Review

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Foreword

This *Review* adds some important articles to Concawe's Low Carbon Pathways project, a programme started several years ago to develop a holistic view of how the refining industry could contribute to Europe's decarbonisation objectives. Concawe believes that the refining industry could contribute to reducing transport's greenhouse gas (GHG) emissions, in addition to the reductions achievable through the use of electrification and hydrogen, by supplying low-carbon liquid fuels (LCFs), e.g. sustainable biofuels and e-fuels, which could decrease emissions from the existing passenger car fleet as well as from the hard-to-decarbonise heavy-duty road transport, aviation and maritime transport sectors.

It is important to understand the availability of biofuels based on the potential development of sustainable biomass, as sustainable biofuels could bring an important contribution to the decarbonisation of transport. The first article summarises a study that Concawe contracted to Imperial College London Consultants, which evaluates the potential availability of sustainable biomass in Europe, and the consequent potential production of biofuels after deduction of the biomass that would be required for other non-energy and energy uses.

The second article summarises a study that Concawe performed to evaluate the theoretical potential, from now up to 2050, for the production of LCFs within the EU refining system, in terms of total volumes, the number of potential plants required, the contribution to GHG emission reductions in transport (following a well-to-wheels approach) and the level of investment needed for the transformation of the refining industry.

The third article refers to an important study conducted by a research consortium composed of IFPEN, Sintef and Deloitte at the request of Concawe and other stakeholders (associations and companies active in the low-carbon and renewable hydrogen value chains). The study is based on unique and extensive energy and transport modelling, and delivers a comprehensive analysis of the dynamics of the European energy transition and of the contribution of renewable and low-carbon hydrogen to European climate objectives.

The fourth article explores how blends of gasoline, diesel fuel and ethanol ('dieseline'), which have shown promise in engine studies examining low-temperature combustion using compression ignition, could be used without developing a flammable atmosphere in the headspace above the liquid in a vehicle fuel tank. A mathematical model designed to predict the flammability of dieseline blends, including those containing ethanol, was developed and validated experimentally, and used to study the flammability of a wide variety of dieseline blends parametrically.

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Contents

This article summarises a study undertaken to estimate the potential sustainable biomass availability in the European Union and the UK by 2030 and 2050, and to assess the production of sustainable advanced biofuels for 2030 and 2050 on the basis of this potential biomass availability. The study was conducted by Imperial College Consultants at the request of Concawe, and the results have been published in a report entitled *Sustainable biomass availability in the EU, to 2050*.

The analysis covers domestic (EU-27 + UK) feedstocks of agricultural, forest and waste origin included in Annex IX of RED II (Parts A and B). Food and feed crops, and other sustainable feedstocks accepted by RED but not included in Annex IX, are not included in this study. Three scenarios have been analysed: (i) low biomass mobilisation; (ii) improved mobilisation in selected countries due to improvements in cropping and forest management practices; and (iii) enhanced availability through research and innovation measures as well as improved mobilisation in all countries due to improvements in cropping and forest management practices. A number of conservative assumptions have been made in the analysis.

The study analyses the sustainable biomass availability for all markets, and then estimates the amount that could be available for bioenergy after excluding the anticipated demand from non-energy sectors (Part 1 of the study). It then presents (Part 2) the status of the various applicable technologies and value chains based on their maturity for market deployment, and assesses the potential production of sustainable advanced biofuels for 2030 and 2050 on the basis of the biomass potentials calculated in Part 1. An Excel™ file containing the detailed data per country is included in the final study report.

This article is intended to serve as a brief summary of the report while guiding the reader through the same path that Concawe walked while understanding the future role of sustainable biomass in Europe towards 2050.

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Within the context of the European Green Deal, and through a scenario analysis exercise, a new report published as part of Concawe's *Low carbon pathways/Refinery 2050* series aims to explore the theoretical potential for the production of low-carbon liquid fuels (LCFs) within the European Union (EU) refining system, both in terms of total volumes of low-carbon fuels, their contribution to reducing CO_2, and the potential number of plants required to make a meaningful contribution to climate neutrality in the EU by 2050. This article provides an overview of the findings presented in the report.

With a broad focus on the road, aviation and maritime sectors, and through consideration of three potential demand scenarios, aspects such as the volume of LCFs required to make substantial contributions to reducing GHG emissions in transport (following a well-to-wheels approach), as well as the level of investment needed for the transformation of the refining industry, are investigated to provide a quantitative indication over a reference time frame from now until 2050. For the purpose of simplification, this assessment includes only a limited number of examples of low-carbon feedstocks and technologies (food-crop based, hydrotreated vegetable oil (HVO), biomass-to-liquid (BTL), e-fuels, clean hydrogen, and carbon capture and storage), and estimates a need for LCF volumes ranging from ~70 up to ~160 Mtoe/year, together with an estimated cumulative investment of ~190–660 B€/year by the end of the period, assuming that the economic/market conditions are in place and depending on which of Concawe's three (low/medium/high) 'alternative 1.5°C scenarios' is considered. Complementing this analysis, a separate article in this edition of the *Review* summarises the results of a study undertaken by Imperial College Consultants (London) which looks into the availability of sustainable biomass, and identifies no major constraints in the realisation of Concawe's three scenarios.

This article provides the technical basis behind the FuelsEurope publication, *Clean fuels for all*, which describes the EU refining industry's proposal for a potential pathway to climate neutrality by 2050, but highlights that the results of the study are not intended as a roadmap for the industry: other trajectories could be defined or may evolve depending on the framework conditions as well as on the successful development and scale-up of the different technologies and their related value chains.

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The transition towards a decarbonised European energy system requires a wide range of solutions to ensure that energy supply remains secure and affordable for all European consumers. Renewable and low-carbon hydrogen can be produced by promising technologies, and are versatile and clean fuels capable of being used across the energy supply chain. The potential and adaptability of renewable and low-carbon hydrogen have gained the interest of policy makers and industry. Not only can hydrogen help to decarbonise the energy supply, it can — together with electrification and renewables — foster energy system integration.

A new report, entitled *Hydrogen4EU: charting pathways to enable net zero*, has been published which delivers a comprehensive analysis of the dynamics of the European energy transition, and of the contribution of renewable and low-carbon hydrogen to European climate objectives. This report, prepared by a research consortium composed of IFPEN, SINTEF and Deloitte Finance, and financed by Concawe and important stakeholders in the low-carbon and renewable hydrogen value chain, is based on unique and extensive energy and transport modelling. It seeks to inform industry players and policy makers to foster the development of an optimal pathway for Europe's energy transition that leverages the full potential of low-carbon and renewable technologies to achieve net-zero emissions by 2050 at the least cost. This article provides a summary of the analysis.

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Blends of gasoline, diesel fuel and ethanol ('dieseline') have shown promise in engine studies examining low-temperature combustion using compression ignition. However, unlike gasoline or diesel fuel alone, such mixtures could be flammable in the headspace above the liquid in a vehicle fuel tank at common ambient temperatures. It is therefore important to understand the flammability characteristics of such mixtures.

The addition of a small amount of gasoline to diesel fuel can lower the flashpoint to give a flammable mixture. However, further gasoline addition can make the vapour too rich to burn, and hence the parameter of most interest is the upper flammability limit (UFL) temperature. A mathematical model designed to predict the flammability of dieseline blends, including those containing ethanol, was developed and validated experimentally, and used to study the flammability of a wide variety of dieseline blends parametrically. Explicit correlation equations have also been derived which enable the model to be implemented.

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Sustainable biomass availability in the EU towards 2050 (RED II Annex IX, Parts A and B)

This article summarises a study undertaken to estimate the potential sustainable biomass availability in the European Union and the UK by 2030 and 2050, and to assess the production of sustainable advanced biofuels for 2030 and 2050 on the basis of this biomass potential.

Author

Alba Soler

Objective

Within the framework of the European Commission's long-term strategy, Concawe's cross-sectoral Low Carbon Pathways project identifies opportunities and challenges for different low-carbon technologies and feedstocks, and their potential to achieve a significant reduction of the CO_2 emissions associated with both the manufacturing and use of refined products in Europe in the medium (2030) and longer-term (2050). Accessibility to sustainable low-carbon biofeedstock is one of the key drivers to achieve a low-carbon EU economy by 2050.

In this context, one of the key questions regarding the role of biofeedstocks in the transport sector is the potential availability of sustainable biomass (included in Annex IX, Parts A and B of RED II[1]) in the EU and UK, and under which conditions and assumptions biomass availability can be improved and biomass potential maximised safely and sustainably by 2050 without any negative impacts (e.g. by preserving natural high-value areas, maintaining and improving biodiversity, and reducing the use of arable land as well as the use of fertilisers and other chemical inputs).

This article summarises a study undertaken by Imperial College Consultants at the request of Concawe, the results of which have been published in a report entitled *Sustainable biomass availability in the EU, to 2050*.[1] The work presented in the report covers only domestic (EU-27 + UK) feedstocks of agricultural, forest and waste origin included in Annex IX of RED II (Parts A and B as shown in Table 1) and imports to the EU. A short overview of the potential for imports to the EU and the potential algae availability, based on other studies, is included as an annex in the Imperial College report.

The biomass feedstocks included in Annex IX (Parts A and B) which have been considered in the Imperial College study are presented in Table 1 on page 5.[2] Food and feed crops, and other sustainable feedstocks accepted by RED II but not included in Annex IX, are not included in the scope of this study.

1 https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

2 Feedstocks from (g) to (n) from Annex IX Part A have not been included because there were no consistent statistical datasets available at the time of the study. These include: (g) Palm oil mill effluent and empty palm fruit bunches; (h) Tall oil pitch; (i) Crude glycerine; (j) Bagasse; (k) Grape marcs and wine lees; (l) Nut shells; (m) Husks; and (n) Cobs cleaned of kernels of corn.

Table 1: Biomass feedstocks from RED II Annex IX (Parts A and B) considered in the Imperial College study

RED II Annex IX, Part A	Agricultural feedstocks	Forest feedstocks	Bio-wastes	Algae
(a) Algae if cultivated on land in ponds or photobioreactors				Overview based on recent studies
(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC			Paper, cardboard, wood waste, animal and mixed food waste, vegetal waste, municipal solid waste	
(c) Bio-waste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive			Paper, cardboard, wood waste, animal and mixed food waste, vegetal waste, municipal solid waste	
(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale, and the agro-food and fish and aquaculture industries, and excluding feedstocks listed in Part B of this Annex	Secondary agricultural residues from agro-industries			
(e) Straw	Cerial, straw, maize stover			
(f) Animal manure and sewage sludge	Solid and liquid manure from poultry, pigs, cattle		Sewage sludge	
(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely bark, branches, pre-commercial thinnings, leaves, needles, treetops, sawdust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil		Primary forest residues, secondary forest residues		
(p) Other non-food cellulosic material	Oilseed crop residues, agricultural prunings			
(q) Other lignocellulosic material except saw logs and veneer logs		Stemwood (fuelwood), post-consumer wood		
RED II Annex IX, Part B				
(a) Used cooking oil			Used cooking oil	
(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No. 1069/2009.			Animal fats categories 1 and 2 are included in Animal and mixed food waste	

Part 1: Sustainable biomass availability for all markets and bioenergy

Methodology

This study capitalises on knowledge and findings from relevant initiatives and studies that have addressed feedstocks across all EU Member States3 [2,3,4] using harmonised datasets and methodological approaches.[5]

Among these, the authors have focused, in particular, on the following work conducted by the European Commission's Joint Research Centre (JRC) and the Commission's Directorate General for Research and Innovation (DG RTD):

- JRC (2015). 'ENSPRESO - an open data, EU-28 wide, transparent, and coherent database of wind, solar and biomass energy potentials' (website, updated 2019).[6]
- DG RTD (2017). *Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe*.[7]

The study, conducted by Imperial College Consultants at the request of Concawe, considers up-to-date assumptions, that are in line with the European Green Deal, about the sustainable increase of available European biomass, acknowledging the biophysical restrictions of land resources and feedstocks as well as the adverse effects of climate change (e.g. desertification, reduced yields, land marginalisation, etc.).

The study integrates the counterbalancing mechanisms of using new machinery, efficient crop management practices (seeding/irrigation systems, crop rotation, cover crops, agroforestry and disease control in the field) as well as precision farming, which will allow the development of plants to be monitored in the field to better target their needs and ease farm management.

A detailed annex is included in the main report, describing the methodologies used for the estimation of sustainable biomass availability.

3 Studies undertaken before 2020 include data from the UK.

Scenarios for future biomass availability

Key assumptions

This section outlines the key assumptions for the scenarios examined in the study (no double counting has been taken into account in this study). All scenarios were developed in accordance with the following principles:

1. **A strong political will to deliver the European Green Deal targets and increase societal awareness that biomass availability is essential to achieve the transition to a zero-carbon, zero-pollution economy towards 2050**
   The target to cut emissions to at least 55% of 1990 levels by 2030 has been set[8] within the European Green Deal, and the European political system has reacted positively. To achieve carbon neutrality by 2050, the agriculture, forestry and other land use (AFOLU) sector has been targeted with the goal of becoming carbon neutral by 2035.[8] This implies improvements in cropping and forest practices, and a reduction in the amount of arable land in favour of environmental benefits such as carbon storage, biodiversity, etc.

2. **Covid-19 has shifted attention and the funding focus to the transition for achieving zero carbon through economic recovery, social resilience and welfare**
   As the 2020 Covid-19 pandemic spread reapidly, the focus on the European Green Deal diminished and attention shifted to economic recovery and social resilience. The study considers that the pandemic is not having a negative impact on biomass deployment but a positive one, as an effective economic recovery can stimulate the broadening of the biomass feedstock base which, in turn, will result in economic benefits for local producers.[9,10]

3. **RED II and Annex IX set the regulatory framework for advanced biofuels, bioliquids and biomass fuels**
   Within the 14% target of renewables in the transport sector, the RED II Directive establishes a dedicated target for advanced biofuels and biogas produced from the feedstocks listed in Part A of Annex IX. The contribution of advanced biofuels as a share of the final energy consumption in the transport sector shall be at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030 (double counted). Part B of Annex IX also includes feedstocks for the production of biofuels and biogas for transport, for which the contribution towards the minimum share of 14% shall be subject to a cap. These fuels may also be considered to be twice their energy content, and include (a) used cooking oil and (b) animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.[4]

   This study assesses the role of biomass in meeting both the 2030 and the 2050 targets as set by RED II and the European Green Deal, taking into consideration the respective ambitions announced by the aviation and maritime sectors.[11,12,13] The focus of the study is on the feedstocks listed in RED II Annex IX Parts A and B.

