:

- establish, in a transparent and objective manner, a consensual well-to-wheels energy demand and GHG emissions assessment of the substitution of a wide range of automotive fuels and powertrains in 2030 and beyond in Europe;
- consider the viability of each fuel pathway and estimate the associated macro-economic costs; and
- have the outcome accepted as a reference by all relevant stakeholders.

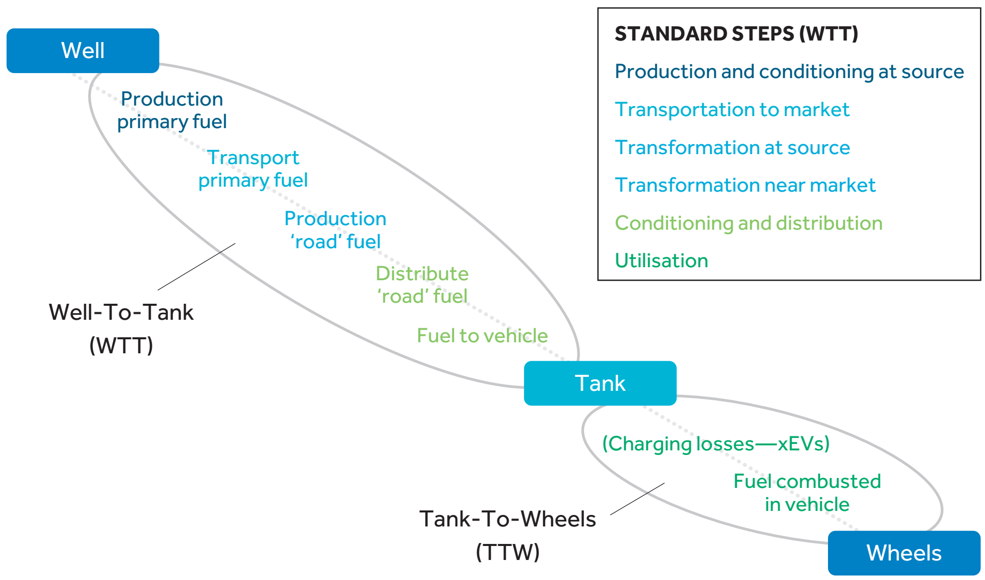
The WTW modelling of vehicles consists of three main parts (see Figure 1 on page 27):

1. A well-to-tank (WTT) analysis[1] which accounts for the energy and GHG emissions associated with the supply of energy carriers.
2. A tank-to-wheels (TTW) analysis[2,3] which accounts for the energy conversion and the associated GHG emissions while the vehicle is in use.
3. A well-to-wheels (WTW) report[4] which integrates the whole process of fuel production and consumption.

The integration of WTT and WTW data is led by Concawe/JRC, while the TTW modelling is conducted by EUCAR. The methodologies and findings are presented in the three main reports (each complemented by a series of appendices), representing the WTT, TTW and the WTW integration of the vehicle/fuel combinations.

More information regarding the consortium and previous publications can be downloaded from: https://ec.europa.eu/jrc/en/jec

Figure 1: System boundary of the JEC WTW analysis (energy expended and CO_2eq)



Note:
The WTW analysis differs from a life-cycle analysis (LCA) as it does not consider the energy and emissions involved in building facilities and vehicles, or the end-of-life aspects.

Well-to-tank (WTT)

Pathways

Scope

The WTT study aims to provide a detailed evaluation of the expended energy—and associated CO_2 emissions—related to the whole supply chain for fuel production. The main objective of the study report is to assist the readers and guide stakeholders in answering questions about:

- possible alternative pathways to produce a certain fuel, and which of these pathways offer the best performance in terms of energy use and GHG emissions; and
- initial prospects on alternative uses for a given resource, looking at how it can best be utilised to produce the final fuel, in terms of both the energy requirement and GHG emissions.

The JEC WTT v5 study assesses the incremental emissions (marginal approach) associated with the production of a unit of alternative fuel, with respect to the current status of production (Section 2.3 in the WTT report). This marginal approach has been chosen as it is instrumental in:

- guiding judgements on the potential benefits of substituting conventional fuels/vehicles with a specific alternative; and
- helping to understand where the additional energy resources would come from for future fuels.

JEC Well-to-Wheels study version 5: a look into the carbon intensity of different fuel/powertrain combinations in 2030

The WTT study encompasses different fuel categories, such as fossil-derived fuels, biofuels from vegetable oil, and various gaseous fuel productions, etc. The WTT report comprises 9 Excel workbook models, structured per energy carrier categories, namely oil, natural gas, biogas, ethanol, biodiesel, hydro-treated vegetable oils (HVO), synthetic fuels, hydrogen, electricity and heat. Within each fuel category, a wide number of potential pathways have been analysed, for example: ethanol produced from wheat, sugar beet, barley, etc.; and biodiesel obtained from different vegetable oils such as rapeseed, soy, sunflower, palm, etc.

The fuel matrix illustrated in Figure 2 illustrates the different possible feedstock-to-fuel pathway combinations.

Figure 2: Well-to-wheels resource-to-fuels pathways (Version 5)

Notes:

1 With/without CCS
2 Biogas
3 Associated with natural gas production
4 EU and US sources
5 Heavy fuel oil
6 Heating oil/diesel
7 Bio-SNG or bio-LNG
8 Forestry residue
9 Black liquor pathway included
10 Via isobutylene and ethanol from sugar beet via the process described by Global Bioenergies

Resource		Fuel: Gasoline, diesel (2017 quality)	Gasoline E10 / gasoline high octane	Synthetic gasoline (pyrolysis-based naphtha)	Diesel B7 (2017 market blend)	Synthetic gasoline	Synthetic diesel	Synthetic diesel (pyrolysis-based diesel)	DME	OME	Ethanol	Methanol	MTBE/ETBE	ED95	Pure vegetable oil	FAME / FAEE	HVO	CNG	CBG	SNG	LNG	LPG	Hydrogen (compressed, liquid)	Electricity	Heat
Crude oil		X[1]	X[1]																				X[5]		X[6]
Coal							X		X			X											X	X	
Natural gas	Piped						X		X	X		X						X					X[1]	X	
Natural gas	Remote						X[1]		X[1]			X						X[1]			X[1]		X	X	
Shale gas																		X							
LPG	Remote[3]												X									X			
Biomass	Sugar beet										X		X[10]												
Biomass	Wheat										X		X	X											
Biomass	Barley/rye										X														
Biomass	Maize (corn)										X[4]							X[2]			X[2]			X[2]	
Biomass	Wheat straw										X			X											
Biomass	Sugar cane										X														
Biomass	Rapeseed															X	X								
Biomass	Sunflower															X	X								
Biomass	Soy beans															X	X								
Biomass	Palm fruit															X	X								
Biomass	Double cropping																	X[2]			X[2]				
Biomass	Wood waste[8]			X			X[9]	X[1]	X[9]	X	X	X[9]								X[7]	X[7]		X[9]	X[9]	X
Biomass	Farmed wood (poplar)			X			X	X[1]	X	X	X	X								X[7]	X[7]		X	X	X
Biomass	Waste vegetable oils															X	X								
Biomass	Tallow															X	X								
Biomass	Palm oil mill effluent																X								
Biomass	Municipal organic waste																		X[2]					X	X
Biomass	Manure																		X[2]		X[2]			X	X
Biomass	Sewage sludge																		X[2]		X[2]				
Renewable electricity (wind)							X			X										X	X		X	X	
Nuclear																							X	X	
Electricity mix																							X	X	

In the WTW v5 report, the energy expended and the GHG results are summarised as interactive pivot charts (in addition to the traditional summary charts used previously in version 4) for all the pathways in each workbook/fuel category, to improve readability for users.

Major updates versus WTT v4

The updated WTT report now includes the following:

- **252 energy carrier pathways** in total (including heat and power in Appendix 4). Energy consumption and GHG emissions data for almost all of the pathways included in version 4 have been updated based on recent literature reviews or new available data sources (e.g. for conventional fuels, the energy and GHG data for crude oil extraction and refining have been updated according to the recent data). The energy use and GHG emissions of all the biofuel pathways have changed significantly compared to version 4, because the latest version implements the basic assumptions outlined in the Renewable Energy Directive (RED II), or forestry residue collection, short rotation forestry, wood chips storage (seasoning), biomass transport, and transport and distribution data for the final fuels. Among many other changes, these are the most significant/apparent compared to version 4.
- **78 new pathways** (in addition to those in v4) have been added to better represent the current state-of-the-art technologies in the fuel sector. Some of the new pathways represent additional features in the existing fuel production facilities (e.g. carbon capture and storage (CCS) in gasoline production, high-octane petrol, etc.), while others represent novel feedstock and innovative production technologies (e.g. sugar beet-based ETBE, synthetic fuels from waste and farmed wood, biogas to hydrogen, etc.). Also included is a new section on power-to-fuels. Additionally, the report investigates the possibilities for using high-octane gasoline for higher energy efficiency in conventional petrol vehicles. Therefore, three types of high research octane number (RON) gasoline (RON 100, RON 102/E5eq and RON102/E10eq) pathways have been included.
- **54 synthetic fuel pathways** are now available in version 5, of which 35 are new. Among the synthetic fuels, two new subcategories have been added: pyrolysis fuels and oxy-methylene dimethyl ether (OME). In addition, the production of synthetic methane, methanol and dimethyl ether (DME) from renewable electricity is now also included. Furthermore, ethanol-based ED95 fuel pathways for diesel-like engines (modelled as a mixture of ethanol, lubricants, i-butanol, polyethylene glycol, etc.) is another interesting addition to version 5. Considering that some production pathways are technologically and commercially more mature than others, the technology readiness level (TRL) and market/commercial readiness level (CRL) have been introduced to complement the analysis and to support the readership in making their potential evaluations. The TRL ranges from 1–9, indicating a spectrum from research, development, demonstration and deployment, while the CRL ranges from 1–6, indicating the status of the various pathways from pilot scale to competitive commercial scale in the market.
- Another important update addresses the different blends of biofuels and the market mix (and availability) of different pathways in each biofuel category. A detailed description, based on different sources, of the current scenario and the predictions for the 2030 market mix of ethanol, biodiesel and HVO are also included.

It is demonstrated throughout the JEC WTT v5 report that the variability among more than 250 different pathways modelled is significant in terms of the WTT energy expended and the GHG emissions when compared with conventional fuels. Factors such as the conversion pathways chosen and the feedstock/resource used have a strong impact on the final results. A specific comparison section has been introduced, which summarises the detailed results by way of:

a) a fuel comparison, which aims to show the WTT energy expended and the level of GHG emissions per type of fuel (e.g. fossil, CNG, DME, etc.), including the range (min/max) and a representative pathway for each of the conversion routes modelled; and
b) a resource-to-fuels comparison, which enables a comparison of the impacts of using different feedstock/resource options to produce a specific fuel.

The most 'representative' pathways have been selected, mainly on the basis of techno-economical evaluations in line with RED II criteria. These representative pathways are used for the JEC WTW integration (more details on the selection criteria are presented in Section 5 of the JEC WTT v5 report, *Comparative analysis*, and also in Appendix 1). Figure 3 on page 31 of this article shows an example of one of the comparisons made among the JEC WTT v5 values (energy expended and GHG emissions) for the selected fuel production pathways presented in the report.

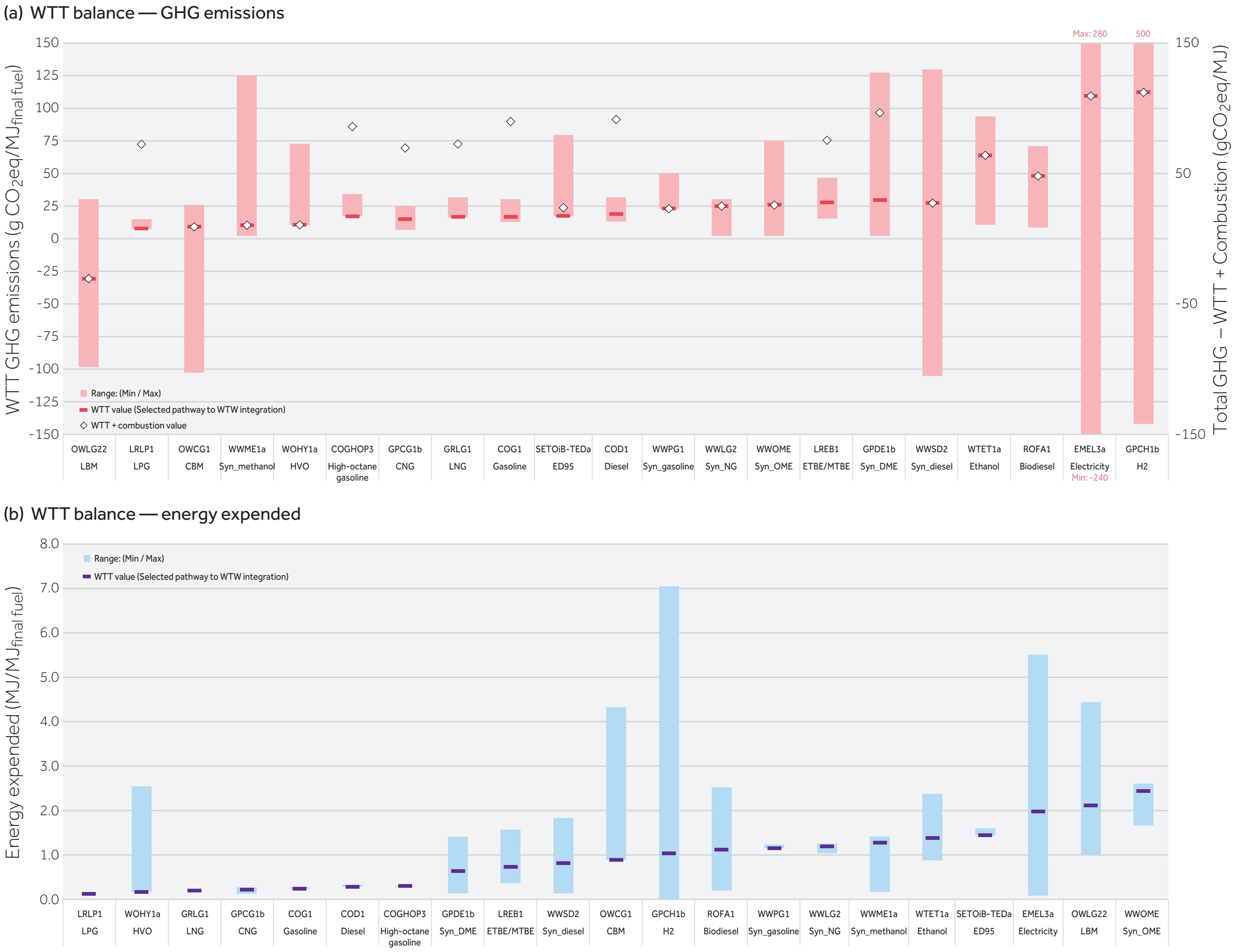
Analysing the results allows the following general conclusions to be drawn:

- In terms of WTT energy required for fuel supply, among fossil-based fuels, the representative pathways for LPG, LNG and CNG are more energy efficient than conventional crude oil-based pathways.
- Among the representative pathways with high energy input, the most energy-intensive WTT pathways result from the use of electricity (when the EU mix is considered), liquefied bio-methane (LBM) and synthetic OME.
- A number of pathways offer the possibility of achieving negative WTT emissions, e.g. LBM/CBM (liquefied bio-methane/compressed bio-methane) as well as electricity and hydrogen when produced from biogas due to the avoided CH_4 and N_2O emissions,[1] and the production of synthetic diesel from biomass when coupled with CCS processes (a portion of CO_2 absorbed from the crops is not released but permanently stored in underground geologic formations — see Section 3.5 of the JEC WTT v5 report).