[4] https://www.legislation.gov.uk/eur/2009/1069/introduction

The European Commission is currently undertaking a study[14] to establish a longlist of potential feedstocks which could be added to the feedstocks already listed in Parts A and B of Annex IX. Feedstocks under consideration include: potato/beet pulp; sugars (fructose, dextrose); molasses; vinasses; spent grains; whey permeate; olive pomace; raw methanol; oil, beans and meals derived from rotation crops; biomass from fallow land; biomass from degraded/polluted land; mixture meadow; damaged crops; animal residues (not fat; Categories 2 and 3); animal fats (Category 3); municipal wastewater and derivatives (other than sludge); soapstock and derivatives; brown grease; fatty acid distillates (FADs); various oils from ethanol production; distillers' grain and solubles (DGS); and other bio-waste.

From the above list, the Imperial College study considers biomass from degraded land only where lignocellulosic biomass crops can be grown. The study does not consider the other feedstocks due to insufficient statistical time series data to form a dataset comparable to the ones used for all countries for agriculture, forestry and wastes.

Food and feed crops, and other feedstocks that are currently used in the EU for biofuel production and accepted by the RED but not included in RED II Annex IX, are not included in the study.

4. **Low-indirect land-use change (ILUC) risk concept**

The RED II Directive introduces the concept of low-ILUC risk biofuels, bioliquids and biomass fuels, which will represent one of the main options for maintaining the current shares of renewables in transport, and for the further development of the market potential for sustainable biofuels in Europe from 2023 onwards, especially in sectors with limited short-term alternatives such as the aviation, heavy-duty road transport and maritime sectors.

The criteria for certification of low-ILUC risk biofuels, bioliquids and biomass fuels have been outlined in Commission Delegated Regulation (EU) 2019/807 of 13 March 2019,[15] supplementing Directive (EU) 2018/2001. This Delegated Regulation defines low-ILUC risk biofuels, bioliquids and biomass fuels as those 'that are produced under circumstances that avoid ILUC effects, by virtue of having been cultivated on unused,[5] abandoned[6] or severely degraded[7,8] land or emanating from crops which benefited from improved agricultural practices.[15,16]

This study includes the low-ILUC risk concept in the scenario assumptions by addressing improved yields and exploitation of unused, abandoned or severely degraded land for biomass production.

[5] 'Unused land' means areas which, for a consecutive period of at least 5 years before the start of cultivation of the feedstock used for the production of biofuels, bioliquids and biomass fuels, were neither used for the cultivation of food and feed crops, other energy crops nor any substantial amount of fodder for grazing animals;

[6] 'Abandoned land' means unused land, which was used in the past for the cultivation of food and feed crops but where the cultivation of food and feed crops was stopped due to biophysical or socioeconomic constraints;

[7] 'Severely degraded land' means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.

[8] The definition for marginal land has not yet been clearly defined.

5. **Biomass for bio-based products**

   The allocation of raw biomass materials to biobased products (bioplastics, biopharmaceuticals, construction materials, biochemicals, etc.) in this study has been performed by estimating the baseline sustainable potentials for all uses (i.e. bioenergy and bio-based products) and deducting the demand for each feedstock category and sector based on the projections of the CAPRI model[9] and statistics from the JRC.[10] The remaining potential is then considered as being available for all bioenergy applications (transport, heat, power, industry, agriculture, service and buildings).

6. **Biodiversity**

   The study accounts for biodiversity risks as defined in the RED II Directive. Biomass availability increases in all three scenarios evaluated (explained below) without including biomass from:

   - conservation of land with significant biodiversity values (such as areas of High Nature Value (HNV), NATURA 2000 areas, etc.) which usually includes protected sites — no such land is considered as being available for biomass feedstocks in this study; and
   - land management that has negative effects on biodiversity — the study accounts for cultivation practices which are based on the following principles: use of domestic species and local varieties; avoiding monocultures and invasive species; preferring perennial crops and intercropping; use of methods causing low erosion and machinery use; low fertilizer and pesticide use; and avoiding active irrigation.

7. **Imports**

   Imported lignocellulosic biomass (pellets from agricultural residues, wood pellets and used cooking oil) for bioenergy is addressed in this study (detailed in Annex II of the Imperial College report) based on recent statistics and projections from recent relevant literature.[17,18,19]

Scenarios

Three scenarios have been analysed in the study:

1. Low biomass mobilisation.
2. Improved mobilisation in selected countries due to improvements in cropping and forest management practices.
3. Enhanced availability through research and innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices.

[9] https://www.capri-model.org/dokuwiki/doku.php

[10] Data-Modelling platform of agro-economics research (European Commission) https://datam.jrc.ec.europa.eu/datam/public/pages/index.xhtml

1. Scenario 1: Low mobilisation (Low)

This scenario assumes low mobilisation of biomass for both 2030 and 2050. Key assumptions include:

- farming and forest practices at 2020 levels;
- a small proportion (25%) of unused, abandoned and degraded land is used for biomass crops; and
- emphasis is placed on the use of residues and wastes in the energy and non-energy bio-based sectors.

2. Scenario 2: Improved mobilisation in selected countries (Medium)

This scenario focuses on the improved mobilisation of biomass resulting from enhanced cropping and forest management practices. These practices take place in countries with:

i) high biomass availability (total estimated biomass potential ≥20 million tonnes per year) and in combination with either good institutional framework, established policies/targets for bioenergy or advanced biofuels, strong infrastructure and strong innovation profiles (Germany, France, Sweden, Finland, Italy, United Kingdom, Austria, Spain); or

ii) low biomass supply costs (Poland, Romania, Czech Republic, Hungary, Bulgaria).

Key assumptions include:

- improved management practices in (i) agriculture, such as crop rotation, cover crops, agroforestry, etc., which can improve soil and increase biomass productivity, and (ii) forestry, such as improved harvesting techniques, fertilisation (where possible), storage and transport optimisation, etc.;
- a significant proportion (50%) of unused, abandoned and degraded land is used for biomass crops; and
- emphasis remains on the use of residues and wastes in the energy and non-energy bio-based sectors.

3. Scenario 3: Enhanced availability through R&I and improved biomass mobilisation (High)

This scenario applies the highest rates for assumptions on increased mobilisation, as well as increased improvements in management practices, which can maximise the availability of sustainable biomass across all feedstocks.

Key assumptions include:

- improved management practices in (i) agriculture, such as crop rotation, cover crops, agroforestry, etc., which can improve soil and increase biomass productivity, and (ii) forestry, such as improved harvesting techniques, fertilisation (where possible), storage and transport optimisation, etc.;
- a significant proportion (75%) of unused, abandoned and degraded land is used for biomass crops;
- improved R&I; and
- emphasis remains on the use of residues and wastes in the energy and non-energy bio-based sectors.

In the three scenarios, biodiversity is included in the estimated potentials, accounting for:

i) conservation of land with significant biodiversity values (direct and indirect); and

ii) land management without negative effects on biodiversity.

Table 2 on page 11 shows the main assumptions for the three scenarios examined.

Table 2: The main assumptions of the three scenarios analysed in the study

		Scenario 1 (Low)	Scenario 2 (Medium)	Scenario 3 (High)
Agriculture	Removal rate of field residues	40%	45%	50%
	Use of prunings	5%	20%	50%
	Moderate yield increases in perennial lignocellulosic crops in unused, degraded and abandoned land	1%	1%	2%
	Share of unused, degraded and abandoned land for dedicated crops, excluding biodiversity-rich land and land with high carbon stocks (current share of unused, degraded and abandoned land for dedicated crops: there are no official statistics—only at experimental and demonstration scale)	25%	50%	75%
Forestry	Stemwood used for energy purposes (current stemwood for energy: 45%)	25%	30%	50%
	Primary forestry residues availability for energy production	40%	50%	60%
	Secondary forestry residues and post-consumer wood availability for energy	55%	60%	65%
Wastes	Bio-waste used for energy production (current collection for bioenergy: 40–45%)	60% in 2030 (65% in 2050) of bio-waste is recycled and 40% in 2030 (35% in 2050) is separately collected and available for bioenergy	50% in 2030 (55% in 2050) of bio-waste is recycled and 50% in 2030 (45% in 2050) is separately collected and available for anaerobic digestion	40% in 2030 (45% in 2050) of bio-waste is recycled and 60% in 2030 (55% in 2050) is separately collected and available for anaerobic digestion

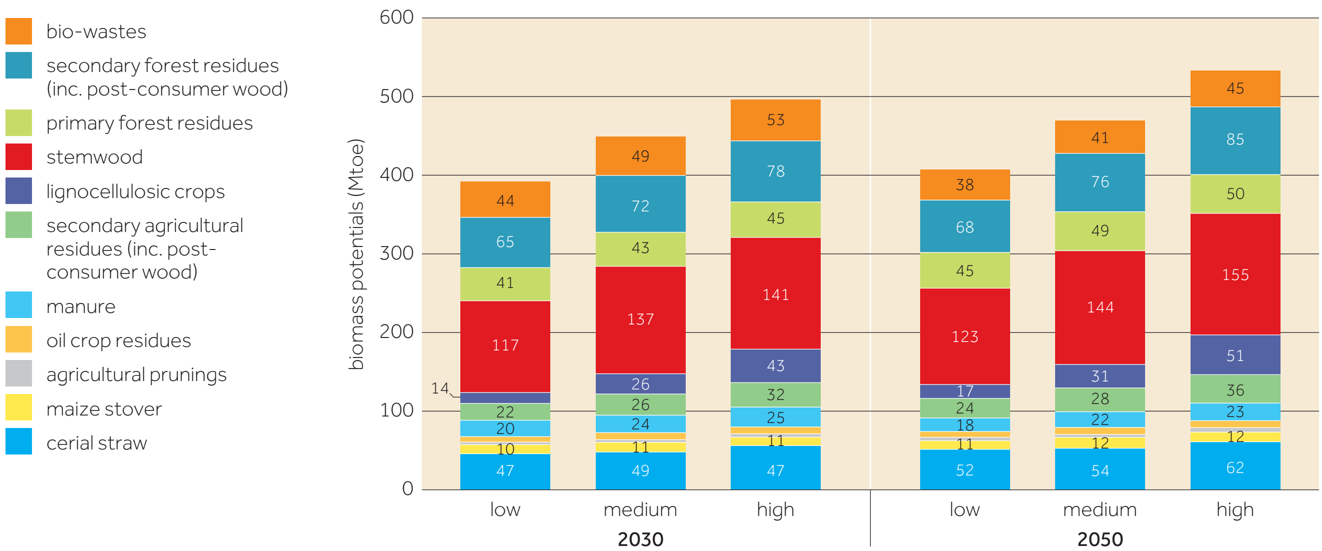
Sustainable biomass availability in the EU towards 2050 (RED II Annex IX, Parts A and B)

Results

Biomass availability for all markets in the EU & UK in 2030 and 2050

This section provides an overview of the estimated sustainable biomass potential from agriculture, forestry and bio-wastes that can be available for all markets (i.e. energy and non-energy markets). The estimated figures for 2030 range from 0.98 to 1.2 billion dry tonnes (392 to 498 Mtoe). The respective numbers for 2050 remain similar and range from 1 to 1.3 billion tonnes (408 to 533 Mtoe).

Figure 1: Estimated total sustainable biomass potentials (RED II Annex IX, Parts A and B) in 2030 and 2050 for all markets



Biomass availability excluding potential demand for non-energy uses (biomass for bioenergy) in the EU and UK in 2030 and 2050

This section presents the estimated biomass potentials for bioenergy (transport, heat and power) (excluding demand for non-energy uses (plastics, pharmaceuticals, etc.). The estimated figures for 2030 range from 520–860 million dry tonnes (208–344 Mtoe) for 2030. The respective numbers for 2050 remain similar and range from 539–915 million dry tonnes (215–366 Mtoe).

The reasons why potentials remain unchanged between 2030 and 2050 despite improvements in biomass mobilisation and increased innovation for higher yields are mostly related to:

- strong pressure for the sustainable use of land and water resources, including a 30% reduction in arable land by 2050;
- the fact that improvements in forest management are slow due to the long growing cycles of forests that prohibit fast changes in growth of potentials; and
- increased awareness of the need for waste reduction and strong commitments to recycling.

Figure 2: Estimated sustainable biomass potentials (RED II Annex IX, Parts A and B) than can be available for bioenergy in 2030 and 2050

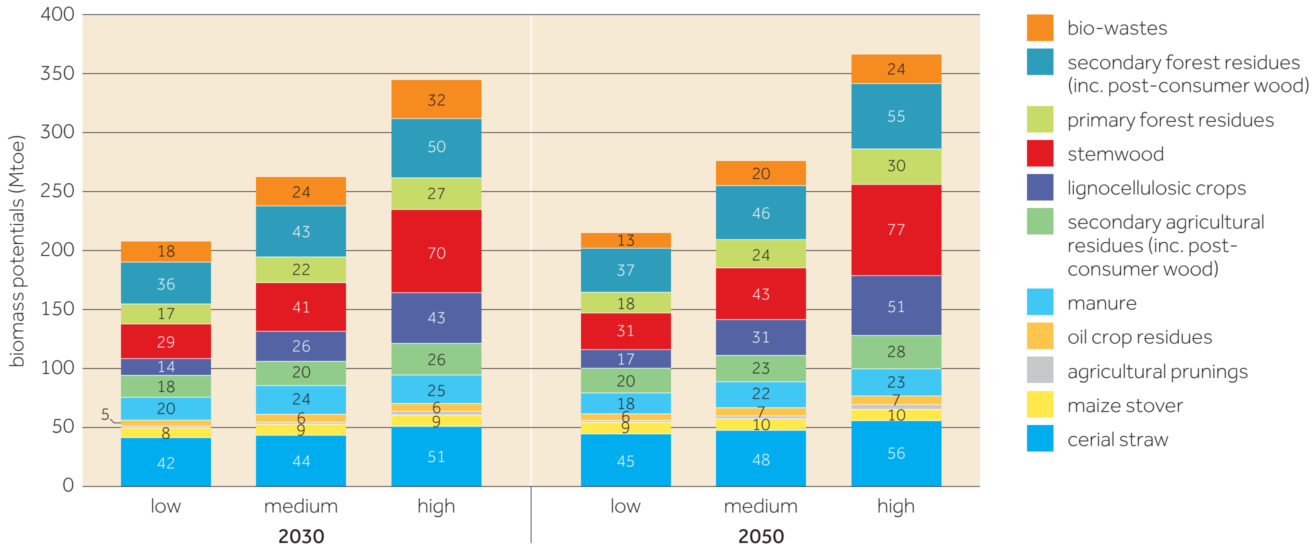
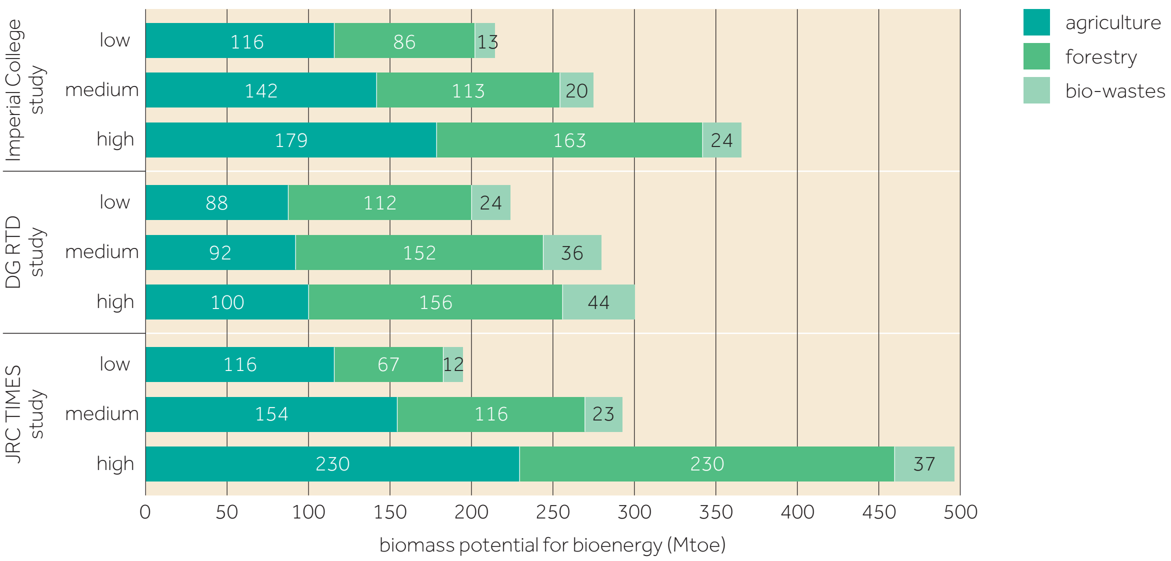