  It is important to point out that, for biomethane, negative emissions are the result of a reduction in GHG emissions compared to a reference use (e.g. avoided CH_4 emissions). In the case of bio-CCS, if CO_2 is permanently sequestered, that pathway is actually increasing the carbon-sink and is actively removing carbon from the atmosphere. (Both pathways actively mitigate climate change, but one is reducing emissions, the other is increasing a sink.)
- It is worth noting that the wide variability observed in some pathways, such as for HVO, compressed/liquefied biomethane (CBM/LBM), H_2 and electricity, is heavily dependent on the conversion route/feedstock chosen, which has a significant impact on the final expended energy and GHG emissions.

[1] It should be noted that the negative GHG emissions for biomethane from manure can only be taken into account as long as there are farms where the storage of untreated manure is in use.

Figure 3: Comparison of WTT values (energy expended and GHG emissions) for some of the selected fuel production pathways



Notes:

1. For each fuel, the bar represents the minimum and maximum values from the pathways modelled in the JEC WTT v5 study. Within the range, the thick line represents the pathway selected as representative of the specific fuel (the codes used in the JEC WTT v5 report are included on the Figure for reference).
2. The figures included in the WTT v5 report reflect the net energy requirement and related emissions required for the production of 1 MJ of fuel (see Section 2.9.4 of the report). In the case of bio-based feedstocks, the bio-credits will have been taken into consideration in the WTW calculations (where the impact of the combustion of the fuel in a specific engine is assessed).
3. Due to the consequential nature of the LCA approach applied, and in accordance with the goal and scope of the JEC WTT v5 report, the values shall not be used in an attributional LCA context.
4. The report includes representative pathways/routes, but additional technologies (not included in v5) are already in development. Therefore, the comparison of various WTT routes has been conducted among the modelled JEC pathways which differ depending on the types of fuels and the routes to produce them. For example, whereas an extensive range of primary energy sources for some fuels/energy carriers (e.g. electricity, hydrogen) have been considered, for others, only some initial examples of potential sources/pathways have been chosen for illustrative purposes (e.g. DME). This issue should be factored in when comparing the range of variation for different fuels.
5. In the case of electricity, negative GHG emissions occur for electricity produced from biogas derived from liquid manure due to credits for avoided CH_4 and N_2O emissions from avoided storage of untreated liquid manure.

- Additionally, it is important to highlight that general conclusions about the most favourable routes, both in terms of GHG emissions and energy consumption minimisation, can be derived only when the whole WTW analysis is taken into account, as the powertrain efficiency has a strong impact on the results (expressed in terms of g CO_2eq/km, including the efficiency of the different powertrains). As an initial approximation, total GHG emissions, including from combustion, are included in the fuel-specific chart in the JEC WTT v5 report.
- Within each of the following categories, the following observations can be made when the WTT energy and GHG emissions are compared:
  - **Fossil:** a number of 'representative' fossil-based pathways such as CNG/LNG or high-octane gasoline can offer lower GHG emission routes than conventional gasoline and diesel, while lower energy intensities are reached mainly by the gaseous fossil fuels. One reason for the slightly lower GHG emissions for high-octane gasoline is the admixture of bio-components.
  - **Crop-derived fuels:** the newly added bio-ETBE route involving ethanol and isobutene from sugar beet shows interestingly low GHG emissions when compared to ethanol from sources other than sugar beet (wheat except WTET4a/b, barley, and corn) or HVO/biodiesel routes, albeit with higher energy consumption. Compared to the associated ethanol pathway, the GHG emissions for the ETBE route are higher.
  - **Wood:** selected pathways for synthetic diesel, DME and hydrogen are the ones with the potentially lowest WTT GHG emissions.[2] Negative emissions can be achieved in pathways implementing CCS.
  - **Biogas:** biogas from manure used as a feedstock for hydrogen production shows promisingly lower WTT emissions than CBM or LBM pathways, but with significantly higher energy requirements. Significant negative emissions can be derived from routes involving biogas from manure due to the avoided CH_4 emissions. This is the reason why biogas-to-hydrogen routes involving biogas from manure show lower WTT GHG emissions than the CBM and LBM pathways, although the energy requirement is higher. It is important to note that this substitution approach is valid under the current assumption that the methane would be released to the atmosphere if not used as fuel. Alternative technologies could also reduce the fugitive methane emissions and, thus, for comparison with such a case, the current pathway calculations would have to be adjusted accordingly.
  - **Electricity and H_2:** it is worth noting that electricity and hydrogen should primarily be considered as energy carriers, with environmental performances determined by the primary source used for their production. More precisely, the GHG emissions savings achieved through the use of electrical energy in the transport sector are determined by the pathway used for producing the power. At least for the transitional phase towards road electrification when power for vehicles is taken from the grid, this can lead either to an increase or a reduction in emissions compared to the baseline, depending on the electricity source used for that purpose (which is out of the scope of the JEC study). If the system reacts to this increased demand by increasing the production from fossil sources (e.g. coal), the effect might be an increase in overall GHG emissions. On the other hand, a

[2] Impacts on forest C-stocks and sinks are not included in this analysis.

substantial uptake of electrical energy for the road sector may act as a driver for increasing the share of renewable energies in the EU mix. These issues are country specific and time specific (as production is a non-steady process by definition) and, as mentioned, considerations such as these are not included in the JEC WTW v5 study. For this reason, the improvements in countries' electricity mixes can only be used as a proxy for deriving a back-of-the-envelope evaluation.

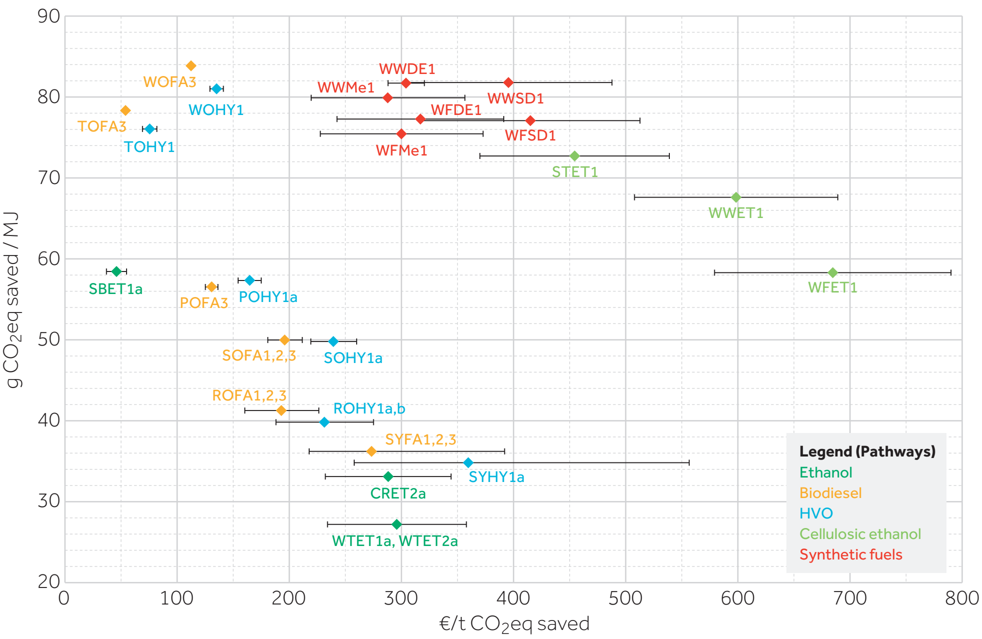
- **E-fuels:** as e-fuels production is based on renewable electricity, the above-mentioned considerations can be extended to these cases. As detailed in Section 3.9 of the WTW v5 report, this route is an example of carbon capture and utilisation (CCU) in a highly energy- and capital-intensive process with high CO_2 abatement potential versus their equivalent fossil-based fuels.

Cost analysis

The production cost for sustainable biofuels and alternative fuels is an interesting research topic, as this eventually impacts on the cost of their potential GHG saving, in terms of €/kg CO_2eq. A specific section of the JEC WTT v5 report is devoted to the analysis and quantification of the production costs—and therefore the costs of GHG savings—for the main conventional and advanced biofuels produced in Europe in the 2014–2016 time frame (see Figure 4). This assessment includes scenarios for 2030, assuming various crude oil prices.

The method used to perform the cost estimation was based on the same principles applied to the JEC WTW v2 (2007) report, with the focus being limited to the 'well-to-tank' part of the fuel production process. The market values of the commodity prices, the costs for plants, and the equipment required have been evaluated for EU-based fuel production.

Figure 4: Results of the comparison between costs and g CO_2eq saved for different sustainable biofuel routes



Notes:

Synthetic fuels included in the WTW integration refer to BTL (biomass-to-liquids) pathways, not to e-fuels which are referred to as power-to-fuels in the context of the JEC WTT v5 report.

The total production costs are calculated as the sum of the capital costs (CAPEX), the cost of feedstocks, and the operational costs (OPEX). A capital charge rate of 12% has been used, representing a return on investment of about 8% without accounting for a profit tax, which returns to the EU. A 20% uncertainty range on the capital investment was also applied.

Tank-to-wheels (TTW)

The tank-to-wheels (TTW) analysis is one of the pillars of the well-to-wheels study, and aims to model the impacts of different fuels and energy carriers when used in current and future state-of-the-art automotive powertrains.

The TTW v5 study covers two different time frames, evaluating both current technologies (NEDC testing cycle) and future technological developments from 2025+ (WLTP testing cycle) to give an outlook on technology sector trends. Version 5 goes beyond the initial scope of the previous version, which focused only on passenger cars, by extending the analysis to include heavy-duty vehicles. The main results presented in the TTW-related reports, covering both passenger and heavy-duty vehicles, are presented below.

Passenger cars

For the passenger cars calculations, a common vehicle platform representing the most widespread European segment of passenger vehicles (C-segment compact 5-seater European sedan) was used.

Conventional powertrains utilise internal combustion engine (ICE) technologies including direct injection spark ignition (DISI) (e.g. Otto cycle engine), and direct injection compression ignition (DICI) (e.g. as used in a diesel engine). The electrification of conventional powertrains is covered in terms of a 48-volt mild hybrid electric vehicle (MHEV), a hybrid electric vehicle (HEV), a plug-In hybrid electric vehicle (PHEV) and a range extender electric vehicle (REEV). The 48-volt MHEV, which is only considered for 2025+, in principle shows the same functionality as the HEV, but represents a simpler approach compared to the dedicated HEV technology. Additionally, pure electric powertrains such as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are also investigated.

Figure 5 on page 35 presents a matrix of fuel-powertrain combinations investigated in the TTW (v5) study; some of the variants were modelled in powertrain simulation in detail, while some others were derived from them based on their fuel properties. All variants are considered for both 2015 and 2025+ except for MHEV and REEV DICI which are considered for 2025+ only. BEVs in 2025+ are defined in two different driving range variants.

All results are summarized in Figure 6 on page 36, in terms of emissions of CO_2eq and energy consumption for 2015 (NEDC) and 2025+ (WLTP) variants.

Figure 5: Automotive fuels and powertrain combinations for passenger cars

2015 powertrain variants

EUCAR v5: 2015 investigation matrix	DISI	DICI	Hybrid DISI	Hybrid DICI	PHEV50 DISI	REEV100 SI	PHEV50 DICI	BEV150	FCEV	PHEV50 FC	REEV100 FC
Gasoline (E5)	■		■		■	■					
Gasoline E10 market blend	■		■		■	■					
Gasoline high RON (var. 1)	■		■		■	■					
Gasoline high RON (Var. 2)	■		■		■	■					
Diesel (B0)		■		■			■				
Diesel B7 market blend		■		■			■				
LPG	■										
CNG	■										
E100	■		■		■	■					
FAME (B100)		■		■			■				
DME		■		■			■				
FT diesel*		■		■			■				
HVO*		■		■			■				
Electricity					■	■	■	■		■	■
Hydrogen (CGH_2)									■	■	■

2025+ powertrain variants

EUCAR v5: 2025+ investigation matrix	DISI	DISI MHEV	DICI	DICI MHEV	Hybrid DISI	Hybrid DICI	PHEV100 DISI	REEV200 SI	PHEV100 DICI	REEV200 DICI	BEV200	BEV400	FCEV	PHEV100 FC	REEV200 FC
Gasoline (E5)	■	■			■		■	■							
Gasoline E10 market blend	■	■			■		■	■							
Gasoline high RON (var. 1)	■	■			■		■	■							
Gasoline high RON (Var. 2)	■	■			■		■	■							
Diesel (B0)			■	■		■			■	■					
Diesel B7 market blend			■	■		■			■	■					
LPG	■	■													
CNG	■	■													
E100	■	■			■		■	■							
FAME (B100)			■	■		■			■	■					
DME			■	■		■			■	■					
FT diesel*			■	■		■			■	■					
HVO*			■	■		■			■	■					
Electricity							■	■	■	■	■	■		■	■
Hydrogen (CGH_2)													■	■	■

* EN15940 synthetic diesel standard to allow optimised engines.