Figure 3 presents comparative estimates of the biomass potentials for bioenergy in the Imperial College, DG RTD and JRC (ENSPRESO database) studies based on feedstocks from Annex IX, Parts A & B (as detailed in Table 1). The potential longlist of feedstocks that are under consideration by the European Commission for inclusion in Annex IX is not included in the figures below.

Figure 3: Comparative estimates for biomass potentials (Mtoe) for bioenergy in the Imperial College, DG RTD and JRC TIMES (ENSPRESO database) studies for 2050



Imperial College's estimation of biomass availability in the High scenario is 22% higher than in the DG RTD high scenario, and 26% lower than JRC TIMES high scenario. The JRC TIMES high scenario gives the technical maximum that can be achieved, without sustainability criteria, allowing dedicated cropping in high biodiversity lands and including first-generation biofuel crops. It cannot be considered for future projections within the EU Green Deal targets.

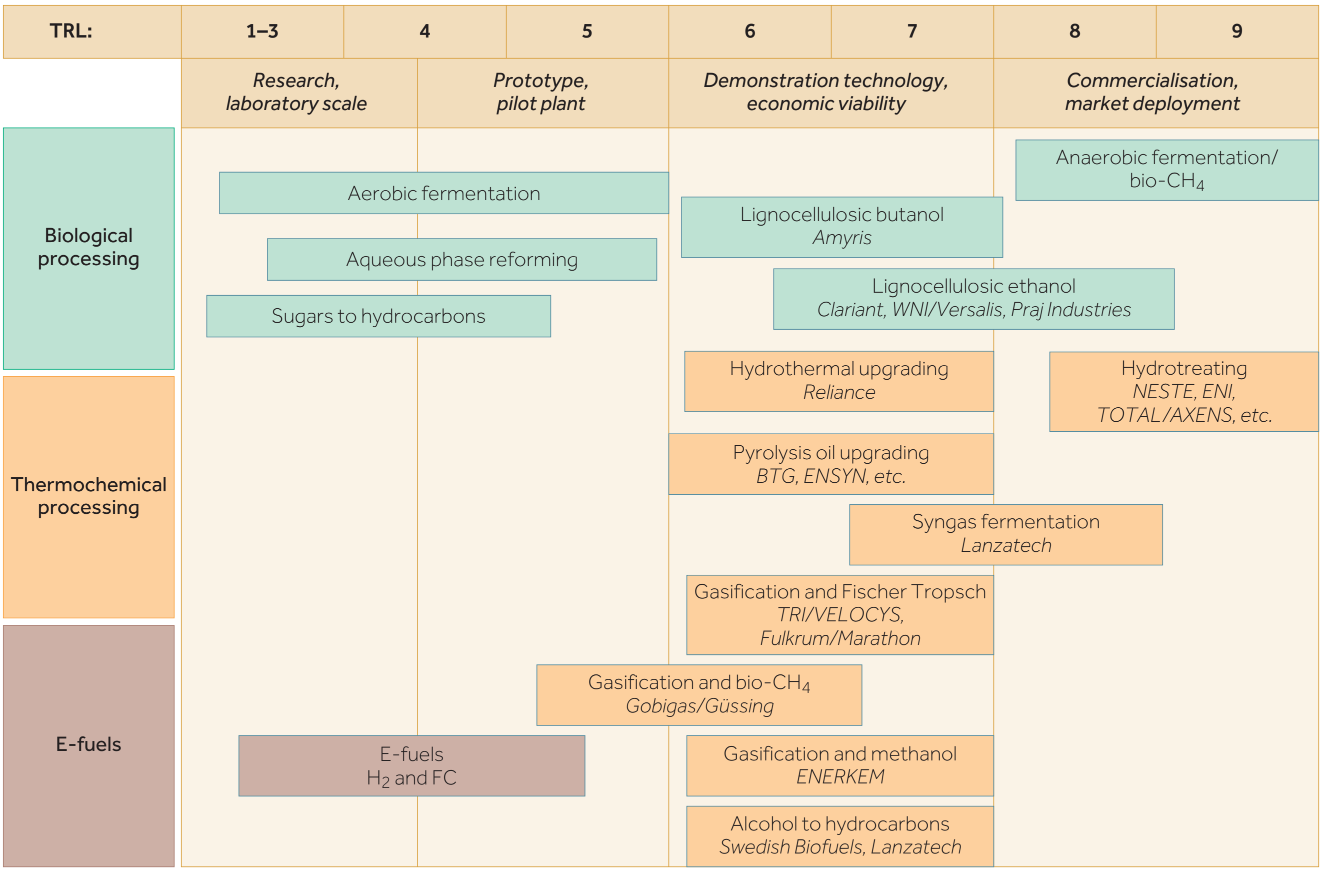
Part 2: Potential biofuel production

Part 2 of the study presents the status of the various technologies and value chains based on their maturity for market deployment, and assesses the potential production of sustainable advanced biofuels for 2030 and 2050 on the basis of the biomass potentials calculated in Part 1.

Biofuel technologies and technology readiness level

A summary of advanced biofuel technologies and their technology readiness levels is presented in Figure 4.

Figure 4: Simplified presentation of technologies and value chains for advanced biofuels



Methodology

A maximum biofuel potential scenario has been estimated considering:

- the sustainable biomass availability per type of feedstock for all bioenergy sectors (2030/2050 Low/High scenarios);
- the available technologies for advanced biofuels per type of feedstock, and the TRL in a given time frame; and
- the maximum conversion yields per type of biomass and feedstock (including conversion efficiency maximization due to H_2 enhancement).

Results

Table 3 summarises the potential advanced biofuel production per feedstock in 2030 and 2050, considering the maximum yields per pathway and the total sustainable biomass for bioenergy calculated in Part 1.

Table 3: High technology scenario: potential advanced biofuel production per feedstock in 2030 and 2050, taking into account the maximum yields per pathway and the total sustainable biomass for bioenergy

Biofuel	Feedstock	2030 estimated advanced biofuel quantity (Mtoe)	2050 estimated advanced biofuel quantity (Mtoe)
Hydrotreated vegetable oil/ renewable diesel	Waste oils and fats	1.9	1.9
	Used cooking oil	2.6	6.5
Biomethane	Sewage sludge	0.1–0.2	1.0–1.2
	Manure (solid and liquid)	1.1–1.3	0.4–0.4
	Agricultural residues (high moisture, sugar beet leaves, etc.)	0.1	0.1
Ethanol and hydrocarbons from enzymatic hydrolysis and fermentation	Agricultural residues (straw-like)	21.0–25.3	N/A
	Lignocellulosic crops (grassy)	5.5–16.6	6.5–19.6
	Biowaste	9.2–16.8	13.2–24.4
Fischer Tropsch from gasification + catalytic synthesis	Solid industrial waste (secondary agricultural and forest industries)	27.9–40.1	56.8–84.0
	Agricultural residues (straw-like)	N/A	54.4–62.4
	Agricultural (woody) and forestry residues	1–1.5	2.4–3.2
	Lignocellulosic crops (woody)	7.6–22.7	16.8–50.8
	Totals	**78.0–129.1**	**160.0–254.5**
	Total liquid advanced biofuels taking into account the total sustainable biomass for bioenergy	**76.7–127.5**	**158.5–252.8**
	Average conversion yield on an energy basis	**37%**	**70%**
	Average conversion yield on a dry mass basis	**15%**	**29%**

A look into demand versus availability

It should be noted that a part of the total sustainable biomass available for bioenergy could potentially be used for power, industry, services and agriculture, and residential heat demand in 2030 and 2050; this will decrease the amount of feedstock available for advanced biofuel production.

No allocation to transport has been developed in this study due to the absence of an economic model. Reference was made to the use of bioenergy estimated by the European Commission in the recently published Impact Assessment[20] (allocation of about 130 Mtoe for 2030 and 170 Mtoe for 2050), as shown in Figure 5.

Figure 5: Use of bioenergy estimated by the European Commission in the recently published Impact Assessment[20]

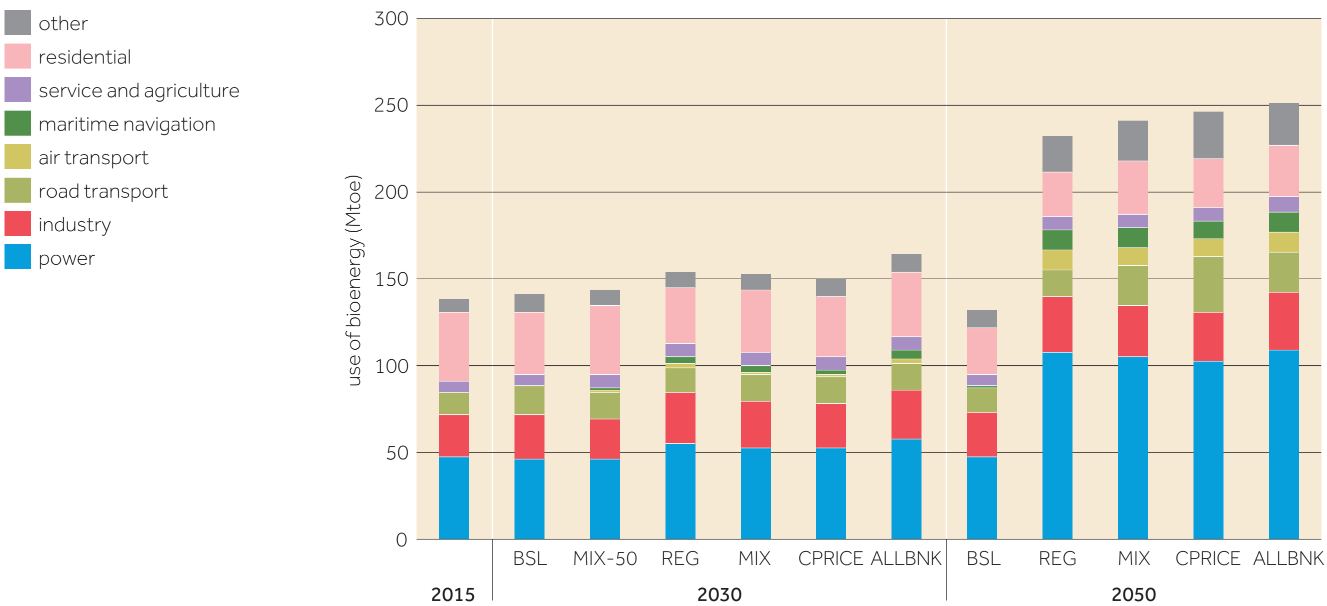


Table 4 on page 17 shows the amount of biomass available for bioenergy according to the Imperial College study, together with with an estimate of biomass imports. The allocation of biomass to non-transport-related uses according to the European Commission's model is also shown, and its impact on the total estimated amounts of biomass available for biofuels in transport is shown both with and without biomass imports.

Table 4: The estimated amount of biomass available for biofuels in transport after accounting for the PRIMES allocation to other, non-transport sectors (both with and without biomass imports)

	2030	2050
Estimated biomass available for bioenergy, excluding imports, in the Imperial College study	208–344*	215–366*
Estimated biomass imports in the Imperial College study — Annex 2 in the full report	48	56
Estimated use of biomass for other non-transport related uses according to the European Commission's PRIMES model	130	170
Estimated biomass available for advanced biofuels, i.e. the balance of biomass available for biofuel, excluding imports, after accounting for the demand for other uses estimated by the PRIMES model	**78–214***	**45–196***
Total estimated biomass left for biofuels in transport, including imports	**126–262***	**101–252***

* The ranges shown correspond to the lowest and highest biomass availability scenarios.

It can be seen from Table 4 that the total estimated net biomass available for biofuel production, after including imports (amounting to 48 Mtoe in 2030 and 56 Mtoe in 2050) and allowing for the use of biomass for other non-transport-related uses (power, industry, service, agriculture and residential, amounting to a total of 130 Mtoe in 2030 and 170 Mtoe in 2050 according to the European Commission's Impact Assessment[20]) is estimated between 126–262 Mtoe for 2030 and 101–252 Mtoe for 2050.

Table 5 summarises the potential sustainable biofuel availability for the production of advanced and waste-based biofuels as defined in the first part of the study (ranges correspond to low/high availability in the High technology conversion scenario, and are shown both with and without the bioenergy sectors and imports considered).

Table 5: Summary of potential biofuel availability (Mtoe)

	Potential biofuel availability — all bioenergy		Potential biofuel availability — allocation to transport based on the PRIMES model	
2030	Potential advanced and waste-based biofuels (EU domestic production)[a]	Potential advanced and waste-based biofuels (EU + imports)[a]	Potential advanced and waste-based biofuels adjusted according to the PRIMES allocation to the non-transport sector (EU domestic production)	Total potential advanced and waste-based biofuels (EU + imports)
	76.7–127.5	94.5–145.3	28.9–79.2	46.7–97.0
2050	Potential advanced and waste/based biofuels (this study)[a]	Potential advanced biofuels, estimated due to imports (this study)	Potential advanced biofuels, adjusted according to the PRIMES allocation to the non-transport sector	Total potential advanced biofuels (EU + imports)
	158.5–252.8	197.7–292	31.5–137.2[b]	70.7–176.4

[a] Potential advanced biofuels taking into account that all the bioenergy estimated in the Low and High scenarios of the Imperial College study were allocated to advanced biofuels for the transport sector. The ranges include the Low and the High biomass availability scenarios, taking into account the maximum conversion yields for the different pathways per type of feedstock.

[b] The potential for advanced biofuels is based on the estimated balance of biomass available for biofuels, and is an approximate estimation considering the same average conversion efficiency as in this study.

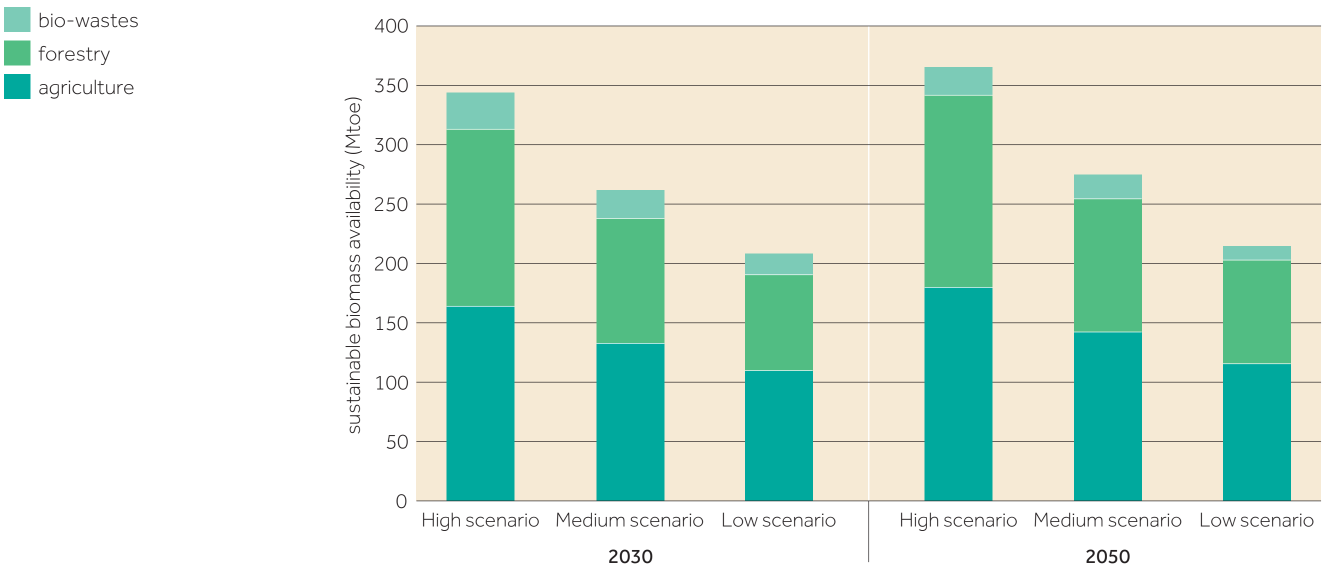
Conclusions

The estimation of the potential availability of sustainable biomass in the EU and the UK by 2030 and 2050 is focused only on the domestic feedstocks of agricultural, forest and waste origin included in Annex IX of RED II (Parts A and B); this is considered a conservative hypothesis assuming that more potential newcomers to Annex IX are currently being analysed by the EU Commission, and is summarised as follows:

- Sustainable biomass availability for all markets: 0.98–1.2 billion dry tonnes (392–498 Mtoe) in 2030, and 1–1.3 billion tonnes (408–533 Mtoe) in 2050.
- From these amounts, the estimated net amount of biomass available for bioenergy ranges from 520–860 million dry tonnes (208–344 Mtoe) in 2030, and 539–915 million dry tonnes (215–366 Mtoe) in 2050 (see Figure 6).

Important R&D developments and implementation of improved management practices are required to achieve this potential availability of biomass. Even if the potential is there, the supply chain would need to be developed to mobilise these resources.

Figure 6: Sustainable biomass availability (feedstocks included in RED II Annex IX, Parts A and B) for bioenergy in 2030 and 2050 as estimated in the Imperial College study



The total estimated net biomass available for biofuel production, after including imports (amounting to 48 Mtoe in 2030 and 56 Mtoe in 2050) and allowing for the use of biomass for other non-transport-related uses such as power, industry, service, agriculture and residential (amounting to 130 Mtoe in 2030 and 170 Mtoe in 2050 according to the European Commission's Impact Assessment[20]) is estimated at between 126–262 Mtoe for 2030 and 101–252 Mtoe for 2050. (Note that the ranges correspond to the lowest and highest biomass availability scenarios.)

Taking into account biomass transformation technologies in the higher TRLs, this could correspond to advanced and waste-based biofuel production of 46–97 Mtoe in 2030 and 71–176 Mtoe in 2050.

Tha fact that a lower availability of biomass in 2050 compared to 2030 leads to a higher production of biofuels in 2050 compared to 2030 is due to the increase in yields that could be achieved in 2050. By then, technologies such as gasification and Fischer-Tropsch could achieve higher conversion yields (from 21% wt in 2030 up to 40% wt in 2050) due to the use of renewable hydrogen.

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

The context

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

Author

Marta Yugo

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

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

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

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

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

Demand scenarios

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

- Scenario 1: High demand (all transport modes)

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

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

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

- Scenario 3: Low demand (aviation and maritime)

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

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

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

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

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

Notes:

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

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

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

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

Notes:

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

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

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

Low-carbon technologies

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

Low-carbon liquid fuels

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

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

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

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

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

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

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

Notes:

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

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

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

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

CO_2 reduction technologies

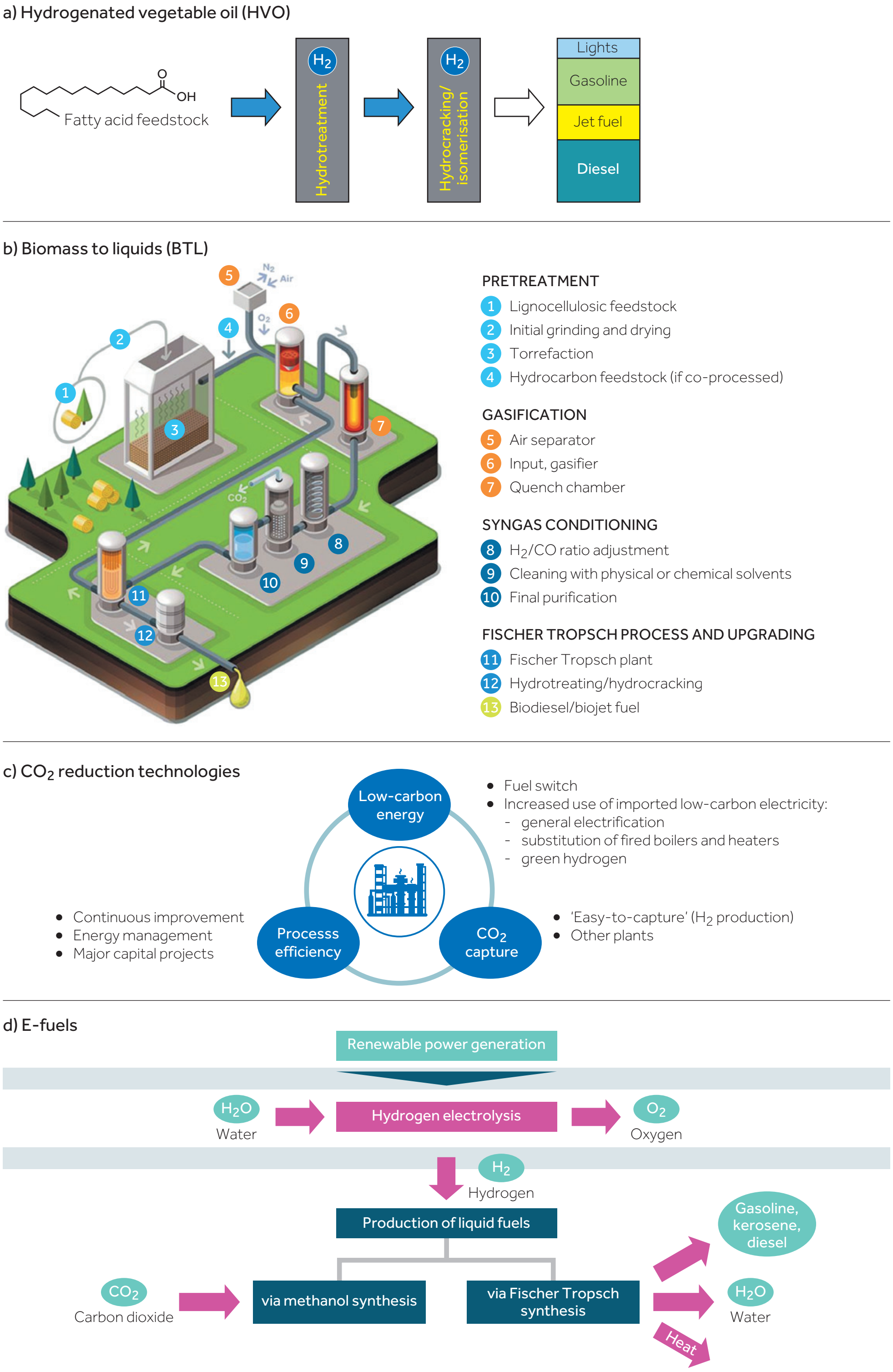
Other key CO_2 reduction technologies such as carbon capture and storage (CCS) and clean hydrogen (H_2) installed or linked to the refineries could help to reduce the carbon intensity of the fuels produced today (mostly from fossil origin) as well as moving forward, as they have clear synergies with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

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

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

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

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



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

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

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

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

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

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

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

Notes on Table 4:

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

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

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

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

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

Results

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

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

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

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

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

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

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

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

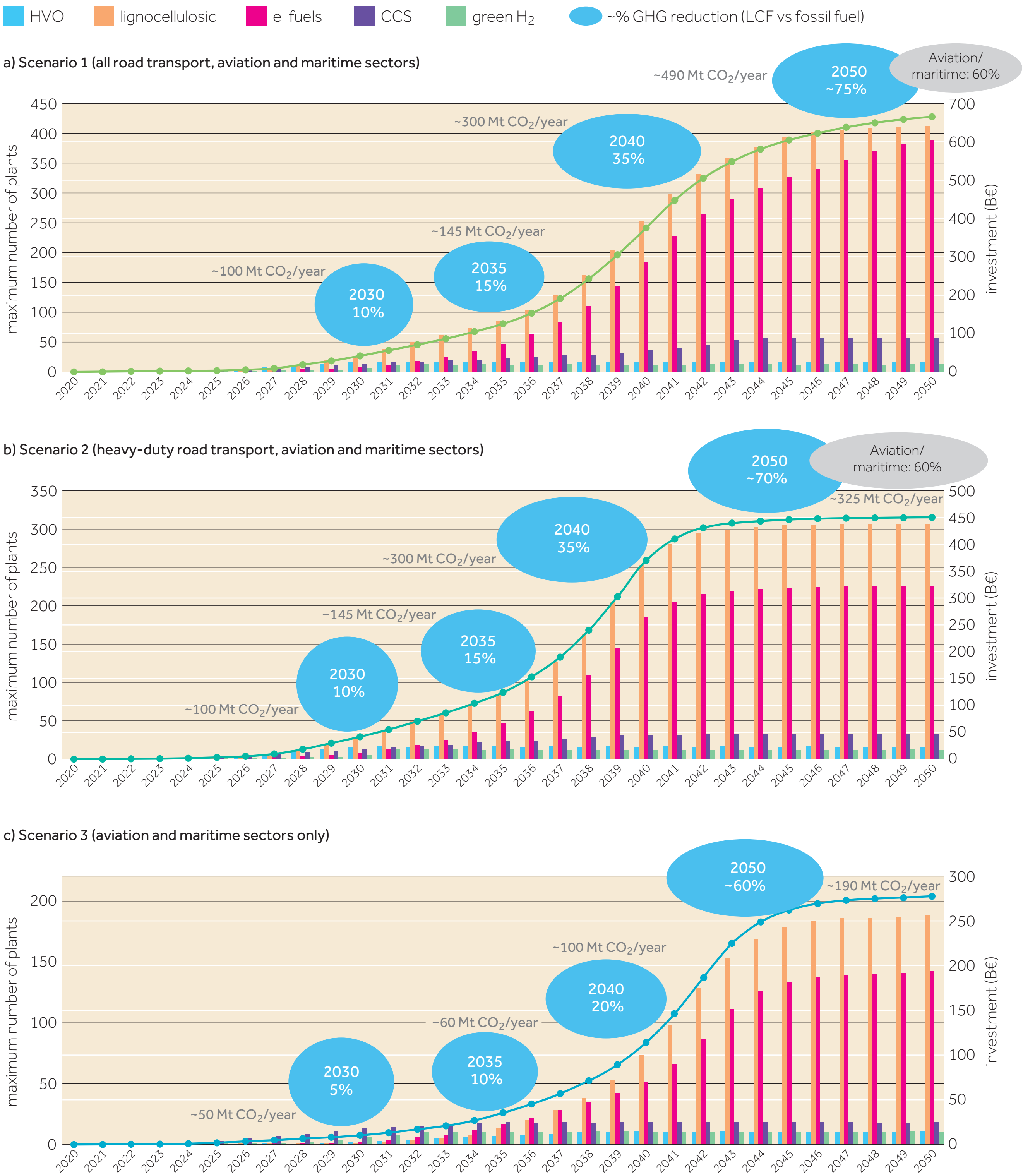
Figure 3 on page 31 builds on the data presented in Table 5 and illustrates the three scenarios graphically. Note that the grey text on each chart indicates the WTW GHG savings in Mtoe/year, while the figures in the blue ovals indicate the percentage reductions in GHG emissions compared to a 100% fossil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