Notes:

All conventional variants (DISI and DICI) are equipped with a 55-litre standard size fuel tank for 2015. This is reduced to a 35-litre fuel tank for 2025+ to ensure a comparable driving range for the more efficient future powertrains.

All HEV, PHEV and REEV (gasoline only) variants are equipped with a 55-litre standard size fuel tank for 2015. For 2025+, to ensure a comparable driving range for the more efficient future powertrains, this is reduced to a 35-litre fuel tank for MHEV and HEV, and further reduced to a 28-litre fuel tank for PHEV and a 21-litre fuel tank for REEV.

Hydrogen fuel tank systems represent compressed gaseous hydrogen (CGH_2) technology. In both 2015 and 2025+, the fuel tank capacity is assumed to be 4 kg, which gives a driving distance well above the 500 km minimum criterion. All FC variants are simulated based on a generic tank system of 90 kg. Battery capacities are 30, 50 and 90 kWh for HEV, PHEV and BEV respectively. The complete vehicle specifications can be found in Section 3.2.1 of the JEC TTW v5 report.

BEV range: 150 km (2015); 2 variants, 200 km and 400 km (2025+).

PHEV EV range: 50 km (2015); 100 km (2025+).

REEV EV range: 100 km (2015); 200 km (2025+).

BEV: Battery electric vehicle

CNG: Compressed natural gas

DISI: Direct injection spark ignition

DICI: Direct injection compression ignition

DME: Dimethyl ether

FAME: Biodiesel (B100)

FCEV: Fuel cell electric vehicle

FT-Diesel: Paraffinic diesel (EN15940)

HEV: Hybrid electric vehicle

HVO: Hydro-treated vegetable oil

LPG: Liquefied petroleum gas

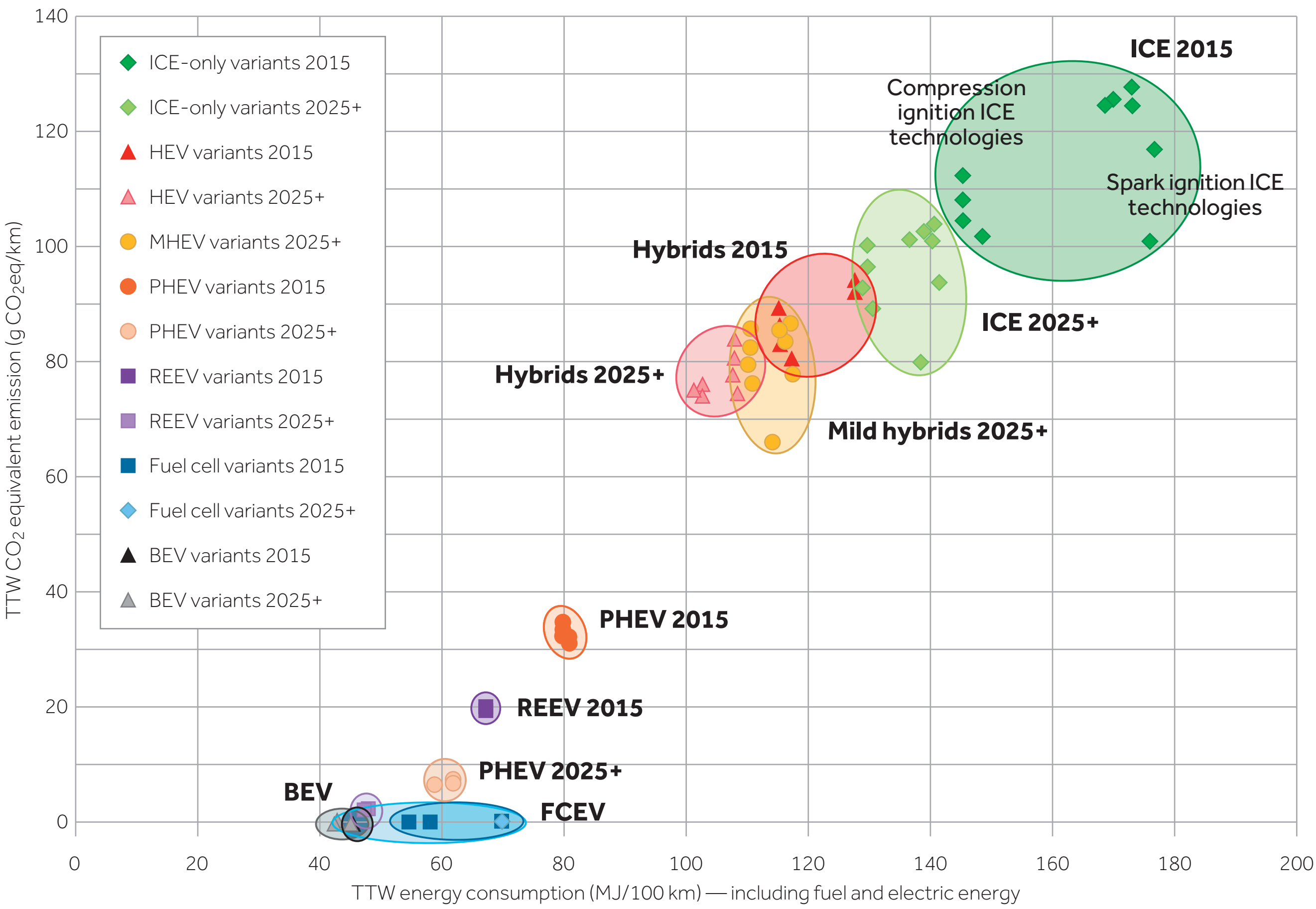
MHEV: Mild hybrid electric vehicle (48 V)

PHEV: Plug-in hybrid electric vehicle

REEV: Range extender electric vehicle

JEC Well-to-Wheels study version 5:
a look into the carbon intensity of different
fuel/powertrain combinations in 2030

Figure 6: Summary of TTW simulation results for 2015 (NEDC) and 2025+ (WLTP) variants



It is worth noting the following with regard to the passenger cars analysis:

- Due to improvements in future powertrain technologies, as well as improvements in fuel quality, ICE powered vehicles will continue to deliver TTW GHG emissions reductions and energy savings compared to the 2015 baseline. Future diesel-type engines will maintain their energy efficiency benefits.
- Hybridisation (mild (48 volt) and full hybrids) will deliver additional reductions in both domains (gasoline and diesel).
- Additional reductions in GHG emissions and energy consumption can be achieved with deeper electrification, i.e. with PHEV and REEV, as well as with FCEV and BEV powertrains. However, the main differentiator between PHEV and REEV is battery size rather than ICE integration.

Heavy-duty vehicles (HDVs)

For the freight sector, two main HDV configurations have been analysed:

- Rigid truck with 18 tonnes gross vehicle mass rating (GVMR), designed for regional delivery missions ('group 4 vehicle').[3]
- Tractor-semitrailer combination with 40 tonnes GVMR, designed for use in long haul missions ('group 5 vehicle').[3]

All vehicle concepts considered have been analysed for the model years 2016 and 2025, whereby 2016 models represent the state-of-the-art on the European market. Vehicle specifications for 2025+ are based on a technology assessment of future improvements. For xEV concepts, it is not possible to identify typical vehicle configurations as these systems are new technologies that are currently under development for HDVs. As a consequence, xEV vehicle specifications and related results as elaborated in the study are theoretical examples only for these new technologies.

The HDV configurations analysed are either a conventional ICE or an electrified propulsion system (xEV). ICE configurations incorporate several technologies including direct injection compression ignition (CI), port injection positive ignition (PI), and LNG high pressure direct injection compression ignition (HPDI). For CI engines the fuels considered were diesel B0, B7 and B100 (FAME) as well as DME, ED95, OME and paraffinic diesel. For PI engines, CNG and LNG fuels were analysed. The electrified propulsion systems include hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), catenary electric vehicles (CEVs), and hydrogen fuel cell electric vehicles (FCEVs). Figure 7 shows a summary of the simulated fuel and powertrain combinations.

Figure 7: Investigated fuel and powertrain configurations and simulated vehicle groups

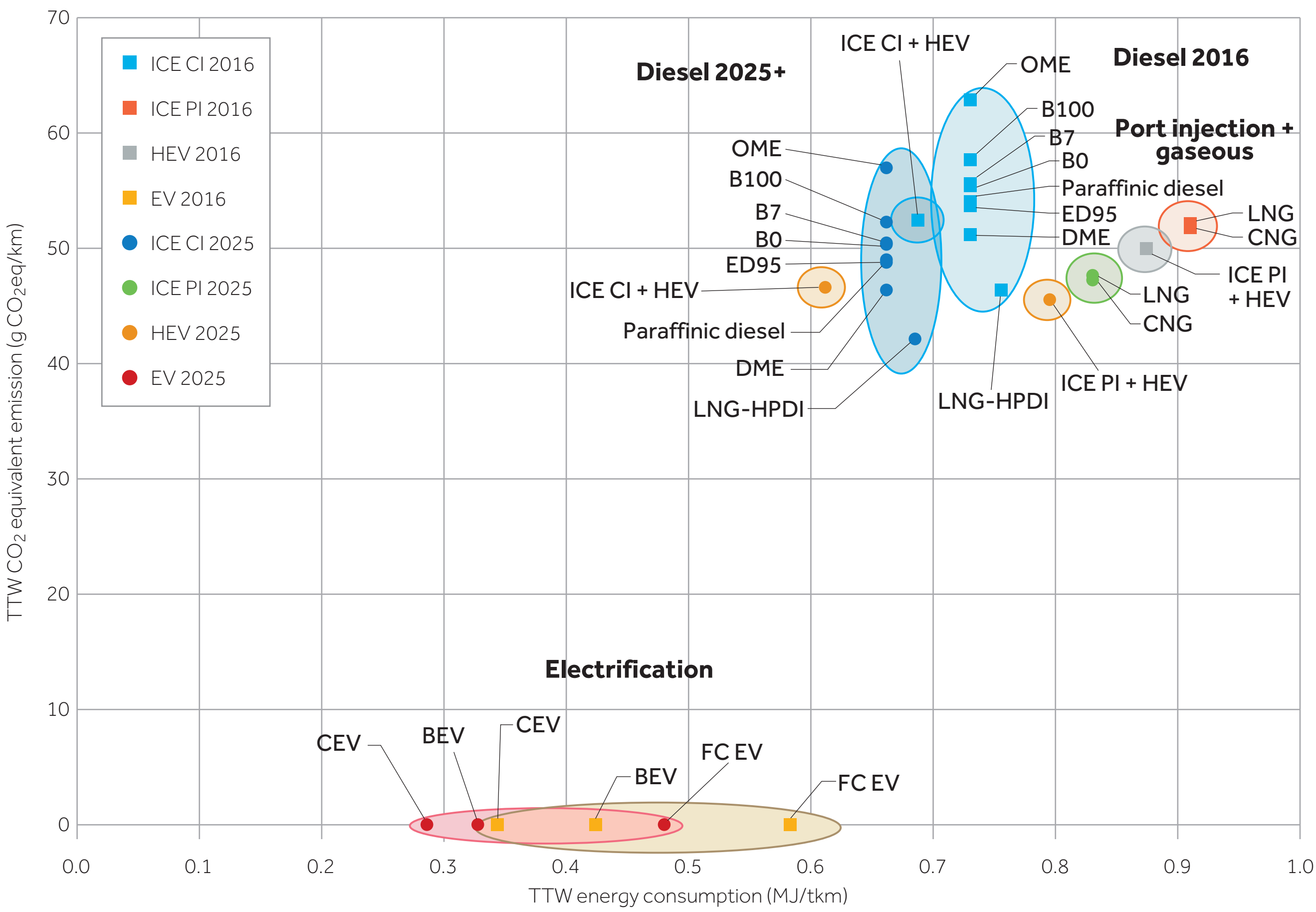
Fuel \ Powertrain	ICE CI	ICE PI	ICE CI + HEV	ICE PI + HEV	BEV	FC-EV	CEV
Diesel B0	4, 5						
Diesel B7 market blend	4, 5		4, 5				
DME	4, 5						
ED95	4, 5						
Electricity					4, 5		4, 5
FAME (B100)	4, 5						
Paraffinic diesel	4, 5						
H-CNG		4, 5		4			
Hydrogen						4, 5	
LNG (EU mix)	4, 5	4, 5		5			
OME	4, 5						

Note:
Configurations highlighted in blue were simulated for both group 4 and group 5 vehicle categories; the green configuration was simulated for a group 4 vehicle only, and the red configuration for a group 5 vehicle only.

[3] Labelling of vehicles by 'group' refers to the method applied in the European Regulation for CO_2 certification of heavy-duty vehicles [5]

As an example of what can be derived from the report, Figure 8 provides a summary of the results of the transport-specific figures (i.e. per tonne-kilometre) for energy consumption and TTW CO_2eq emissions for the group 5 vehicle category (long haul).

Figure 8: Summary results for the group 5 vehicle category (long haul)



Notes:
Group 5 vehicle category. VECTO long-haul cycle. Weighted payload: 13,064 kg for BEV 2016; 14,290 kg for all others.
Analysed propulsion systems vary with regard to performance criteria such as operating range, payload capacity and refuelling time.

Analysing the results of the JEC TTW v5 study enables the following observations to be made:

TTW energy consumption

- Vehicles with single-fuel positive ignition (PI) natural gas (NG) engines have 20–25% higher energy consumption compared to vehicles using conventional diesel technology.
- The energy consumption of dual-fuelled (LNG-diesel) HPDI vehicles is very close to that of conventional diesel technology.
- Of the different configurations of electric components analysed in this study, HEVs have a 5% energetic advantage in long-haul applications and a 5–10% energetic advantage in regional delivery missions compared to their ICE-only counterparts. Higher energy saving potentials can therefore be expected by hybridisation for urban delivery missions.
- For the analysed xEV concepts, CEVs[4] ('electric road') were found to have the lowest TTW energy consumption (around -50% to -60% compared to conventional diesel technology) followed by BEVs (around -40% to -55% compared to conventional diesel technology). FCEVs were calculated to have 20–35% lower TTW energy consumption compared to a conventional diesel vehicle. Compared to BEV and CEV technology, the energy consumption of FCEVs also includes the energy losses in the fuel cell.