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

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

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

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



A look into feedstock availability

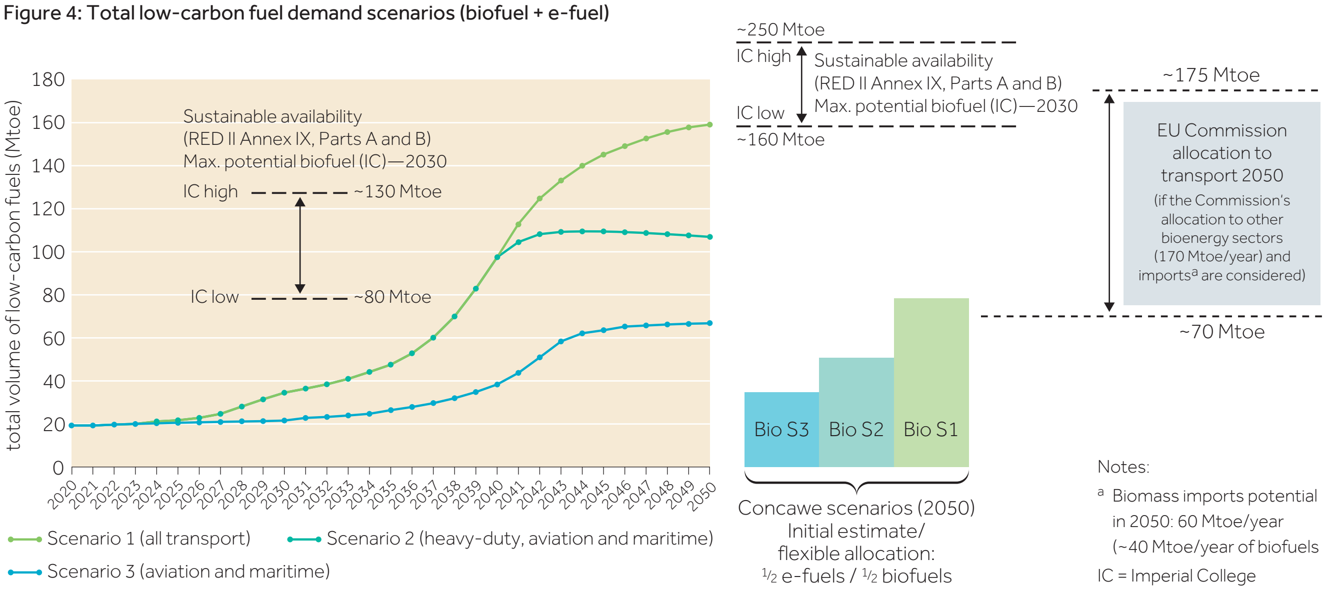
Complementing this study, a report recently published by Imperial College London[9] allows the comparison between the demand for LCF (assessed in the three scenarios described above) with the maximum potential sustainable feedstock availability for the bioenergy sector, with respect to the transport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

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

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

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

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



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

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

Important note

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

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Hydrogen for Europe

A new report co-financed by Concawe and a number of key stakeholders in the low-carbon and renewable hydrogen value chain details a study to assess the contribution of renewable and low-carbon hydrogen to achieving net-zero emissions in Europe by 2050. This article provides a summary of the analysis.

Author

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Introduction

About the study

The Hydrogen for Europe study is the result of a cross-sectoral and multidisciplinary research partnership that aims to inform the debate on the contribution of low-carbon and renewable hydrogen towards European energy transition goals. Based on sound analytics and robust scientific modelling prepared by the research partners (IFP Énergies Nouvelles (research), SINTEF Energi AS (research) and Deloitte Finance SAS (project management)), and advised by industry, policymakers, academics and civil society, the partnership aims to chart science-based pathways exploring the potential of hydrogen in a decarbonised European energy system. The study builds on current European Union (EU) targets and ambitions by filling the knowledge gap on how hydrogen may contribute to shaping the EU's energy landscape, and by assessing the support needed to realise this ambition. The research was funded by 17 partners (see Figure 1).

Figure 1: The research consortium and funding partners to the Hydrogen for Europe study

Reseach consortium

Funding partners

Methodology: scenarios and modelling

The study explores a mix of solutions and considers technological, sectoral and geographical projections across two potential pathways depicting alternative futures that lead to carbon neutrality:

1. The Technology Diversification pathway is based on already-approved national targets, and assumes no obstacles to the deployment of different technologies, as well as perfect market foresight on investment decisions. This pathway considers an array of decarbonisation technologies, deployed as needed, which allows for the de-risking of investments through the creation of a more competitive and efficient zero-carbon energy system.
2. The Renewable Push pathway prioritises the deployment of renewable energy through increased targets (beyond current policy goals) for the share of renewables in gross final energy consumption by 2050. While this pathway does not result in significant changes in consumption patterns, it sees a key role for hydrogen in helping to absorb, store and transport the additional energy resulting from the increased generation of renewables.

The Renewable Push pathway differs from the Technology Diversification pathway by way of a series of targets for the share of renewables in gross final energy consumption; these targets are more ambitious for 2030 compared to today's policy (40% versus 32% in the Technology Diversification pathway) and include binding targets for 2040 (60%) and 2050 (80%).

The results for each pathway are generated using three scientific models which consider the system life cycle (MIRET-EU), costs and investments (Integrate Europe) and external competition (Hydrogen Pathway Exploration—HyPE). Both pathways otherwise assume a level playing field between technologies.

The scientific models

The Hydrogen for Europe study relies on a detailed model-based analysis with a full representation of the European energy system and its transition from 2020 to 2050. The modelling architecture combines two state-of-the-art partial-equilibrium models (MIRET-EU and Integrate Europe) which have been enhanced specifically to tackle the objectives of the study. Both models are research-oriented tools, built on sound mathematical formulations, that have transparent modelling frameworks and deliver robust results. The HyPE model developed by Deloitte for this project is used to explicitly assess the potential of imports from neighbouring regions, thus going further than what is usually represented in European hydrogen studies and reflecting the recent expectations for the role of imports.

MIRET-EU

The MIRET-EU model encompasses the entire life cycle of an energy system, from primary resource to utilisation. This model is well suited to help decision makers as it provides data over medium- to long-term time horizons, and can easily contribute to energy roadmaps by providing clear information on technologies and fuels in all sectors based on data and expert knowledge. This model allows for great flexibility, and can take environmental emissions into account, as well as almost all policies at all levels.

Integrate Europe

Integrate Europe is a cost-minimisation and investment optimisation model for energy systems that assesses how to bring available energy to users in the most economical ways possible while complying with environmental targets. This model promotes early investment in promising technologies, even if they are not yet competitive in the market, as it recognises that this is key to driving down costs.

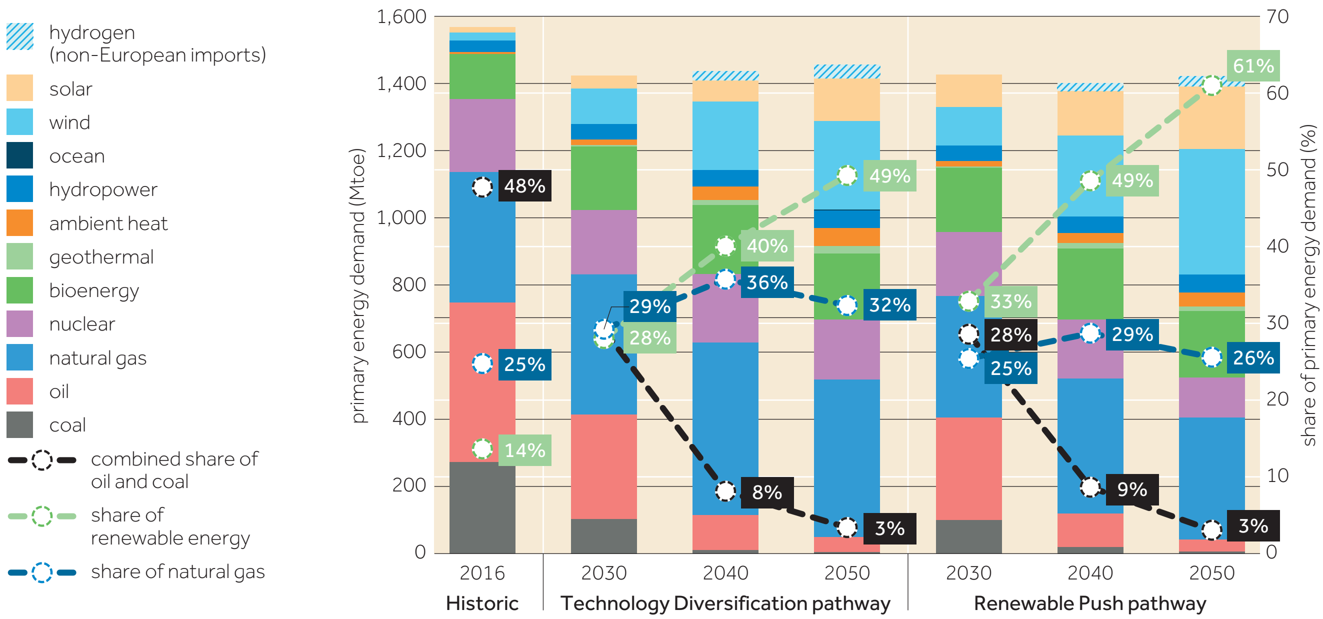
Hydrogen Pathway Exploration (HyPE)

HyPE provides the MIRET-EU and Integrate Europe models with low-carbon and renewable hydrogen imports from EU neighbours. This model represents competition between domestically produced hydrogen and imports, and is in line with the EU hydrogen strategy which focuses on clean hydrogen trade, and highlights the potential partnership with southern and eastern neighbourhood countries.

Primary energy demand and pathways to net zero emissions

In achieving net-zero emissions, the primary energy mix is fundamentally reshaped in the two pathways (see Figure 2). Primary energy demand sees a pronounced shift to renewable energy. The share of renewable energy in primary energy demand reaches up to 49% in 2040 and 61% in 2050 in the Renewable Push pathway, sustained mostly by significant investments in wind and solar. This uptake is mirrored by a declining role of oil and coal, for which the combined share of primary energy demand drops to 3% in 2050 in both pathways.

Figure 2: The evolution of total primary energy demand in the Technology Diversification and Renewable Push pathways, 2016 to 2050

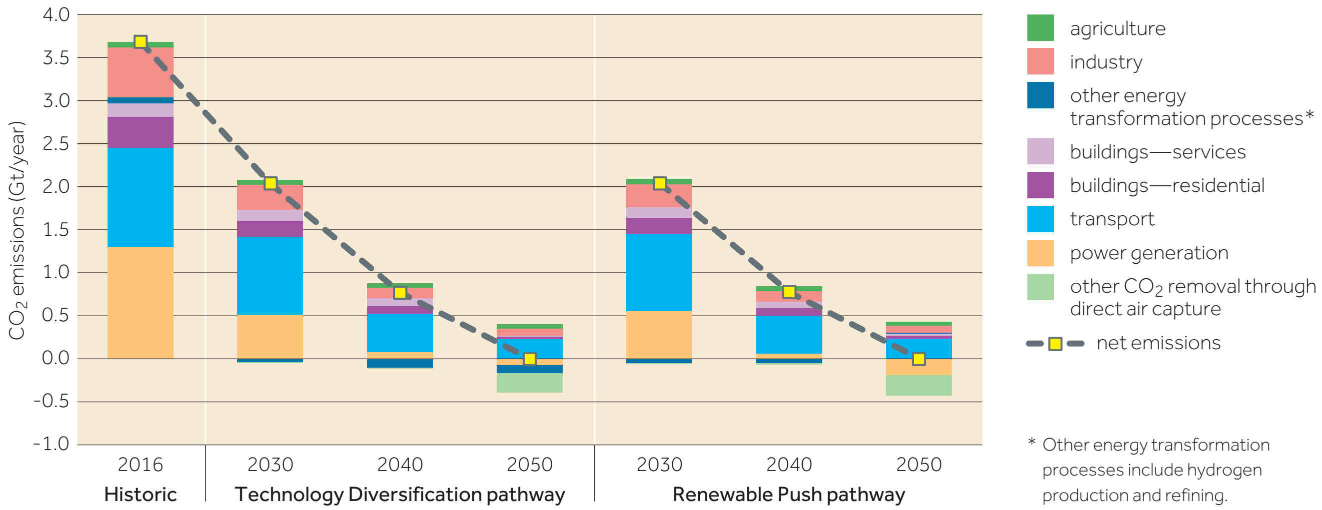


Natural gas is an element of continuity in the energy mix: the use of natural gas remains resilient in the Renewable Push pathway, where it provides important flexibility as a complement to renewables. Natural gas offers the greatest benefits when coupled with carbon capture, utilisation and storage (CCUS). Much of its use is thus transferred from final energy consumption to transformation processes, e.g. for hydrogen production, where low-carbon hydrogen helps to foster the growth of the hydrogen economy, or in power generation, where natural gas provides flexible power for load following and back-up generation.

At the final consumption level, energy efficiency and electrification play their expected role in the transition to net-zero emissions. Final energy consumption is reduced by nearly a quarter in 2050 when compared to 2005, achieving along the way the binding target of a 32.5% reduction by 2030 (compared to a business-as-usual scenario) for the EU member states. Electricity's share in gross final energy consumption increases by almost 50% between today and 2050, with step changes observed in industry, transport and buildings. While this confirms the high expectations put on electrification, it also highlights the complementary roles played by molecules and other energy carriers to decarbonise energy end-use; the Renewable Push pathway also foresees the accelerated deployment of renewables. In both pathways, more than half of total gross final energy consumption is supplied by non-electrified technologies in 2050.

The two pathways follow a progressive trajectory towards deep decarbonisation, and achieve climate neutrality by 2050 (Figure 3). By 2030, CO_2 emissions at the European level are reduced by 55% compared to 1990 levels. This reduction is led by fuel switching in the power and industry sectors. CO_2 emissions then continue to decrease precipitously to reach net-zero emissions in 2050. The results suggest that the development of a fully operational CCUS value chain (including carbon capture and storage from fossil fuels, biomass and direct air capture) is indispensable for the success of the energy transition. Negative emissions from biomass and direct air capture with carbon capture and storage (CCS) serve to offset the residual emissions from the hard-to-abate sectors.