TTW CO_2 equivalent emissions

- The use of alternative fuels in diesel CI engines can change the TTW CO_2-equivalent emissions, compared to using market blend B7 diesel, from -8% (dimethyl ether, DME) to +13% (oxymethylene ether, OME) due to differences in the lower heating value (LHV)-specific carbon content of the fuel.
- Vehicles driven by PI engines using CNG or LNG have 5–10% lower TTW CO_2-equivalent emissions than conventional diesel engine technology. This mainly results from the fact that the energetic disadvantage is overcompensated by the lower energy-specific carbon content of NG (ca. -23% compared to B7).
- The TTW CO_2-equivalent emissions of dual-fuelled (LNG-diesel) HPDI vehicles are 15–20% lower than conventional diesel technology due to the high proportion of NG.
- For BEV, CEV and FCEV propulsion systems, the TTW CO_2-equivalent emissions are zero per definition.

It should be noted that, although the TTW v5 study provides a representative overview of the passenger and HDV vehicle sectors, the powertrains investigated in each case represent theoretical vehicle configurations only, and are not specific to any existing commercial vehicle or brand.

[4] Note that ~10% of additional losses in the overhead infrastructure would need to be considered (as a proxy), but these are currently not included in the JEC TTW v5 report.

WTW integration

Methodology and criteria

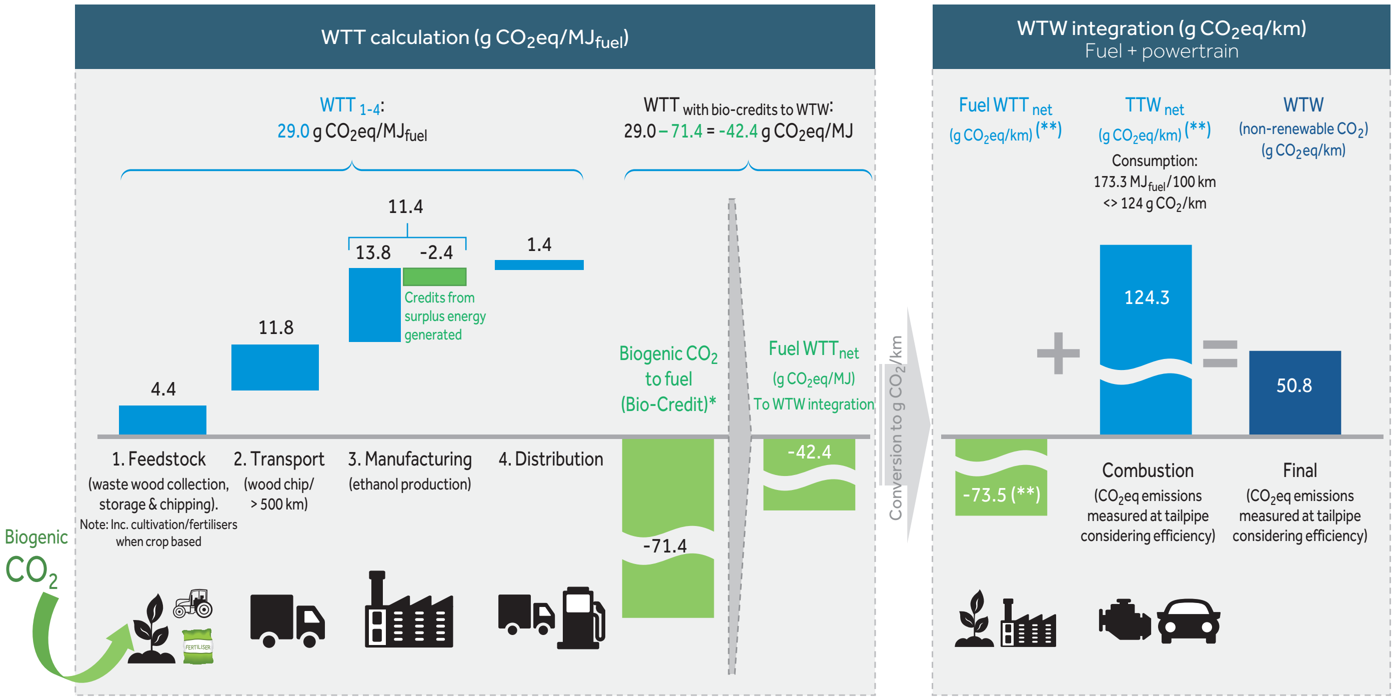
The WTW methodology integrates a selection of the fuels and vehicles from the WTT and TTW studies. These combinations enable calculations to be made in terms of MJ or g CO_2eq per kilometre distance travelled.

Due to the major revisions incorporated in the JEC v5 reports, both for the WTT analysis (more than 250 resource-to-fuel pathways modelled) and the TTW analysis (more than 60 powertrain combinations), the number of potential routes to be combined in the WTW analysis has increased considerably since version 4 of the report (i.e. there are now more than 1,500 possible combinations). This has led to the need for an appropriate way to present the results. Therefore, a number of WTT pathways have been selected to show the variability of the conversion routes, due to the different feedstocks and processes modelled, to enable a comparative analysis of the alternatives to be made.

In order to select the relevant WTW combinations, a series of criteria have been applied to filter the WTT pathways. A thorough analysis of the compliancy with RED II criteria has been used as one of the main guidelines. Some additional novel technologies, with lower TRL or CRL, have also been considered for the integration, to show their potential for reducing GHG emissions if deployed effectively in Europe. The selected WTT pathways have been combined with the relevant powertrain options to obtain the WTW results.

For illustrative purposes, Figure 9 on page 41 guides the reader through the link between the WTT calculations (production routes) and the integration with the TTW values. Using a selected example, the figure details the rationale behind the calculations included in the individual WTT spreadsheets and in the WTW integration file.

Figure 9: Simplified chart showing the steps towards the well-to-wheels CO_2-equivalent calculations
(the example used is a wood-based pathway (ethanol—WWET1b) + gasoline DISI technology, 2015)



(*) CO_2 released back to the atmosphere when 1 MJ of the fuel is totally combusted. Equivalent to the amount of CO_2 initially captured by the tree during the photosynthesis process (net zero effect).

(**) WTT fraction related to the amount of fuel consumed in a specific powertrain:
$WTT_{net\ to\ WTW}$ = -42.4 (g CO_2eq/MJ) x 173.3 MJ_{fuel}/100 km <> -73.5 g CO_2eq/km

Note: As detailed in Section 2.9.4 of the JEC WTT v5 report, the WTT figures reflect the net energy requirement and related emissions required for the production of 1 MJ of fuel (WTT_{1-4} in Figure 9). In the case of bio-based feedstocks, the bio-credits will be taken into consideration in the WTW calculations (where the impact of the combustion of the fuel in a specific engine is assessed).

Results

When the JEC WTT and TTW v5 results are combined, factors such as the conversion pathways chosen and the feedstock/resource used, together with the specific powertrain technology in the 2015/2025+ time frames, have a strong impact on the final results, which are expressed both in terms of energy expended (MJ/MJ_{fuel}) and GHG emissions (g CO_2eq/km). This new version of the study presents the outcome of the WTW integration in two different ways, as described on the following pages.

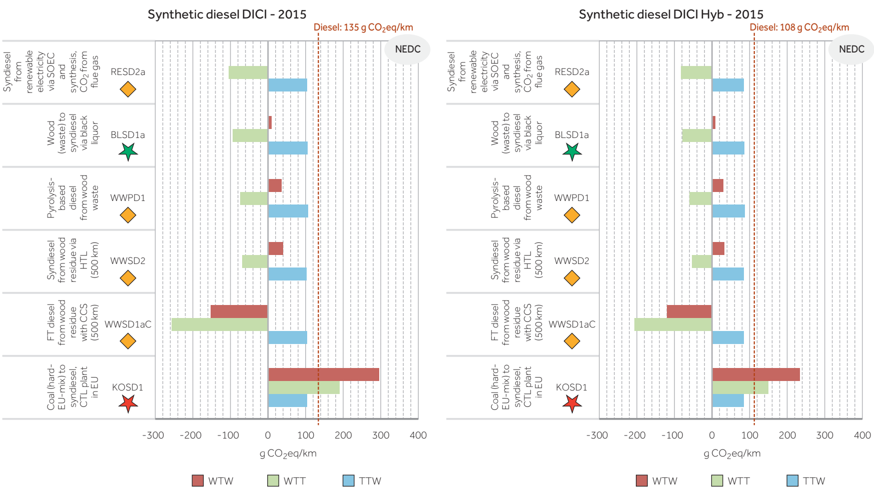
a) Detailed results

This section of the WTW report presents detailed results for each type of fuel/powertrain combination, expanding on the WTW GHG emissions and energy expended results, obtained by decoupling the contribution of both WTT and TTW elements (showing the variability for the selected WTT pathways and time horizons). The details are grouped as follows:

- ICEs — liquid fuels
- ICEs — gaseous fuels
- xEVs
- FCEVs

As an example, the BEV-related charts for passenger cars are shown in Figure 10 for both the 2015 and 2025+ time frames and for the different types of fuel/powertrain configurations explored.

Figure 10: Synthetic diesel — GHG emissions (g CO_2eq/km)

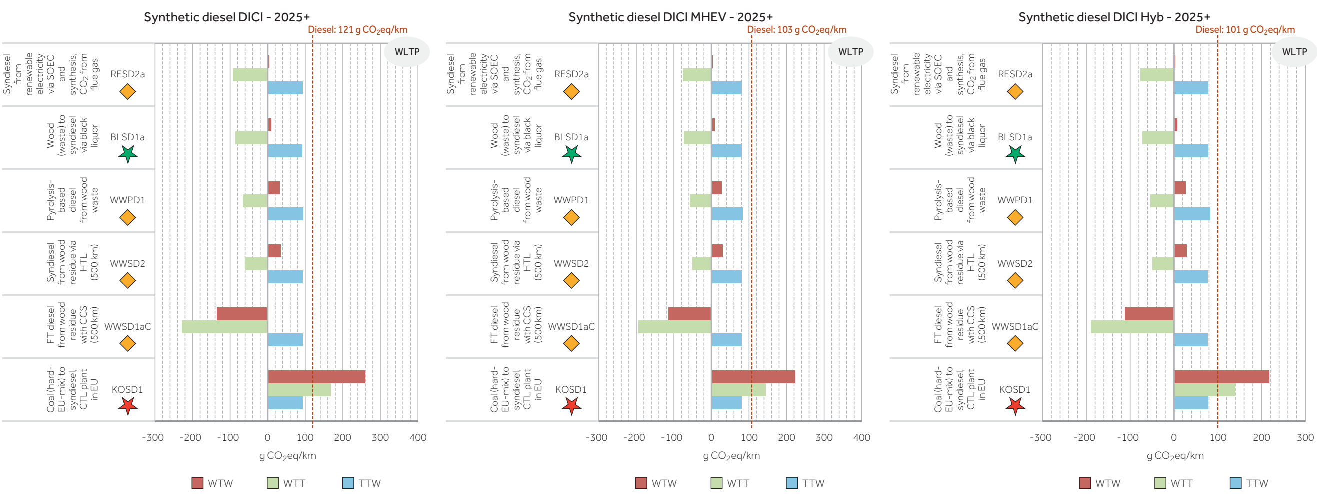


Being a synthetic mix of molecules optimised to result in very similar properties to regular fossil-derived product, **synthetic diesel** offers the advantage of being a drop-in fuel, easily usable in standard infrastructures, and powertrains.

GHG performances of synthetic diesel production and use are mainly determined by the primary source of energy used for its production (WTT). When produced from coal, synthetic diesel does not offer any advantages (even doubling the associated GHG emissions), if compared with regular fossil diesel.

Benefits can be achieved through the FT conversion process, using residual feedstocks such as waste wood, black liquor and pyrolysis oil derived from wood waste, or via power-to-liquid using renewable electricity. In these cases, the potential saving offered by using synthetic diesel can be remarkable. As interesting pathways, the e-fuel route combined with DICI vehicles (RESD2a) approach zero WTW emissions when renewable electricity is used while negative WTW emissions could be obtained in the case of wood residue coupled with CCS (BECCS schemes). These latter pathways were not commercially available at the time of publication.

Regarding the e-fuel route, as CO_2 is considered to be a waste in the JEC WTT v5 study, there is no difference between the direct air capture (DAC) or flue gases pathways.



Source: Section 3.2 of the JEC WTW v5 report[2]

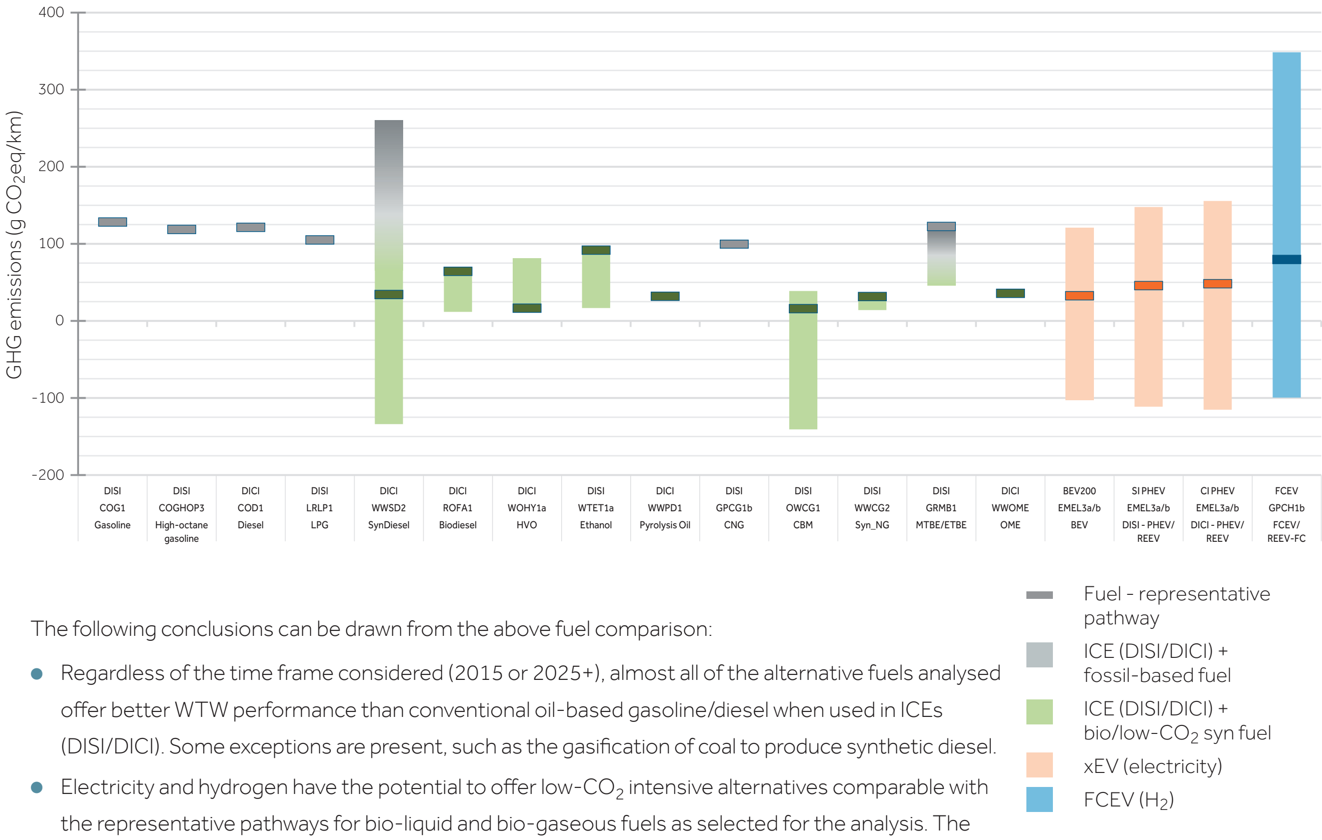
b) Comparative analysis

To help readers understand the variability in the WTW results due to the feedstock/fuel production route chosen and the powertrain technology for the time frames explored in the study (2015 and 2025+) with different test cycles, two type of comparative charts are presented in the report:

1. **Fuel comparison charts:** these charts show the variability due to the use of different type of fuels (and for each fuel, the representative selected pathway and the range as defined in Appendix 1 of the main JEC WTW v5 report) for the main selected powertrain technologies.
2. **Powertrain comparison charts:** in these charts, the impact of modifications in the main powertrain technologies through, for example, different levels of hybridisation or battery sizes, are explored for each type of fuel and its representative feedstock/conversion pathway.

Examples of the comparative GHG emissions-related charts for passenger cars in the 2025+ time frame are presented below in Figure 11 (fuel comparison), and in Figure 12 (powertrain comparison) on page 44.

Figure 11: WTW fuel comparison (2025+ WLTP) — GHG emissions



Source: Section 3.1 of the JEC WTW v5 report[2]

The following conclusions can be drawn from the above fuel comparison:

- Regardless of the time frame considered (2015 or 2025+), almost all of the alternative fuels analysed offer better WTW performance than conventional oil-based gasoline/diesel when used in ICEs (DISI/DICI). Some exceptions are present, such as the gasification of coal to produce synthetic diesel.
- Electricity and hydrogen have the potential to offer low-CO_2 intensive alternatives comparable with the representative pathways for bio-liquid and bio-gaseous fuels as selected for the analysis. The use of renewable electricity for xEVs (HEVs excluded) and FCEVs offer one the lowest WTW energy-intensive combinations similar to the use of biomethane and synthetic diesel (e-fuels) in DICI.

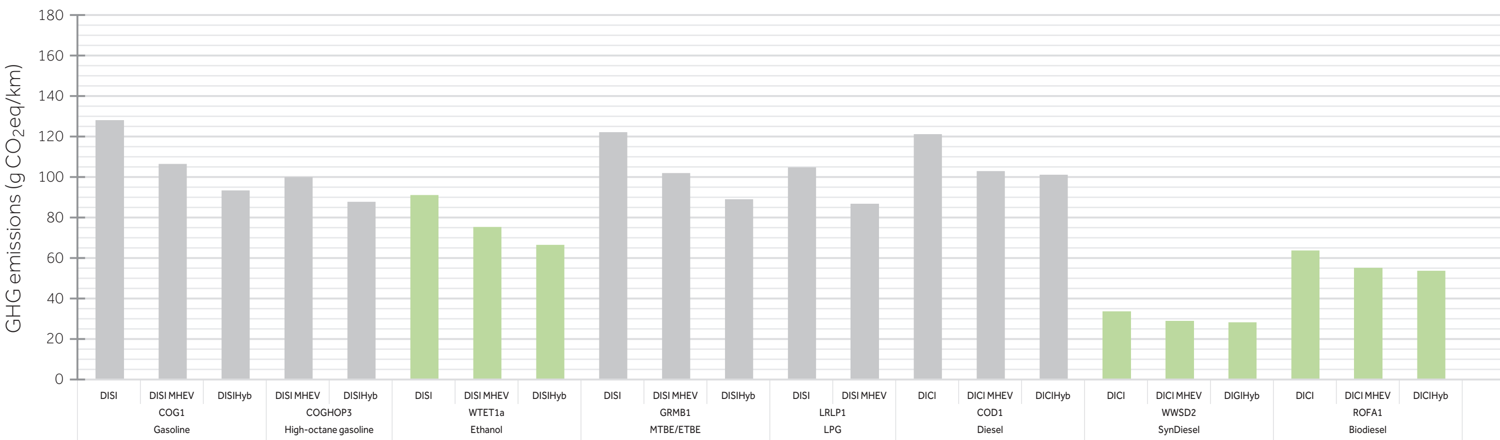
- Interestingly, PHEV technology (when powered with the EU mix and conventional gasoline/diesel fuel) shows a similar CO_2-intensive route to the use of an FCHEV in 2015 (with hydrogen produced through the conventional natural gas reforming route), but this changes towards 2025+ in favour of the BEV/PHEV/REEV alternatives (if no low-CO_2 intensive hydrogen is used).
- It is worth noting that: (1) this comparison includes the effect of the change in the test cycle from 2015 (NEDC) to 2025+ (WLTP), partially offsetting the potential WTW benefit (i.e. emissions reduction); (2) the fuel component considers the state-of-the-art technology of fuels already or close to being commercialised at scale in the market; and (3) availability issues are not included in the scope of the JEC WTW v5 study.

Note: as mentioned, the charts above include selected pathways modelled for the JEC WTW v5 integration (they do not represent all possible WTW fuel and powertrain combinations; the criteria for pathway selection is explained in Section 2.5.2 of the JEC WTW v5 report). Additional promising low-CO_2 intensive pathways that are not yet available at the commercial scale (TRL <6), have not been included in this WTW comparison, but the detailed data are available in the JEC WTT v5 report to enable readers to conduct their own in-depth assessments.

The following conclusions can be drawn for the passenger car segment based on the powertrain-derived data shown in Figure 12 (below):

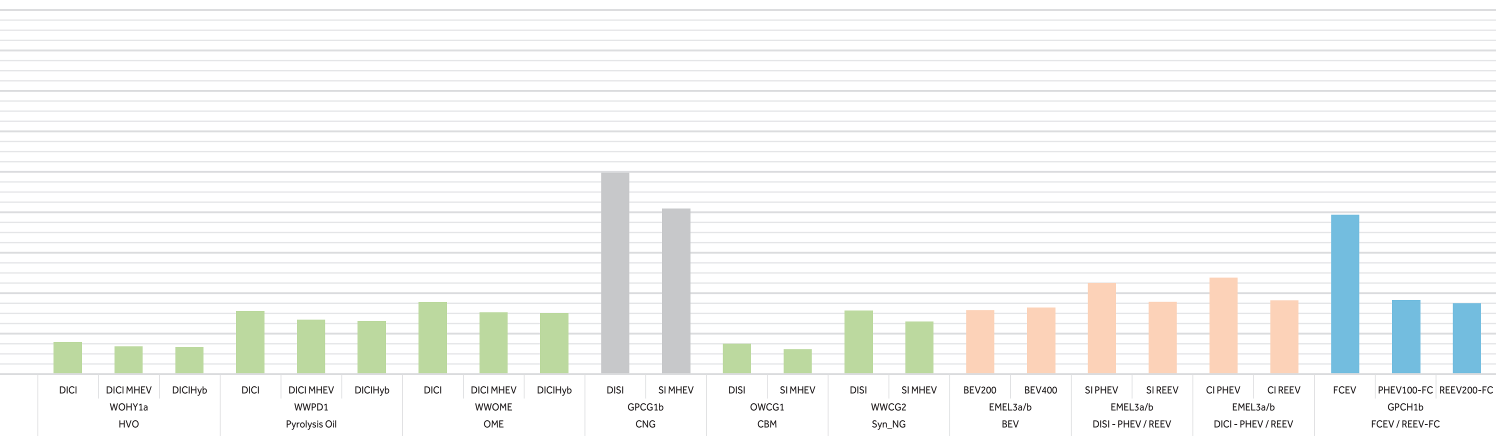
- In general, the hybridisation of ICEs offers an effective option to reduce fuel consumption, by up to ~25% (better performance is achieved with gasoline powertrains compared to diesel powertrains) when focused on non-plug-in HEVs.
- For gasoline/DISI types of engines, the combination of high compression and high-octane gasoline (102 RON) offers a similar performance to DICI (diesel) vehicles when approaching 2025+. For the high-octane gasoline pathways, the wheat-to-ethanol pathway WTET5 (biogas from DDGS for internal energy use) instead of the representative wheat-to-ethanol pathway WTET1a (using an

Figure 12: WTW powertrain comparison (2025+ WLTP)—GHG emissions
(an example of a powertrain comparison chart for passenger cars in the 2025+ time frame)



NG-fired boiler) has been used. The difference in the WTW GHG balance for the high-octane gasoline pathway COGHOP3 (variant with the highest ethanol share) amounts to about 2% versus the conventional gasoline pathway. With regard to the contribution from alternative fuels, the ethanol, MTBE and especially the bio-ETBE routes show interesting WTW GHG emissions reductions (up to 2/3 in the case of bio-ETBE).

- LPG used in DISI engines offers a ~15% reduction in WTW GHG emissions versus pure DISI in 2015, slightly increasing the potential mitigation benefit of DISI when approaching 2025+.
- With regard to diesel-like alternatives, the selected fuel pathways offer routes to lower the GHG emissions of conventional DICI engines in 2015 from ~50% up to 85% (bio and synthetic diesel pathways; synthetic diesel is understood here as BTL—biomass/waste derived fuels). The GHG emissions reductions offered by full hybridisation technology per se are not as significant as those offered by mild hybridisation technology.
- xEV technology is expected to improve significantly towards 2025+ (including battery size increases). In 2015, FCEV and PHEV/REEV offer similar WTW results (~15% better performance for PHEV/REEV versus FCEV). The difference increases when approaching 2025+ mainly due to the less CO_2-intensive electricity mix used in 2030 for the selected pathways (the combination of FCEV and PHEV/REEV in the same powertrain for the representative pathway (natural gas-based) offers similar results to DISI/DICI PHEV/REEV, especially as the percentage of the time being driven in electric-mode is expected to increase. In the case of H_2, a combination of different pathways has not been assessed in the WTW v5 study (as an H_2 2025+ mix).
- Of all the combinations of fuel/energy carriers and powertrains explored in the WTW v5 report, the HVO pathway with the DICI hybrid technology (waste as feedstock) and the use of CBM in a spark-ignition MHEV represent the lowest GHG-intensive routes.
- It is also important to note that, while NEDC test cycles were applied to 2015 powertrains, the WLTP test cycle is utilised in the 2025+ scenario. This change of test cycle, which provides for a more realistic measurement of driving emissions, partially offsets the reduction in GHG emissions due to the fuel efficiency measurements achieved by the powertrain technologies.



The full details, charts and conclusions for both passenger cars and heavy-duty segments are covered extensively in the JEC WTW v5 report. Concawe encourages readers to digest the information provided in the report, and to forward any suggestions or enquiries to the JEC emailbox: JRC-infoJEC@ec.europa.eu.

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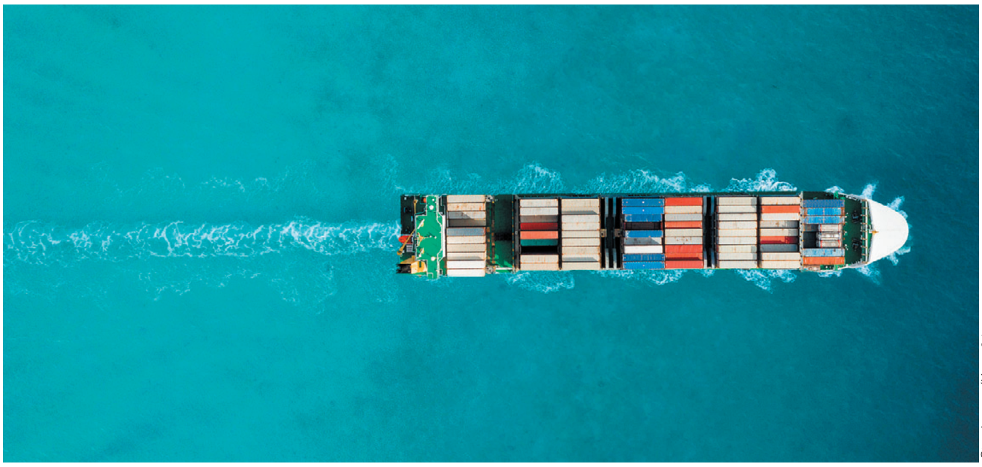
A review of the options for decarbonising maritime transport by 2050



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This article summarises Phase 1 of a new research project being undertaken by Concawe to investigate potential technological, operational and energy pathways to reduce emissions from the maritime transport sector towards 2050. Phase 1 of the project provides the context, and describes the various measures identified for decarbonising the sector, including the options for alternative fuels and energy carriers.