Figure 3: The evolution of CO_2 emissions by sector in the Technology Diversification and Renewable Push pathways, 2016 to 2050



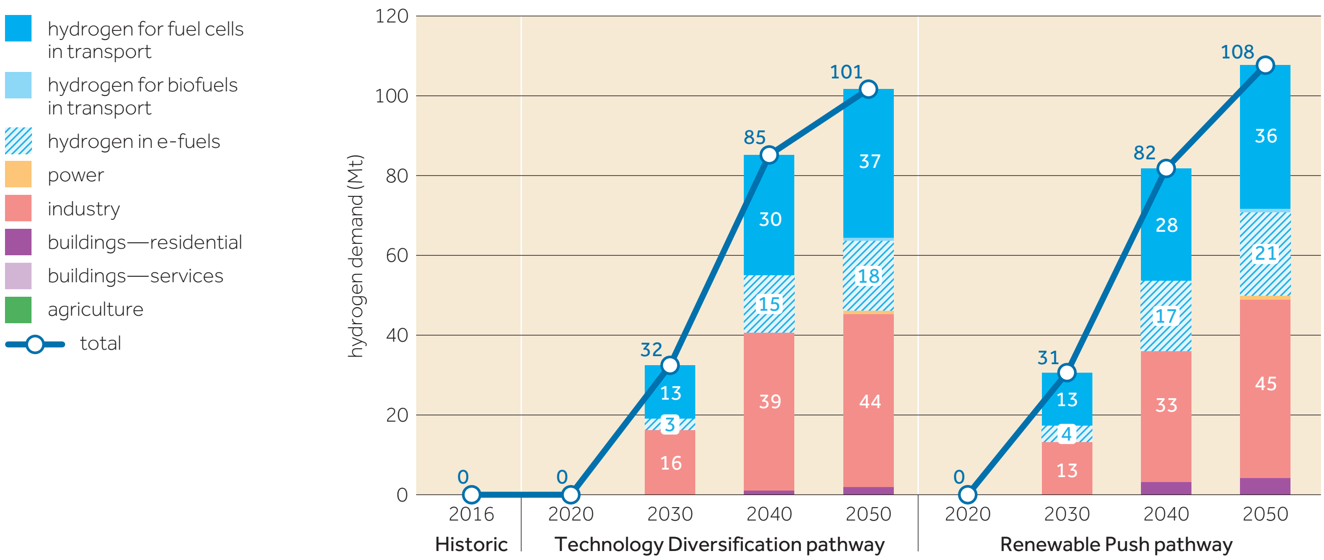
* Other energy transformation processes include hydrogen production and refining.

The hydrogen value chain

Hydrogen plays a major role in the decarbonisation of the energy sector. In light of the ambitious decarbonisation objectives, European hydrogen demand in these pathways exceeds 30 Mt by 2030, which is triple the current policy objective described in the EU's hydrogen strategy. The demand for hydrogen ramps up substantially in the 2030s and 2040s, and exceeds 100 Mt by 2050 in both pathways. This is equivalent to more than 3,300 TWh or around 300 Mtoe (in lower heating value). The Renewable Push pathway, which shows a stronger deployment of renewable energy, demonstrates hydrogen's complementarity with renewable energies, helping to absorb, store and transport the bulk of the additional energy from renewable sources.

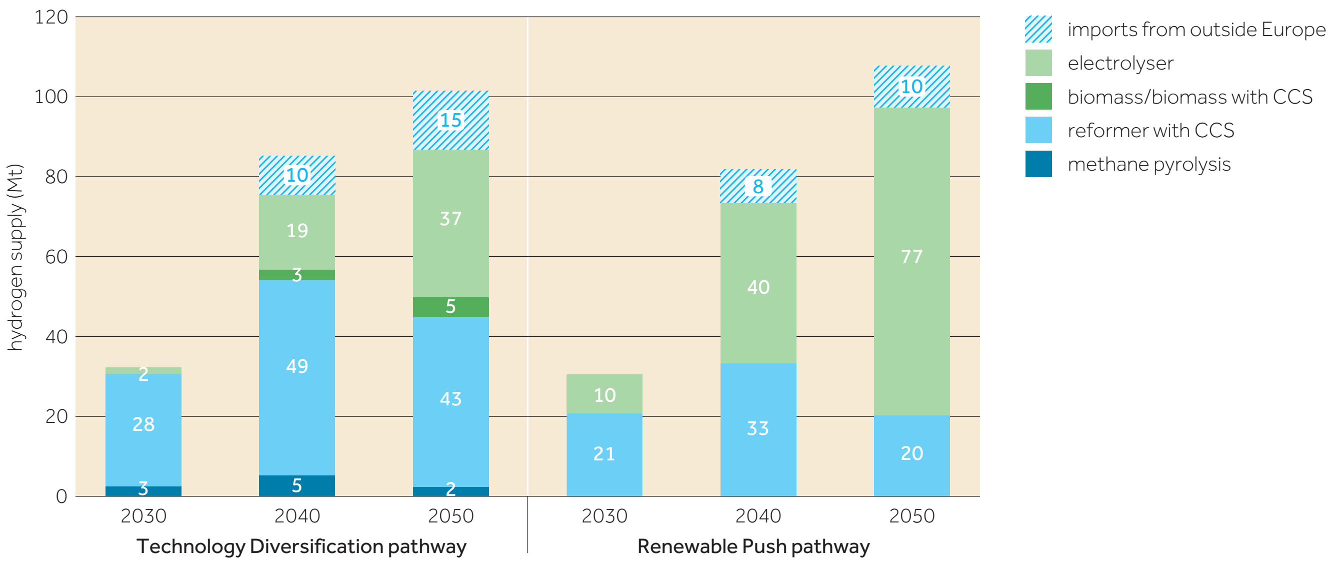
The sectoral breakdown of hydrogen demand confirms the versatility of hydrogen in decarbonising the energy system (Figure 4). Hydrogen can provide an answer to the challenges of deep electrification and the limits of energy efficiency improvements. It proves to be a cost-efficient solution for certain hard-to-abate energy uses in transport and industry.

Figure 4: The evolution of hydrogen energy-related demand by sector in the Technology Diversification and Renewable Push pathways, 2030 to 2050



In the two pathways, European hydrogen production rises steeply over the next three decades, relying on a diverse production mix comprising renewable and low-carbon technologies (Figure 5).

Figure 5: The evolution of the European hydrogen supply in the Technology Diversification and Renewable Push pathways, 2030 to 2050



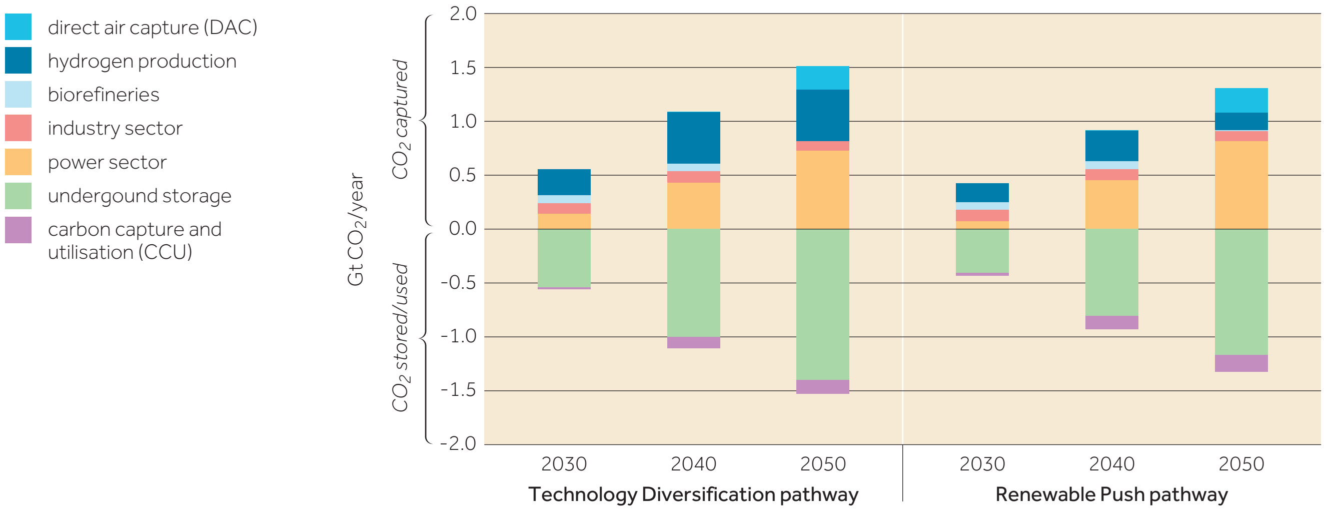
Some of the hydrogen needed in the transition to net-zero emissions is imported from outside Europe. The results show that imports of renewable and low-carbon hydrogen burgeon in the 2030s, including from North Africa, Russia, Ukraine and the Middle East. Imports play an important role in complementing European production of hydrogen, and in serving countries that have limited options for cost-efficient domestic hydrogen production. In the Technology Diversification pathway, up to 15 Mt of imports are able to compete on cost terms with domestic production, thus contributing nearly 15% to total hydrogen supply in Europe.

Key results for the EU hydrogen economy

Carbon capture

The development of low-carbon hydrogen and of other technologies such as biomass with CCS is highly dependent on the parallel deployment of the CCUS value chain and the ability of CO_2 storage capacities to grow rapidly over the next 30 years. The Technology Diversification pathway reaches an injection capacity limit of 1.4 Gt/year in 2050. This injection capacity has been derived as a reasonable estimate from a survey of existing literature and expert knowledge. However, the modelling also shows that higher levels of CO_2 injection capacities would allow for a bigger role for low-carbon hydrogen (see Figure 6 on page 40).

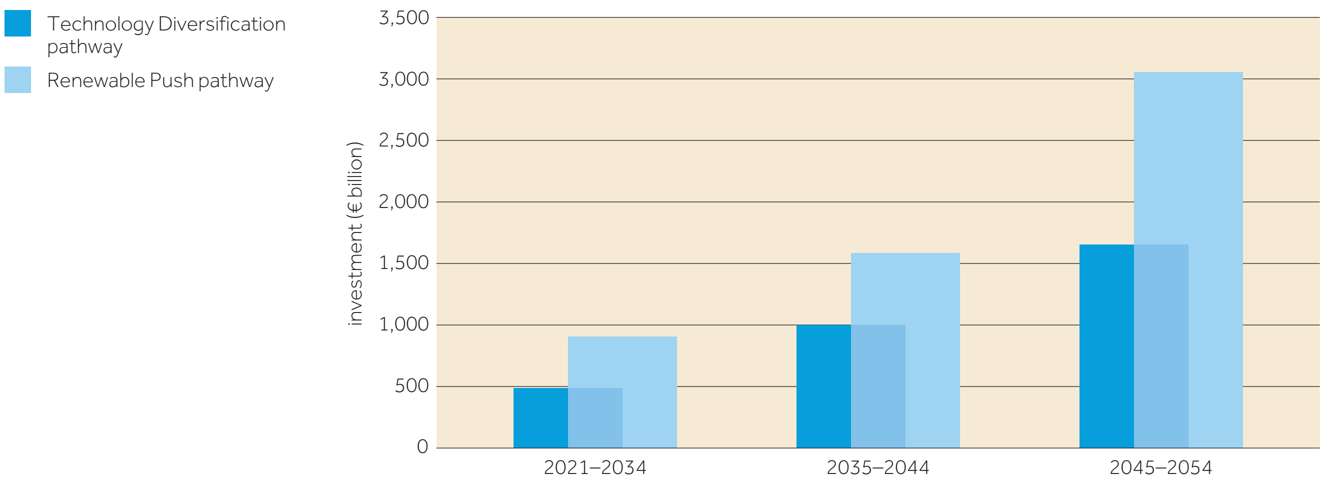
Figure 6: The evolution of CO_2 capture (positive values), use and storage (negative values) in the Technology Diversification and Renewable Push pathways, 2030 to 2050



Investments

Achieving high levels of renewable hydrogen and renewable energy in the system, in the latter half of the period to 2050, requires significant investments, underpinned by the accelerated deployment of renewable energy and electrolyser supply chains, and the optimal utilisation of renewable energy in Europe. In the Renewable Push pathway, more than 1,800 GW of dedicated solar and wind capacities and more than 1,600 GW of electrolysers need to be installed by 2050 to sustain the renewable hydrogen trajectory and reach more than 75 Mt of hydrogen output by 2050.

Figure 7: Investments in the hydrogen value chain (including off-grid renewables) per period supply in the Technology Diversification and Renewable Push pathways, 2021 to 2054



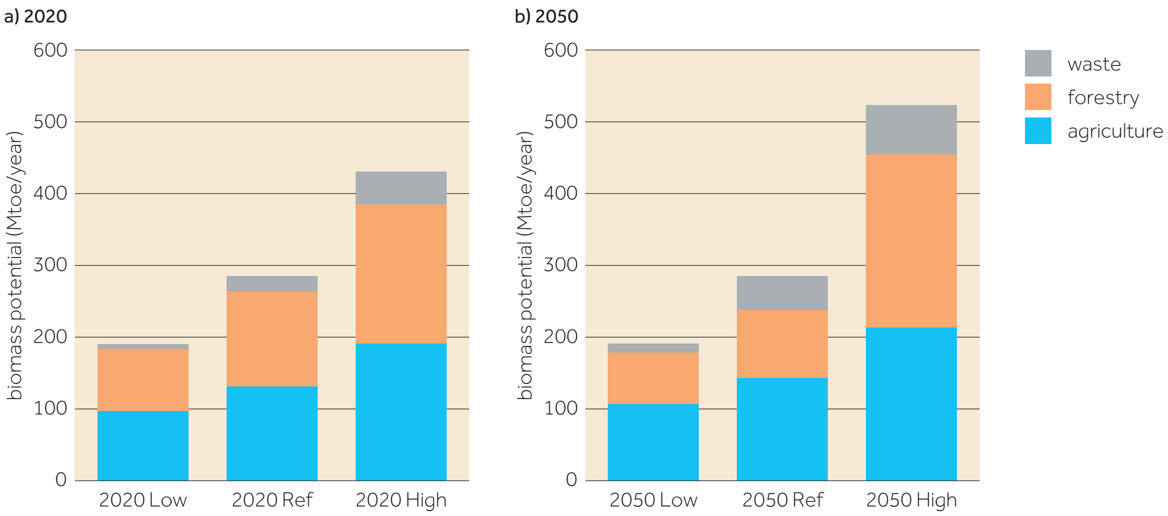
Considering the hydrogen value chain as a whole, the results show that trillions of euros in investment are needed to leverage the full potential of hydrogen in the energy transition (Figure 7). These investments need to start in a timely manner to ensure that demand and supply grow in lockstep, and to avoid technology lock-outs and mitigate the risk of stranded assets. The difference of more than €2 trillion in capital spending between the two pathways demonstrates the higher capital intensity of a pathway focusing on renewable assets and electrolysers. As such, one of the main challenges of the Renewable Push pathway is the ability to mobilise almost twice as much capital over the next 30 years to accomplish the hydrogen uptake.

The trajectory drawn by the Technology Diversification pathway shows the lowest investment costs. It is important to remember that this is founded on two principal paradigms: technology neutrality, assuming a comprehensive approach to decarbonisation that includes the potential of all technologies; and reliability, transparency and effectiveness of the policy framework. It assumes that all barriers and uncertainties are addressed along the way by policymakers and industrial leaders.