Introduction

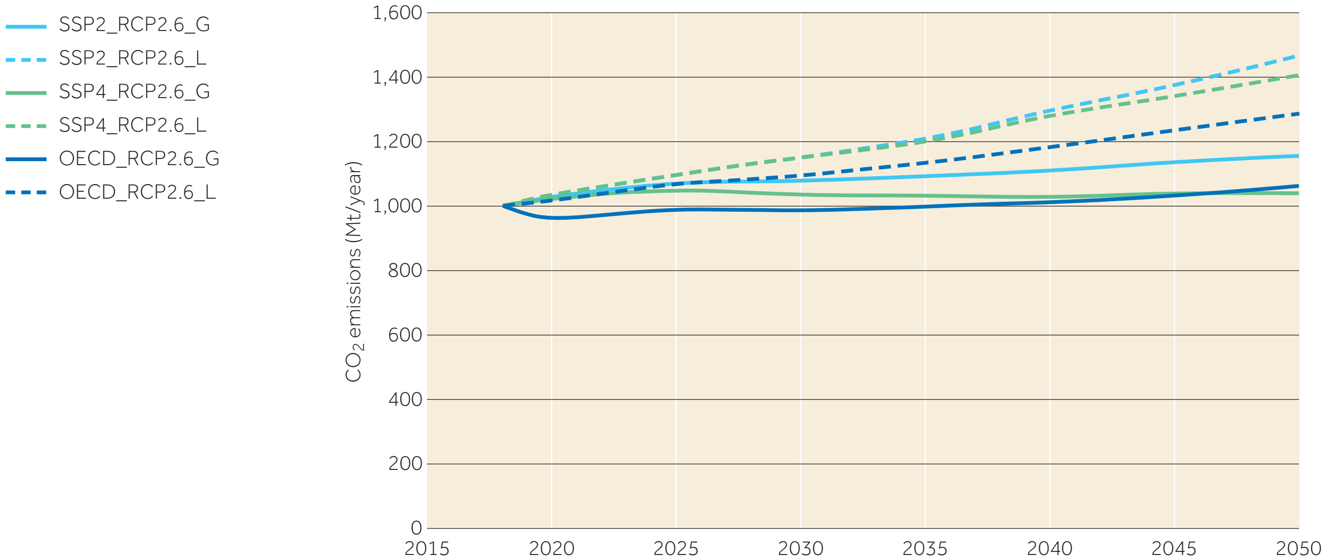
The main challenge for the maritime transport sector over the next decade is to develop a decarbonisation pathway to achieve the current 2050 ambition. The complexity of the sector requires the involvement of all of the industry's stakeholders in preparing a quantified and practical review of options to decarbonise the maritime sector by 2050.

Shipping is the backbone of international trade and commerce, and the maritime transport sector recognises the importance of decarbonisation to help reach the goals of the Paris Agreement. Maritime transport was responsible for 1,076 million tonnes of greenhouse gas (GHG) emissions in 2018—about 2.9% of global anthropogenic GHG emissions, according to the 4th International Maritime Organization (IMO) GHG study. In this study, in a business-as-usual scenario, emissions in 2050 range from 1,000 to 1,500 Mt/year, representing around 4–8% of global emissions. In this context, efforts are under way to achieve the IMO's ambition of reducing carbon emissions from international shipping by at least 50% in 2050 compared to 2008 levels (470 Mt CO_2eq versus 940 MT CO_2eq, respectively). This ambition also aims to reduce the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 (again compared to a 2008 base year).

Concawe is funding a research project entitled 'Assessing technological, operational and energy pathways for maritime transport to reduce emissions towards 2050', which is being conducted by Ricardo Energy & Environment. The study will provide quantified, evidence-based and neutral analysis to support high-level decision-making, in particular with regard to investment scale-up. The analysis will include the identification of barriers and enablers to climate change responses in the maritime sector, from a broad range of technical, economic and regulatory perspectives.

This article is a summary of Phase 1 of the project, which provides the context for the maritime transport sector and its drivers, and describes the technological and operational measures identified for decarbonising the sector, as well as the options for alternative fuels and energy carriers.

Figure 1: Projections of total maritime ship CO_2 emissions in the business-as-usual scenarios
(GDP growth in line with recent projections, energy transition in line with the 2°C target)

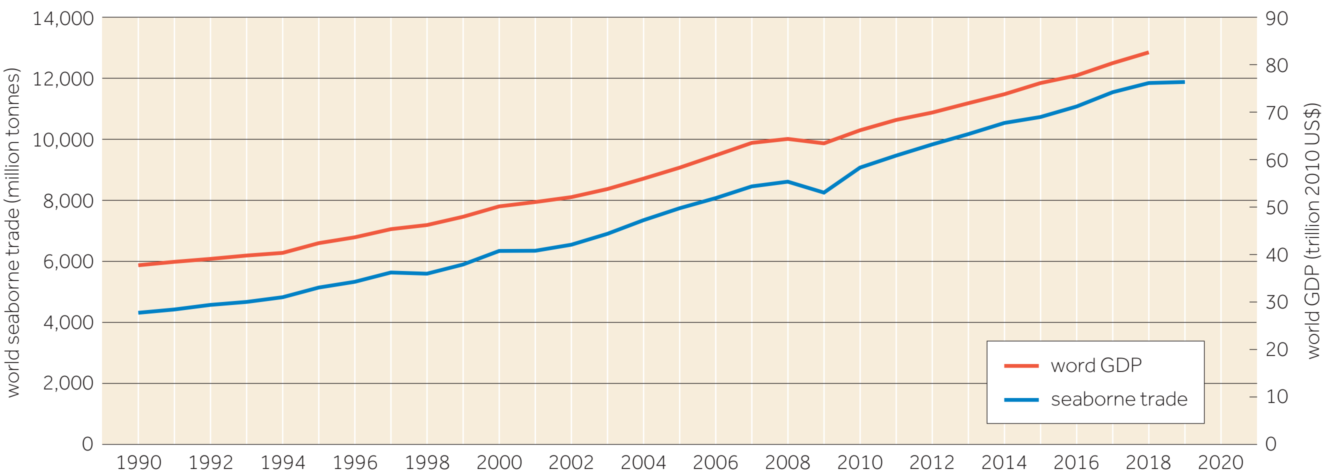


Context—historic and future trends

Historically, seaborne trade has been correlated with world GDP. World seaborne trade grows approximately in line with world GDP (it was slightly higher in the period 1990–2018), and has more than doubled over the past 20–25 years. In light of the anticipated growth in global GDP, there is therefore a need to decouple international shipping emissions from economic growth.

Figure 2: Correlation between world GDP and seaborne trade

Source: World Bank (world GDP data) and Clarkson Research Services Ltd (seaborne trade data)



Population and economic growth are the key drivers of the demand for all modes of transport. Higher levels of economic activity, triggered by an increase in consumption, production, intensification of trade, or a combination of several factors, usually implies an increase in demand for transport. With continued economic growth, the demand for the international transport of freight is expected to continue to grow in the future, although different levels of growth in different global regions are likely to lead to changes in the distribution of demand. Overall, the OECD expects global freight demand to triple by 2050, relative to 2015. If this is realised, seaborne trade will exceed 120,000 billion tonne-miles by 2050.

Projecting transport demand requires a deep understanding of economic growth and patterns of international activity; increased protectionism or a global economic downturn would have an important impact on the demand for transport. This is especially true for maritime transport, which is highly dependent on the intensity of international trade, and more so than other transport modes. The OECD notes that the future of the maritime freight sector depends, in particular on, international trade agreements, the development of transcontinental inland routes, changes in global energy use and the growth in e-commerce.[1]

Figure 3: Global shipping demand towards a 2050 horizon for a range of scenarios

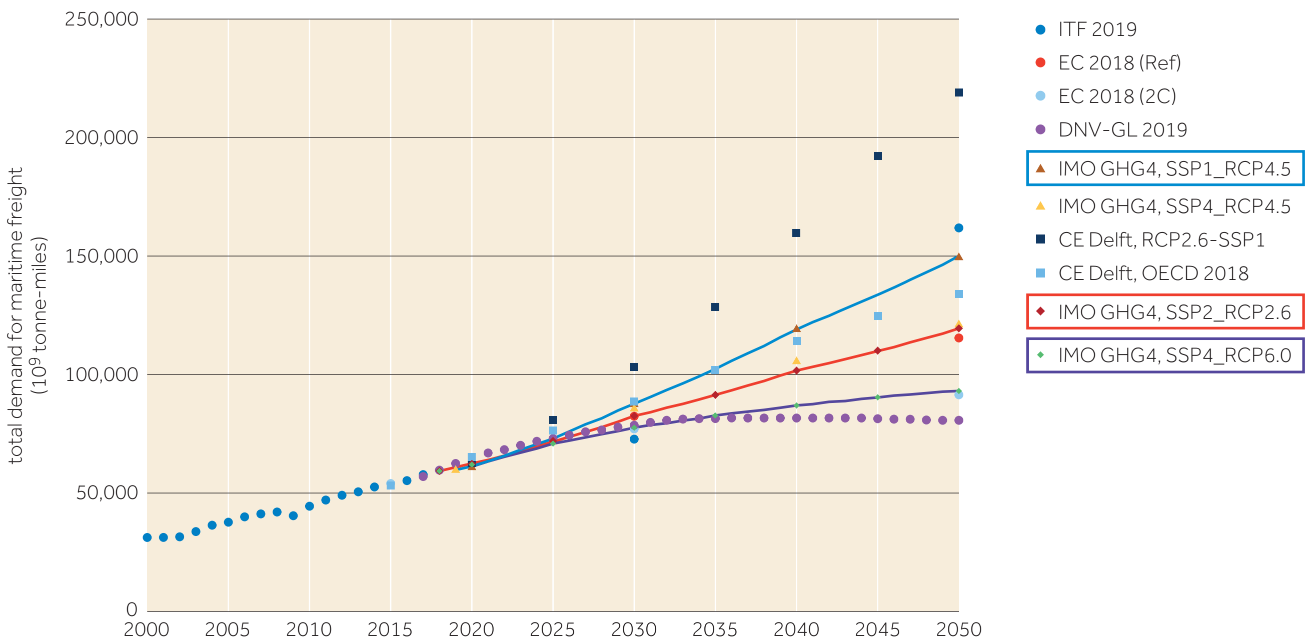


Figure 3 shows the projected demand for maritime freight shipping towards a 2050 time horizon for a range of scenarios. Three scenarios from the IMO's 4th GHG study were selected for the Concawe research project, as they are representative of the lower and upper bounds of the various scenarios identified. The projections shown in the Figure are based on GDP and population projections from the so-called Shared Socio-Economic Pathways (SSPs) developed by the IPCC, as well as the Representative Concentration Pathways (RCPs—long-term changes in energy use and atmospheric concentrations).

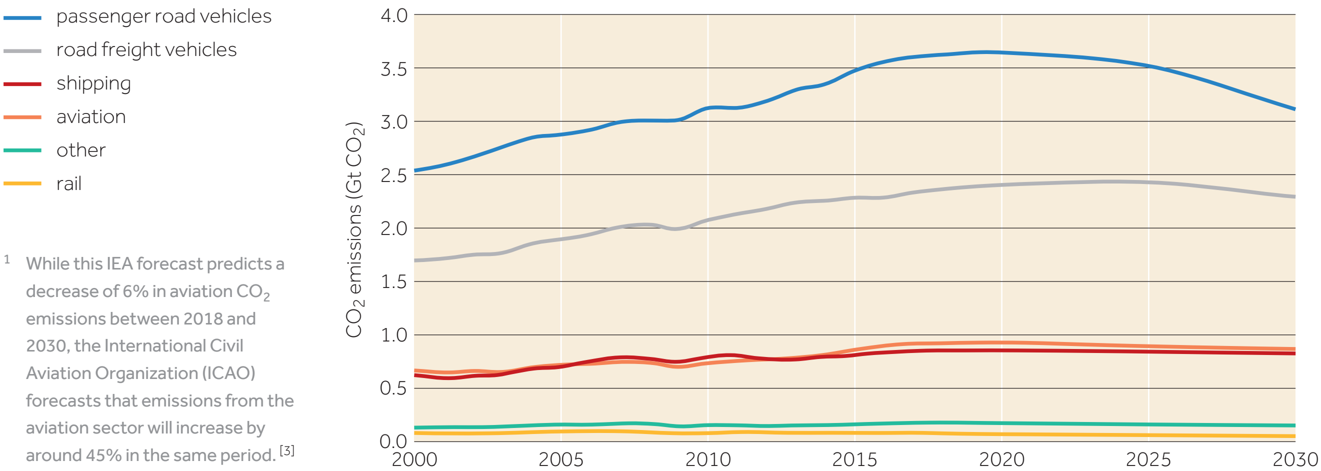
The three selected scenarios are defined as follows:

- High Demand scenario, IMO GHG4, SSP1, RCP4.5:
  - SSP1 = 'sustainable development — taking the High Road' + 2.4°C, medium-low mitigation
  - Annual GDP growth rate = 4.73%
  - Average growth rate for maritime transport (tonne miles) = +3.0% p/a
- Central scenario, IMO GHG4, SSP2, RCP2.6:
  - 'Middle of the Road", compatible with 2.0°C warming limit
  - RCP2.6 = 2.6 W/m^2 (watts per square metre of the Earth's surface) by the end of the century
  - Average growth rate for maritime transport (tonne miles) = +2.2% p/a
- Low Demand scenario, IMO GHG4, SSP4, RCP6:
  - SSP4 = 'inequality — a road divided', +2.8°C medium baseline, high mitigation
  - Annual GDP growth rate = 3.13%
  - Average growth rate for maritime transport (tonne miles) = +1.4% p/a

The three main ship categories for CO_2 emissions are container ships (~25% of sector emissions), bulk carriers (~20%) and oil tankers (~15%). Between them, these three categories of ships produced 60% of the total GHG emissions from international maritime shipping.

Figure 4: Transport sector CO_2 emissions by mode, historic and projected, 2000–2030[1]

Source: International Energy Agency [2]



[1] While this IEA forecast predicts a decrease of 6% in aviation CO_2 emissions between 2018 and 2030, the International Civil Aviation Organization (ICAO) forecasts that emissions from the aviation sector will increase by around 45% in the same period. [3]

As shown in Figure 4, road transport, both passenger and freight, was responsible both for the majority of the increase in emissions from 2000–2018 and the majority of the expected decline in emissions from 2018 through to 2030. Road transport is also responsible for the majority of current (2018) emissions from transport, as well as anticipated emissions by 2030 (around 75% of total emissions in both years). In comparison, shipping is responsible for around 11% of total emissions, a value that remains unchanged by 2030, and which is almost three time less than for road freight, while representing five times more tonne kilometres moved (OECD and ITF, 2019).