Sensitivity analysis for bioenergy

The Technology Diversification pathway uses the alternative 'Business as Usual' trajectory from ENSPRESO for bioenergy potential in Europe. The sensitivity analysis considers the ENSPRESO Reference trajectory (see Figure 8) for bioenergy potential. Compared to ENSPRESO's alternative 'Business as Usual' trajectory, the Reference trajectory has around 45–50% greater bioenergy potential in Europe over the period to 2050, due to the wider utilisation of forest resources and related market developments.

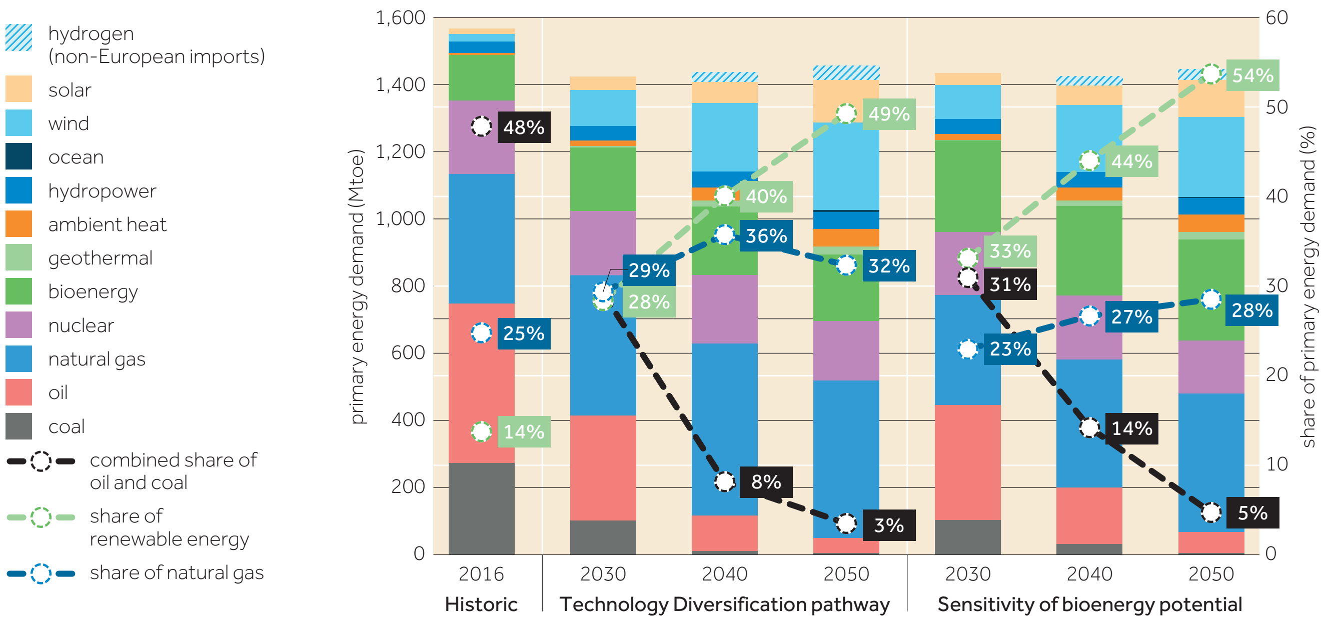
Figure 8: Concawe's elaboration based on the ENSPRESO report [1]



[1] https://www.sciencedirect.com/science/article/pii/S2211467X19300720?via%3Dihub

The higher potential of bioenergy in Europe leads to a more important role for this energy source in terms of primary energy demand. In 2030 and 2050, bioenergy represents 19% (+40% increase in supply compared to the Technology Diversification pathway) and 21% (+50%) of total primary energy demand, respectively, in Europe in the sensitivity analysis. Bioenergy displaces natural gas but also solar PV, wind and nuclear in the energy mix, the shares of which are lower in this sensitivity analysis.

Figure 9: The evolution of total primary energy demand in the Technology Diversification pathway, and the sensitivity of bioenergy potential, 2016 to 2050



Bioenergy plays a greater role in power generation and in hydrogen production, where it is combined with CCS (BECCS).

The higher potential of bioenergy does not significantly impact the level of hydrogen demand in the long term. By 2050, hydrogen demand in the sensitivity analysis stands at around 100 Mt, similar to the level reached in the Technology Diversification pathway. However, some notable shifts are observed in the evolution of hydrogen demand over the outlook period. The growth of hydrogen demand (and thus of the whole hydrogen economy) happens later in the sensitivity analysis, mostly because the use of BECCS allows for more negative emissions and shifts some of the need for hydrogen to the end of the period. In the sensitivity analysis, hydrogen demand is half its 2030 level observed in the Technology Diversification pathway (around 15 Mt compared to 30 Mt), but gradually catches up from 2030 to 2040 (-24%) and 2050 (-2%).

These changes lead to slightly different numbers regarding cumulative investment in the hydrogen value chain. Total cumulative investments in the hydrogen value chain are lower in the sensitivity analysis. They stand at around €2.9 trillion, which is around €0.2 trillion less than cumulative investments in the Technology Diversification pathway, with marked decreases in investments in all categories except biomass. The overall energy system cost, discounted over the outlook period, is about €2.5 trillion lower (-2.5%) in the sensitivity analysis than in the Technology Diversification pathway.

Conclusion

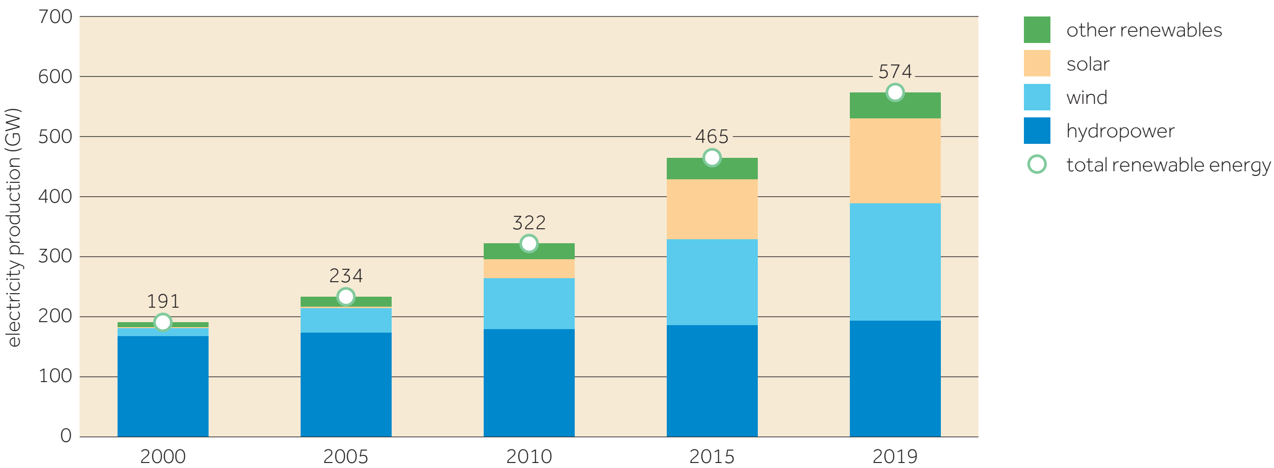
European hydrogen production and use could increase dramatically, driven by policy, with the demand for hydrogen potentially exceeding 100 Mt. The transport sector accounts for more than half of hydrogen demand, followed by industry, particularly the steel and chemical industries.

Both low-carbon and renewable hydrogen are necessary to enable a fast, lower risk and more cost-effective pathway to net zero. A mix of hydrogen types will be needed regardless of the policy path chosen. By 2050, more than half of total gross final energy consumption will be supplied by non-electrified technologies such as low-carbon hydrogen and biomass.

The development of renewable hydrogen requires more than 1,800 GW of dedicated solar and wind capacities to be installed by 2050 (3 to 4 times the current installed capacity in the EU, see Figure 10) and more than 1,600 GW of electrolysers, implying a difference of more than €2 trillion in capital spending.

The development of the hydrogen value chain relies on a dedicated energy infrastructure that includes transport and distribution, storage and refuelling options, and which connects supply and demand. Nearly 15% of the hydrogen needed in the transition to net-zero emissions could be imported from outside Europe.

Figure 10: The evolution of installed renewable energy capacity for electricity production in Europe, 2000 to 2019



Predicting vapour composition and flammability in a fuel tank

Fuel blends consisting of a mixture of gasoline, diesel fuel and ethanol — referred to as dieseline — have shown promise for use in high-compression engines. Such mixtures could be flammable in the headspace above the liquid in a vehicle fuel tank at common ambient temperatures, and it is therefore important to understand the flammability characteristics of these fuel blends.

Authors

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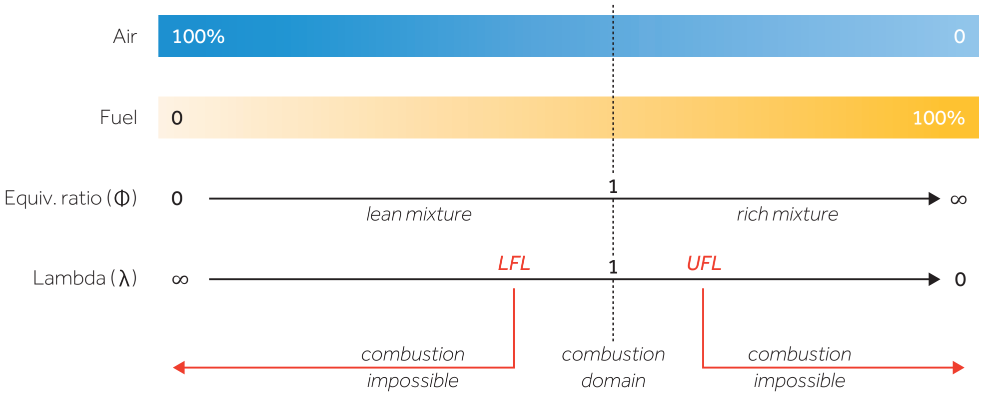
Background

Current road fuel standards ensure that fuel can be stored in a tank onboard a vehicle in safe conditions. This means that, among other things, the fuel tank should remain free from any risk of fire or explosion. It is therefore desirable to avoid storing a flammable fuel/air mixture in the tank.

For any given fuel there exists a range of concentrations of its vapour in air in order for the mixture to be flammable. Beneath the lower end of that range, referred to as the lower flammability limit (LFL), the fuel/air mixture is too lean to support combustion. Similarly, there is an upper limit of concentration, referred to as the upper flammability limit (UFL), above which the fuel/air mixture is too rich to burn.

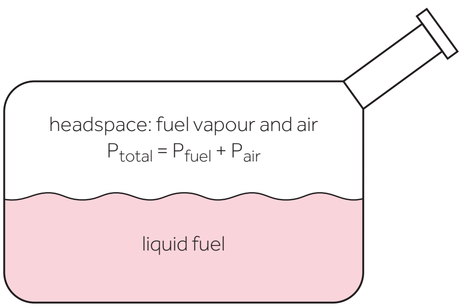
Figure 1: Lower and upper flammability limits



The range between the upper and lower flammability limits broadens slightly as temperature increases; nevertheless, over the range of ambient temperatures of interest for automobile fuel tanks, the two limits are essentially constant for any particular fuel vapour composition. The LFL and UFL values quoted in the literature for different compounds are typically those measured at room temperature.

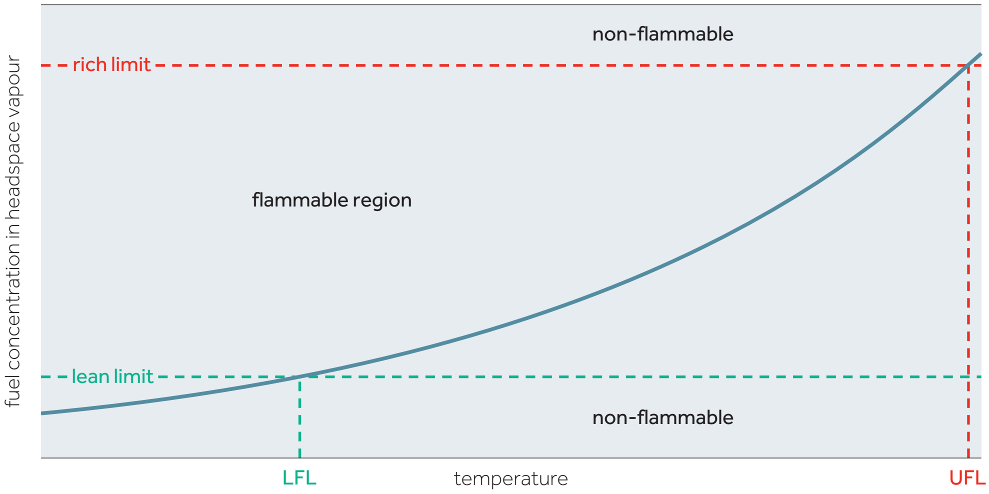
In a fuel tank, the so-called 'headspace' above the liquid contains a quantity of air and fuel vapour as shown in Figure 2.

Figure 2: Schematic representation of a vehicle fuel tank



The concentration of fuel vapour in the headspace at equilibrium depends only upon the temperature for any specific fuel. As the temperature rises, the vapour pressure of the fuel increases, thereby increasing the vapour concentration in the headspace (see Figure 3).

Figure 3: Flammability of the headspace vapour in a fuel tank

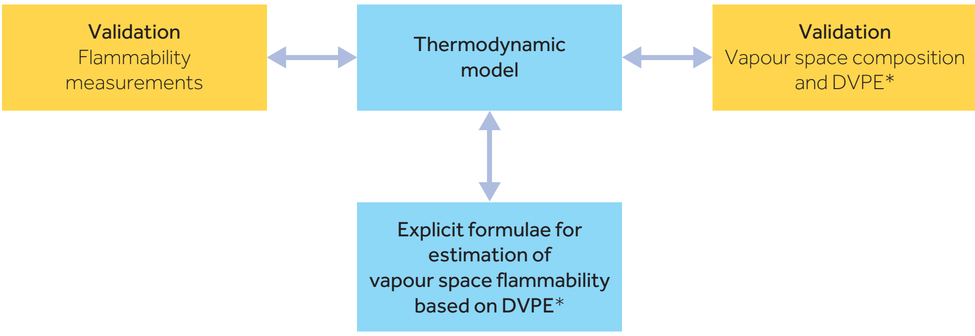


Eventually the vapour concentration reaches the lean limit, at which point the mixture in the headspace becomes flammable. The temperature at which this occurs at equilibrium is the LFL temperature. This is similar to the flashpoint temperature, but the apparatus, test procedures and pass/fail criteria are different for flashpoint and flammability limit tests. As a result, the flashpoints measured for liquid fuels are usually close to, but not necessarily exactly the same as, their LFL temperatures.