Figure 5: Global freight demand by mode

Source: OECD and ITF[1] and ICAO[4]

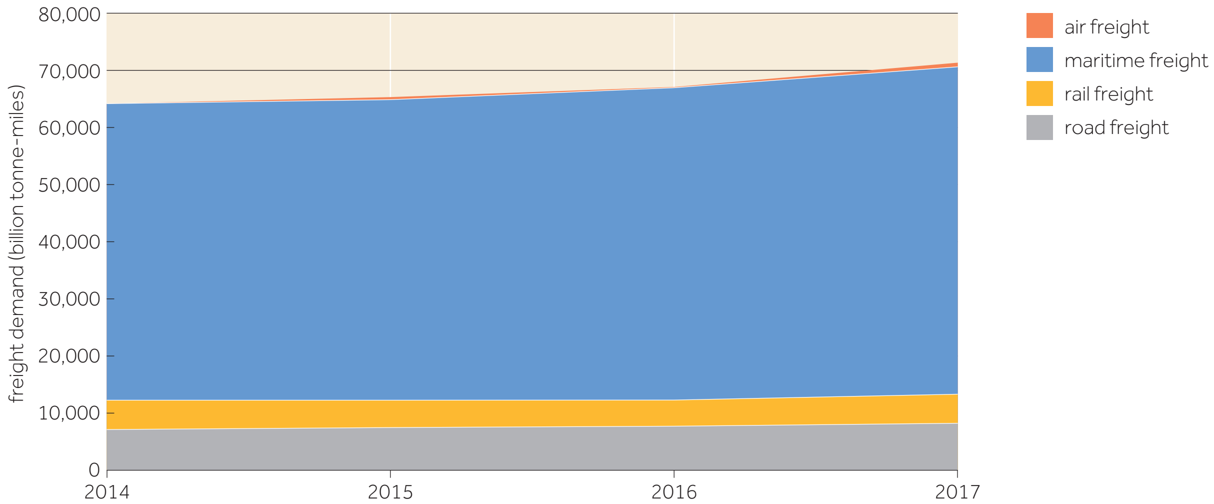


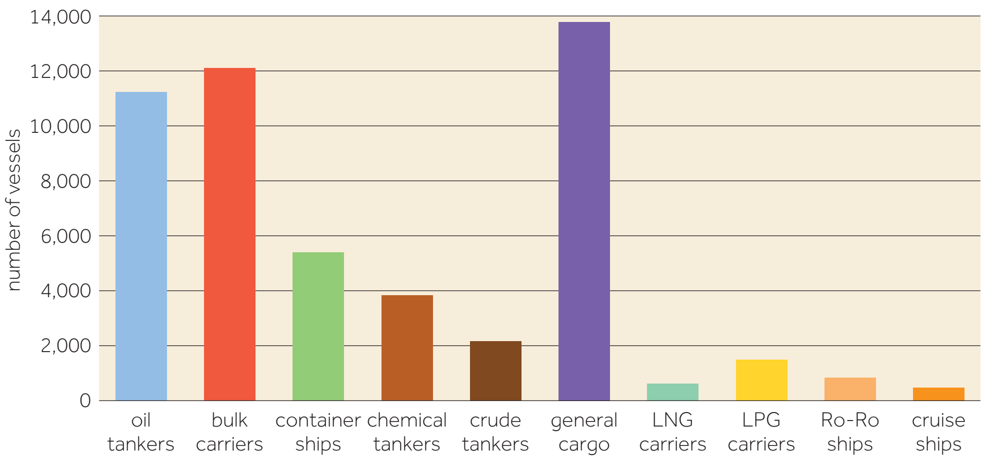
Figure 5 shows that maritime transport meets approximately 81% of global demand for freight transport (in tonne miles), with road and rail providing approximately 12% and 7% respectively. Aviation meets an almost negligible 0.16% of demand.

Global marine fleet

The current commercial maritime transport fleet consists of more than 51,600 vessels (excluding tugs, fishing boats and other non-transport vessels), with a total deadweight tonnage (DWT) of more than 2.3 billion tonnes. Figure 6 shows the numbers of vessels in the fleet, split into the main categories. The key vessel categories by number are oil tankers, bulk carriers and general cargo vessels.

Figure 6: Global maritime fleet by number of vessels per category

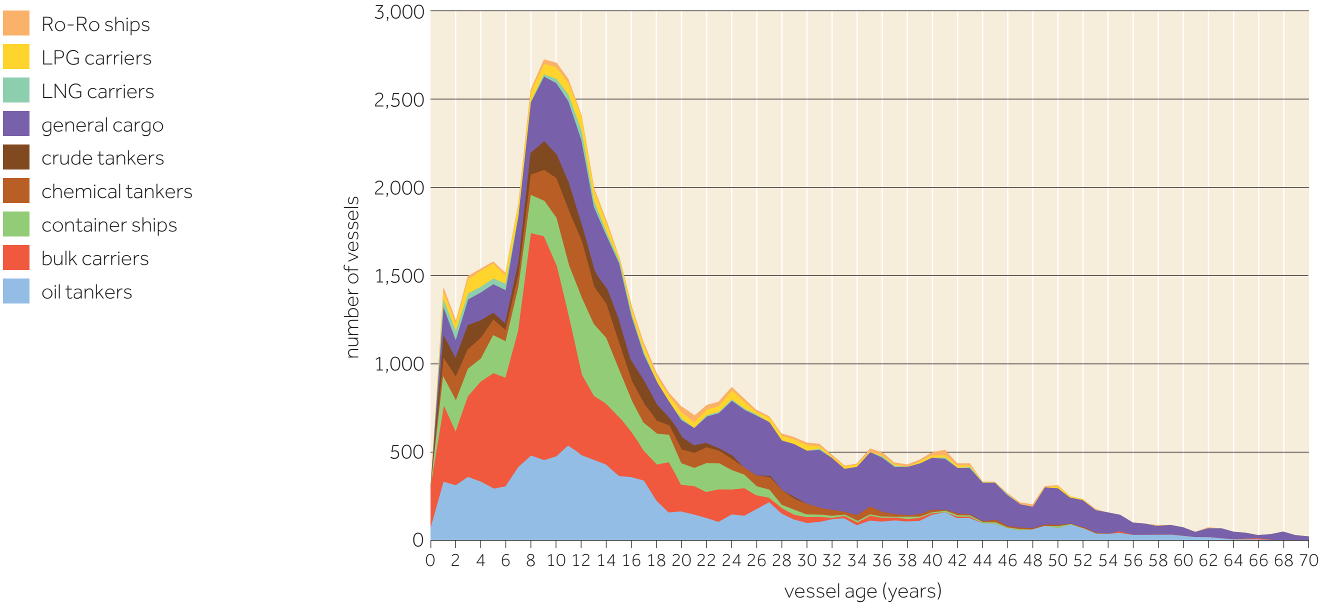
Source: Clarkson Research Services Ltd, World Fleet Register[5]



A key element in the calculation of the future fleet composition is the age profile of the current fleet—see Figure 7.

Figure 7: In-service fleet by age and category

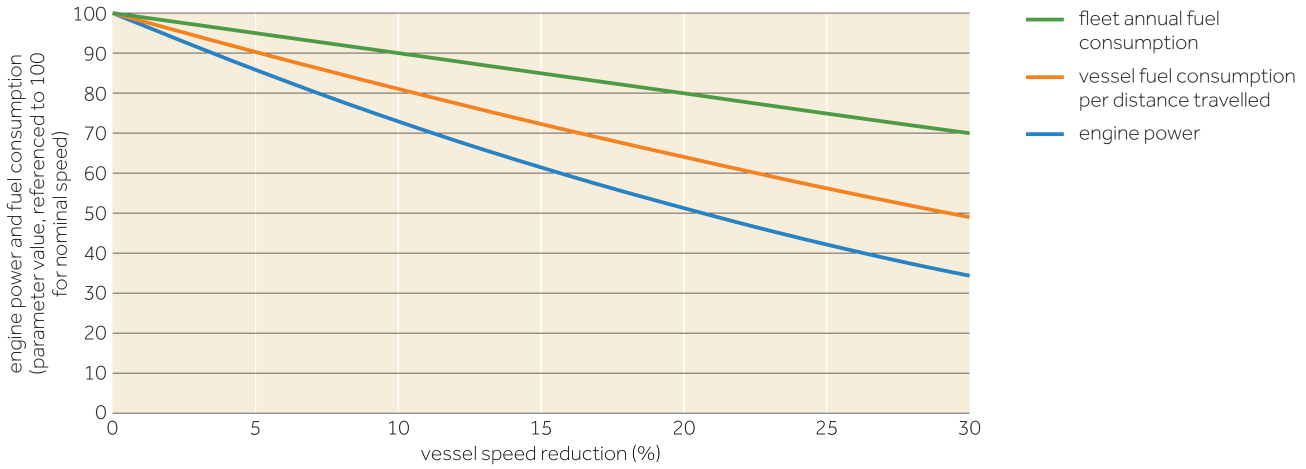
Source: Clarkson Research Services Ltd, World Fleet Register [5]



Speed

The speed of a ship has a significant influence on both earnings and costs for a ship operator. The cubic relationship between speed and fuel consumption is a key factor in determining the optimal speed of a vessel. In numerical terms, a 10% reduction in speed leads to a 27% decrease in power demand. Accounting for the lower distance covered, a 10% speed reduction results in a 19% reduction in fuel consumption per unit of distance.[6] Figure 8 on page 53 illustrates this effect by showing how the required engine power and fuel consumption per unit of distance vary with speed reduction (power and fuel consumption are referenced to a value of 100 at the nominal vessel speed). However, the reduction in speed also results in a reduction in productivity (or utilisation); each vessel will deliver fewer tonne miles in a given period (e.g. a year), therefore more vessels will be required to deliver the original total supply. As a result, the fleet-level fuel consumption required to deliver the same supply forms a linear relationship with speed (-10% fleet annual fuel consumption for a 10% speed reduction).

Figure 8: Effects of slow steaming on the power required, vessel fuel consumption per distance, and overall fleet fuel consumption



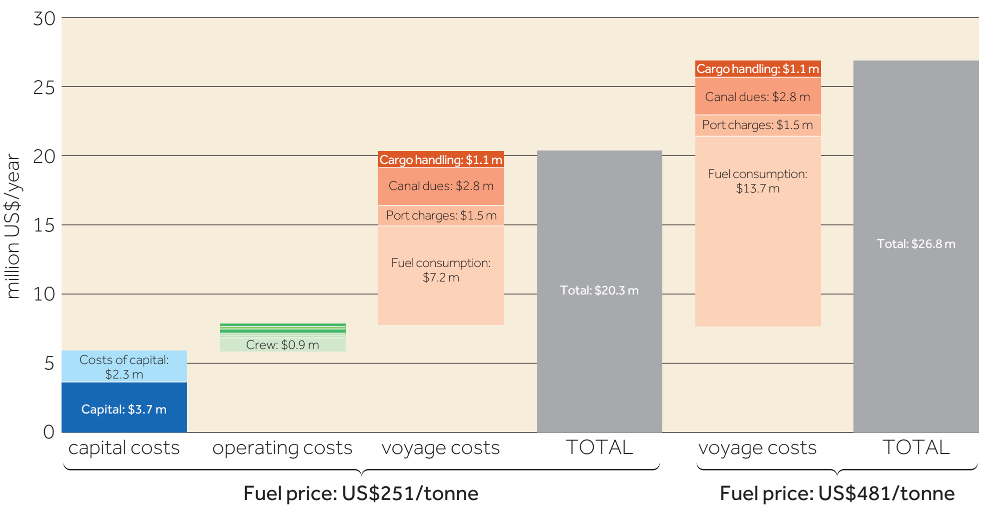
Costs

Fuel price is by far the most important and most volatile determinant of the average vessel costs, being especially pronounced for older and less efficient vessels. The high dependence of vessel operating costs on fuel price provides a strong business driver to reduce the cost of fuels used, and has been the trigger for the universal adoption of heavy fuel oil (HFO, in general the lowest-priced liquid fossil fuel) for maritime transport.

As shown in Figure 9, the ratio of fuel costs versus the total cost structure increases from 35% to 51% when the fuel price increases from US$251/t to US$481/t (2020 economics with Brent at ~US$40/bbl versus 2018 economics with Brent at US$55/bbl, respectively).

Figure 9: Fuel price sensitivities for a 13,000 TEU[a] main liner container, 5 years old

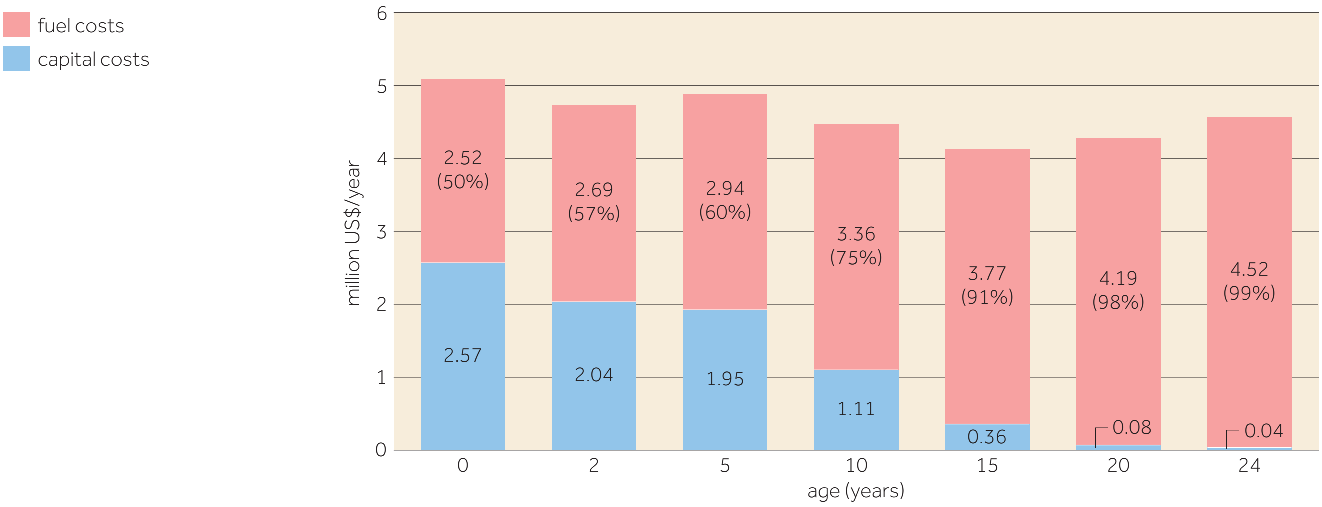
Source: Ricardo literature review and calculations



[a] TEU = twenty-foot equivalent units

The age of a vessel is a key determinant of both capital and fuel costs (Figure 10), because, in general, a vessel depreciates faster at the beginning of its useful life and newer vessels are more efficient. Therefore, applying fuel economy measures will be key in a highly competitive environment for the international shipping sector.

Figure 10: Age sensitivities for a 75,000 dwt bulk carrier — capital and fuel costs (fuel costs of US$481/t)



'Split incentive'

Because of its structure, the shipping sector is more susceptible to a specific potential barrier to the introduction of new technologies, known as the 'split incentive' problem, than other transport sectors. Responsibilities such as fuel charges, operational measures, technological investments and cargo loading can be allocated either to shipowners or ship charterers. Whether there is an incentive for a shipowner to implement energy efficiency measures is often highly dependent on the charter rate that the charterer pays to the ship owner. If the party paying for its implementation does not accrue the benefit of the energy efficiency measure, this can act as a barrier to the adoption of the measure when ordering a new ship.

Short-term technology measures to reduce emissions

Most short-term technology measures identified to decarbonise international shipping will prove to be useful. Many offer significant efficiency gains (above 40%) at an affordable cost-effectiveness (US$/t CO_2 avoided), with the range being on average US$5–50/t CO_2. Some of these technologies are already implemented in the existing fleet, but there is further reduction potential for some of these technologies, especially where the technological readiness level (TRL) is high, but uptake is limited.

The short-term measures considered are:

- **Ship and propeller design** measures can reduce GHG emissions by reducing resistance. Measures were identified that can each provide a GHG reduction potential ranging from 0.5–10%.
- **Alternative power-assistance technologies**, such as Flettner rotors, towing kites, sails, solar panels and shoreside power can reduce future direct fuel requirements and provide additional auxiliary power, reducing GHG emissions (ranging from 0.5–15% and up to 100% for shoreside power in port only).
- There are several **operational and voyage optimisation measures** that offer GHG savings (ranging from 0–38%). These measures includes slow steaming, advanced port logistics, automation and IT tools development.
- **Engine design** — conventional engine designs already include the best available technology.

Longer-term shifts to alternative fuels will be needed

To achieve the IMO's ambition to reduce carbon emissions from international shipping by at least 50% in 2050 compared to 2008 levels, the fundamental change will be a switch to alternative zero GHG-emission fuels. There are uncertainties in terms of whether one fuel or two fuels (i.e. one for short-sea shipping and one for deep-sea shipping) should be adopted, or whether multiple fuels will be required. However, there are some emerging trends and some agreement that the transition will first apply to short-sea shipping and later to long-distance shipping.

Each of the fuels investigated are summarised below. These have been categorised into two main groups: 'drop-in fuels' which can be used in the existing fleet largely without engine modifications up to certain blend limits, and other alternative fuels which require significant engine/fuel system modifications, alternative engines and/or infrastructure.

'Drop-in fuels'

- **FAME (fatty acid methyl ester):** To date, the use of FAME blended with conventional marine fuels such as HFO has proven to be compatible in blends containing up to 20% FAME,[7] although the current fuel standard for distillate fuels (ISO 8217 2017) limits FAME content to 7%.[8] The main barriers to future uptake include ensuring sustainability of feedstocks, and competition with other transport sectors.
- **HVO (hydrotreated vegetable oil):** HVO is compatible with existing infrastructure and engine systems, subject to approval by the manufacturer, although minor modifications may sometimes be required.[9] There is no upper limit for blending HVO. The main barriers to future uptake include ensuring sustainability of feedstocks, and competition with other transport sectors.
- **DME (dimethyl ether):** Although DME has been a known substitute for diesel for more than 20 years, it has not been widely used as an alternative maritime fuel. DME can be used with marine diesel oil in blends of ≤40%. The use of neat DME requires engine retrofits or specific engine design. The main barrier to future uptake is a need for green DME production and supply.

Other alternative fuels

- **LNG (liquefied natural gas):** As a fossil fuel, albeit with a lower carbon content than HFO, it is recognised that LNG cannot be the final solution for decarbonising shipping. LNG as a marine fuel has already reached market maturity and is in use by vessels currently in operation. Another emerging consideration for LNG is that bio-LNG (liquefied bio-methane) and liquefied synthetic methane (LSM) could be compatible with LNG-fuelled ships. The main barriers to future uptake include methane slip and life-cycle emissions, and suitable bunkering infrastructure.
- **Methanol:** Currently, methanol is produced mainly from natural gas, but can be produced from a number of different feedstock resources including renewable sources such as black liquor from pulp and paper mills, agricultural waste or forest thinning, and even CO_2 that is directly captured from power plants.[9] The main barriers to future uptake include green methanol production and supply, and adequate infrastructure.
- **Ammonia:** Until recently, there has been little motivation to explore ammonia as a maritime fuel. However, if synthesised from renewable resources, 'green ammonia' as a fuel is carbon free. Green ammonia production uses the renewable electrolysis process to separate hydrogen atoms from oxygen atoms within water using electrolysers which are already in extensive commercial use. In this process, the GHG reduction potential of ammonia depends on the percentage of electricity generated by renewable sources. The main barriers to future uptake include green ammonia production and supply, price parity, and the availability of solid oxide fuel cell technology for future use in fuel cells.
- **Hydrogen:** When hydrogen is combusted, the process is carbon free, and if the hydrogen is synthesised using renewable power, it is a completely carbon-neutral fuel with zero CO_2 emissions. Hydrogen has a very low volumetric density which was previously a limiting factor to its use. The main barriers to future uptake include green hydrogen production and supply, cost and price parity.
- **Batteries:** Batteries have been used as an energy carrier for short-sea shipping since 2015. They can provide vessel power through an electrochemical reaction, whereby energy is absorbed and released in the lithium-ion cell within the battery. Compared to using conventional fuels, emissions of CO_2, NO_x and SO_x are reduced when using full electric (battery) and hybrid (battery and diesel) configurations. The energy efficiency of electric propulsion systems can even exceed 90%, compared to about 40% for conventional propulsion with diesel engines.[10] Stakeholders in the sector do not foresee batteries as a realistic energy carrier option for deep-sea shipping. The main barriers to future uptake include fire risk, limited range, cost, weight/size and end-of-life disposal.
- **Fuel cells:** Using fuel cells rather than internal combustion engines can reduce emissions. If the fuel used is hydrogen, the only products produced in the fuel cell reactions are water, electricity and excess heat. If powered by a fuel produced using renewable energy the carbon reduction potential of fuel cells is 100%. Fuel cells require their own storage systems and equipment, and continue to function as long as they have a fuel source. The main barriers to future uptake include capital and maintenance costs, proving the feasibility of scale-up, bunkering availability, and the longevity of fuel cells.

Table 1 provides a summary of the maximum potential reductions in net emissions available from the different alternative fuels described, with the costs and cost-effectiveness calculated for each fuel based on the production technologies described. The costs are based on estimates available from the literature and do not reflect projections to 2050.

Table 1: Maximum potential reductions in net emissions, plus costs, cost-effectiveness and compatibility notes for the alternative fuels described (results and figures may evolve as the study has not yet been finalised)

	MAXIMUM GHG REDUCTION POTENTIAL (%)	TRL FOR TRANS-OCEANIC	CURRENT COST (US$/GJ)	CURRENT COST-EFFECTIVENESS (INCLUDING FUEL COSTS) (US$/t CO_2)	COMPATIBILITY
LNG *Global average pathway*	10%	9	7.1	340.1	Requires gas/dual-fuel engine and associated cryogenic storage.
Bio LNG *Liquid manure pathway*	169%	9	11.3	49.5	Same requirements as for LNG.
Methanol *Synthetic methanol pathway*	92%	8/9	28.7	305.3	Not drop-in. Compatible with internal combustion engines.
Ammonia *Municipal waste pathway*	79%*	3/4/5	31.9	400.5	Compatible with internal combustion engines (spark ignition with a hydrogen blend to promote combustion, and dual-fuel with pilot diesel).
Hydrogen *Biomass gasification pathway*	95%*	3/4/5	89.2	1,028.7	Compatible with internal combustion engines (spark ignition and dual-fuel) but requires development and a supporting fuel).
FAME *Waste cooking oil pathway*	84%	9	17.0	174.0	Drop-in (blended only <20% FAME). May face competition for feedstock availability from other sectors.
HVO *Waste cooking oil pathway*	91%	9	17.2	163.3	Drop-in (blended and neat). May face competition for feedstock availability from other sectors.
Batteries *(Lithium-ion)*	66%	4/5/6	-	-	Not compatible with internal combustion engines as part of a prime mover. Have a role in coastal or short-sea shipping. May have a role in reducing emissions from auxiliary power in deep-sea shipping. Require their own storage systems and equipment.

Notes: Maximum potentials are shown, with the exception of ammonia, hydrogen and battery electric. In theory, 100% reduction (or higher) may be achievable with 100% renewable electricity for these fuels; however, the time frame and costs for these production pathways are not clear at present, therefore data for the pathways with the next highest reduction potential are shown.

Different alternative fuels have been identified, together with their GHG reduction potential, respective costs and current TRLs. Given the uncertainties around the future development of the different fuels and the different production pathways associated with them, it is not possible at present to identify the specific fuels that are most likely to be developed and adopted in the future. However, it is possible to identify criteria that may be used when assessing fuels for potential commercial production and widespread use by the fleet. These criteria include:

- the price relative to conventional fuels;
- certainty of the GHG reduction potential and well-to-propeller (WTP) emissions;
- adequate fuel availability; and
- low competition from other sectors in the timing of deployment, e.g. aviation.

Conclusion

The shipping industry is entering a challenging decade, as the sector will have to reduce its overall emissions while the demand for transport continues to increase, i.e. by decoupling emissions from growth. There will not be a unique path, and the timing for deployment of the cheapest measures from the CO_2 cost abatement curve will be crucial. Improvements in ship technology and operational measures are the most financially attractive options for reducing CO_2 emissions (with costs ranging from US$5–50/t CO_2). Alternative fuels and energy carriers will also be necessary, and the uncertainty is higher with regard to the timing and identification of the specific fuel/energy supply that will need to be developed.

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Next steps in the study

Phase 1 of this study considered the background to the development of the maritime sector, and a range of technologies and fuels that can contribute to the future decarbonisation of the sector. It has also identified three scenarios for the future growth of demand for maritime transport, and three packages of measures (technologies/operational measures/alternative fuels).

Phase 2 of the study (due to be published in Q1 2021) will perform a 'deep-dive' investigation of those packages, exploring their potential uptake and impact on the emissions from the different ship categories (and ship sizes, where appropriate). For each scenario, a model will be developed of the evolution of the maritime fleet, including the introduction of newly built ships as driven by the demand for trade (and taking account of the retirement, or demolition, of older ships). The technology developments for new ships and fuels, and the evolution of the fleet, will be combined into a set of pathways showing how decarbonisation of the sector can develop through to 2050.

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Abbreviations and terms

ALK	Alkylation
Ar	Argon
BEV	Battery Electric Vehicle
BIO-LNG	Liquified bio-methane gas
BIO-SNG	Bio-Synthetic Natural Gas
BTL	Biomass To Liquids
CAPEX	Capital Expenditure
CBG	Compressed Bio Gas
CBM	Compressed Bio-Methane
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CD	Crude Distillation
CEV	Catenary Electric Vehicle
CGH_2	Compressed Gaseous Hydrogen
CH_4	Methane
CI	Compression Ignition
CKU	Coking Unit
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COE	Cost Of Electricity
CRL	Commercial Readiness Level
DAC	Direct Air Capture
DDGS	Distillers' Dried Grains with Solubles
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DME	DiMethyl Ether
DMF	DiMethylFormamide
DWT	DeadWeight Tonnage
ECBM	Enhanced Coal Bed Methane
EDP	Electricidade de Portugal
EOR	Enhanced Oil Recovery
ETBE	Ethyl Tertiary-Butyl Ether
EU	European Union
EUCAR	European Council for Automotive R&D
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester
FCC	Fluid Catalytic Cracker
FCEV	Fuel Cell Electric Vehicle
FT	Fischer Tropsch
GDP	Gross Domestic Product
GHG	GreenHouse Gas
GTL	Gas To Liquids
GVMR	Gross Vehicle Mass Rating
H-CNG	Hydrogen Compressed Natural Gas
H_2	Hydrogen
H_2O	Dihydrogen Monoxide (Water)
H_2S	Hydrogen Sulphide
HC	HydroCracking
HD	HydroDesulphurisation
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HFO	Heavy Fuel Oil
HMU	Hydrogen Manufacturing
HPDI	High Pressure Direct Injection
HVO	Hydrotreated Vegetable Oil
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
JEC	JRC-EUCAR-Concawe (Consortium)
JRC	Joint Research Centre of the European Commission
KHT	Kerosene Hydrotreating
LBM	Liquefied Bio-Methane
LCA	Life-Cycle Analysis
LDS	Atmospheric Residue Desulphurisation
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSFO	Low-Sulphur Fuel Oil
LSM	Liquefied Synthetic Methane
MDEA	Methyl DiEthanolAmine
MEA	MonoEthanolAmine
MHEV	Mild Hybrid Electric Vehicle

Abbreviations and terms

(continued)

MTBE	Methyl Tertiary-Butyl Ether
MTR	Membrane Technology Research Inc.
N_2	Nitrogen
N_2O	Nitrous Oxide
NEDC	New European Driving Cycle
NG	Natural Gas
NHT	Naphtha HydroTreating
NO_x	Nitrogen Oxides
O_2	Oxygen
OECD	Organisation for Economic Co-operation and Development
OME	OxyMethylene Ether
OPEX	Operating Expenditure
P2X	Power To Fuels (E-fuels)
PCC	PetroChemical Cracker
PEG	PolyEthylene Glycol
PHEV	Plug-in Hybrid Electric Vehicle
PI	Positive Ignition
R&D	Research and Development
RCN	Vacuum Residue Conversion
RCP	Representative Concentration Pathway
RDS	Vacuum Residue Desulphurisation
RED	Renewable Energy Directive
REEV	Range Extender Electric Vehicle
RF	ReFormate
RMF	Residual Marine Fuel
Ro-Ro	Roll On, Roll Off
RON	Research Octane Number
SMR	Steam Methane Reforming
SNG	Synthetic Natural Gas
SO_x	Sulphur Oxides
SSP	Shared Socio-Economic Pathway
TEU	Twenty-foot Equivalent Units
TRL	Technology Readiness Level
TTW	Tank To Wheels
VB	Visbreaking
VD	Vacuum Distillation
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTP	Well To Propellor
WTT	Well To Tank
WTW	Well To Wheels
xEV	Electrified Vehicle

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Concawe
Boulevard du Souverain 165
B-1160 Brussels, Belgium

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