Above the LFL temperature the headspace contains a flammable mixture. However, if the tank temperature continues to rise, the concentration eventually reaches the UFL temperature, and the mixture in the headspace then becomes too rich to burn. For example, in the case of pure ethanol, the LFL temperature occurs at approximately -18°C and the UFL temperature is reached at about +43°C. The headspace in an ethanol fuel tank would therefore be flammable at ambient temperatures from about -18° to +43°C.[1]

Generally speaking, gasoline volatility requirements have been driven by considerations of cold weather driveability to allow an ignitable mixture in the engine,[2] with higher vapour pressures stipulated in winter than summer. Nevertheless, there has been a recognition, going back more than 80 years, that it is preferable from a safety perspective to use gasoline fuels which have a fuel/air mixture in the headspace of the tank that is too rich to be flammable.[3] By contrast, diesel fuels have a low volatility (constrained to have a flashpoint greater than 55°C), which enables them to operate at temperatures below the LFL in the fuel tank.[2] Mixtures of gasoline, diesel and ethanol, commonly known as 'dieseline mixtures', with an ignition quality which is intermediate between gasoline and diesel, may facilitate the uptake of advanced combustion concepts such as partially premixed combustion (PPC).[4] The question is, how can these mixtures be stored under safe conditions, being that mixing low and high volatility compounds could lead to a flammable vapour in the fuel tank headspace at ambient temperature? This question is the subject of this article which summarises the work published jointly by Concawe and Nexum Research Corporation in four SAE papers.[5,6,7,8] The elements of the study are outlined in Figure 4.

Figure 4: Elements of the study



* Dry vapour pressure equivalent

The basis of the mathematical model

An outline of the mathematical formulation is given below (for full details please see references 5–8):

1. Find the saturation vapour pressure for each volatile component.
2. Determine the liquid and vapour phase fraction of each component.
3. Determine the amount of air present in the headspace, from the difference between atmospheric pressure and the summed partial pressures of all components.

As part of the above three steps, there is a need to account for non-ideal mixing between ethanol and hydrocarbons using activity coefficients (γ_i):

$$P_i = \gamma_i X_i P_{i\,sat} \tag{1}$$

where:

P_i = vapour pressure of component i in the fuel mixture at equilibrium

γ_i = activity coefficient of component i in the blend (estimated using a Margules two-suffix equation[5])

X_i = mole fraction of component i in the liquid phase of the blend at equilibrium

$P_{i\,sat}$ = equilibrium saturation pressure of component i alone

If no ethanol is present, the activity coefficient for the hydrocarbons is equal to 1.
Equation 1 then represents Raoult's Law for ideal mixtures.

Gasoline can contain several hundred hydrocarbon components. The method puts each hydrocarbon into one of 14 buckets of C_3 to C_8 compounds chosen to represent the volatile hydrocarbon fraction of the gasoline. The hydrocarbons range from propane for the lightest fraction to xylene representing the heaviest.

All heavier hydrocarbon species (e.g. diesel) were considered to have a negligible direct impact on the vapour phase composition and pressure, acting only as inert diluents in the liquid phase.

The rich limit of the mixture is estimated from the literature flammability limits for the 14 hydrocarbon pseudo-components plus ethanol, along with the Le Chatelier mixing rule:

$$X_L = 1 / \Sigma_{i=1}^{N} X_i / X_{Li} \tag{2}$$

where:

X_L = mole fraction of the gasoline vapour in the gasoline/air mixture at the lean or rich flammability limit
X_i = mole fraction of component i in the gasoline vapour
X_{Li} = mole fraction of component i in air at the rich limit if it were present on its own

Experimental measurements to validate the model

There are two aspects to be validated: the ability of the model to predict the properties of the vapour phase; and the determination of flammability based on the vapour phase composition determined by the model.

Various mixtures were created based on the components in Table 1.

Table 1: Components used in the test fuel blends

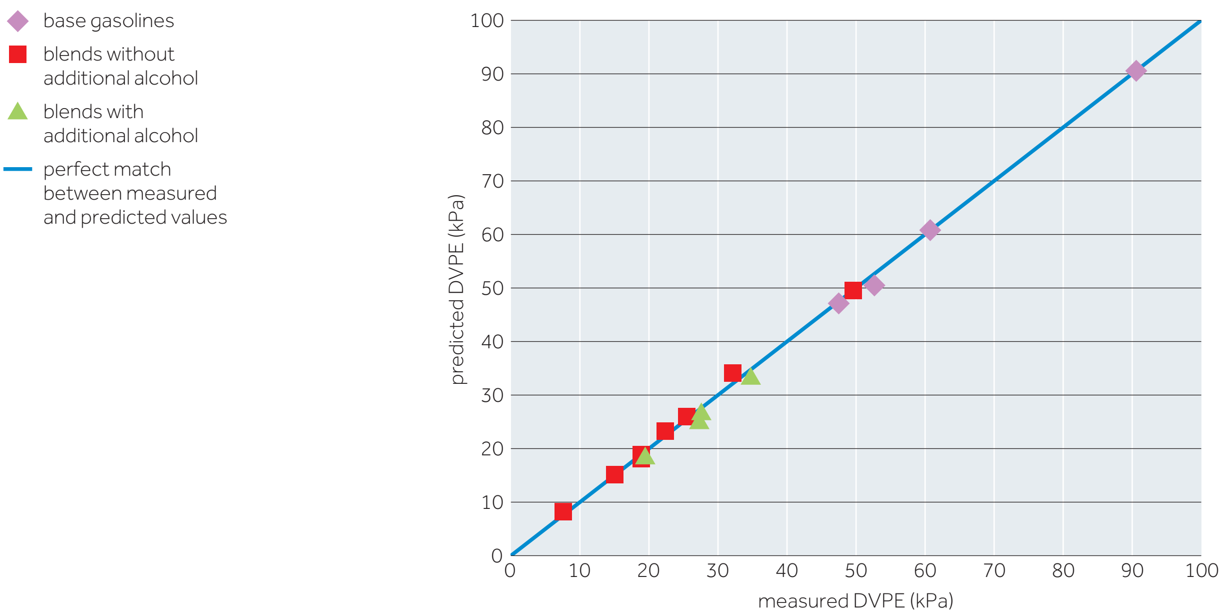
Base fuel	Mixture
Diesel	European ULSD[a], 5% FAME (cloud point = -4°C)
Gasoline G1	45 kPa DVPE gasoline, summer blend (E0)
Gasoline G2	60 kPa DVPE gasoline, mid-season blend (E0)
Gasoline G3	90 kPa DVPE gasoline, winter blend (E0)
Gasoline G4	54 kPa DVPE gasoline, containing ETBE[b] (E0)
Ethanol	Neat ethanol containing no denaturant

[a] Ultra-low-sulphur diesel [b] Ethyl tertiary butyl ether

The measure of 'dry vapour pressure equivalent' (DVPE)[2] is a standard vapour pressure measurement for gasoline, corresponding to equilibrium at 37.8°C (100°F) in a container that is 20% full of liquid fuel. By specifying these conditions in the model, the total vapour pressure computed by the model is then the estimated DVPE for any particular sample composition. DVPE is used here as the primary indicator of the accuracy of the model in predicting the state of the mixture in the headspace, although it is possible that different combinations of components could lead to the same overall vapour pressure.

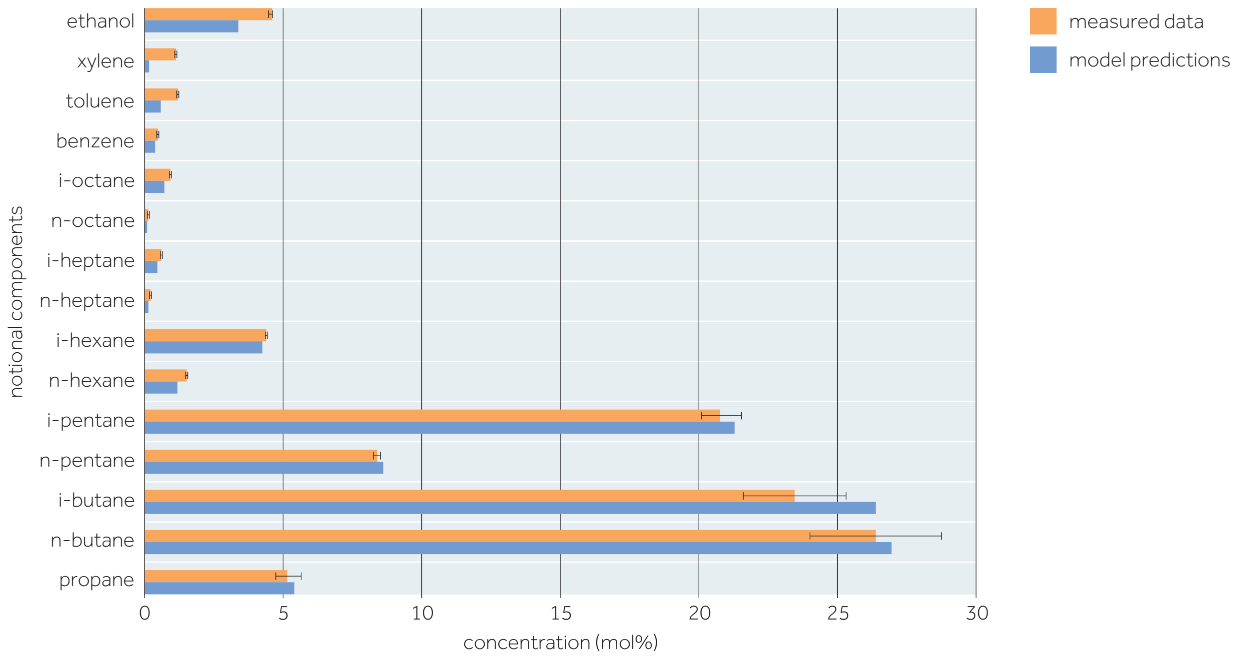
Figure 5 compares the predicted values of DVPE with those measured. A perfect correlation between measured and predicted values would lie exactly along the diagonal line on the figure.

Figure 5: Predicted and measured DVPE



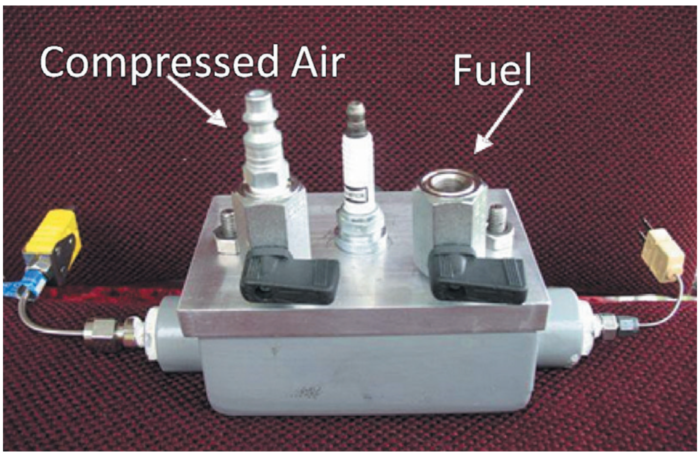
Samples of headspace vapours were collected from 20 ml vials, each 75% full of liquid, which were stored at a constant temperature overnight to achieve equilibrium. The vapour composition (measured by gas chromatography (GC) and then placed into the 15 pseudo-component buckets) was compared against model predictions. An example of the vapour space composition validation is given in Figure 6 on page 49.

Figure 6: Representative prediction of vapour space composition of one of the blends



Actual investigations of the UFLs were conducted in a constant volume vessel (Figure 7).[5] The tank had a 5% fill level representing a realistic worst-case scenario, as an emptier tank results in a leaner headspace that is more likely to be below the UFL. Mixtures were deemed flammable when pressure exceeded a threshold value following ignition. Four replicate tests were conducted at a given temperature.

Figure 7: Upper flammability limit test chamber (Vol = 296 ml)



Predicting vapour composition and flammability in a fuel tank

The model was found to consistently overpredict the UFL temperature measured in the constant volume chamber by 5–10°C (Figures 8 and 9). For blends without ethanol, the UFL temperature can be predicted from the DVPE — the more volatile the fuel the lower the UFL temperature. Ethanol-containing fuels still trend with DVPE, but the trend is slightly different.

Figure 8: Measured and predicted rich temperature limits for dieseline blends with no additional ethanol

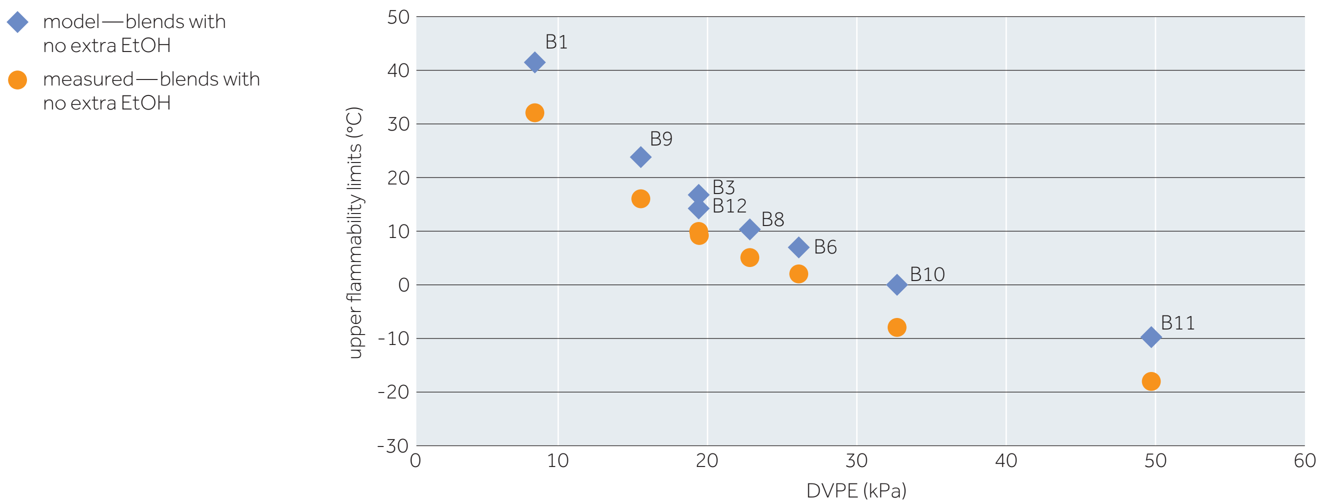
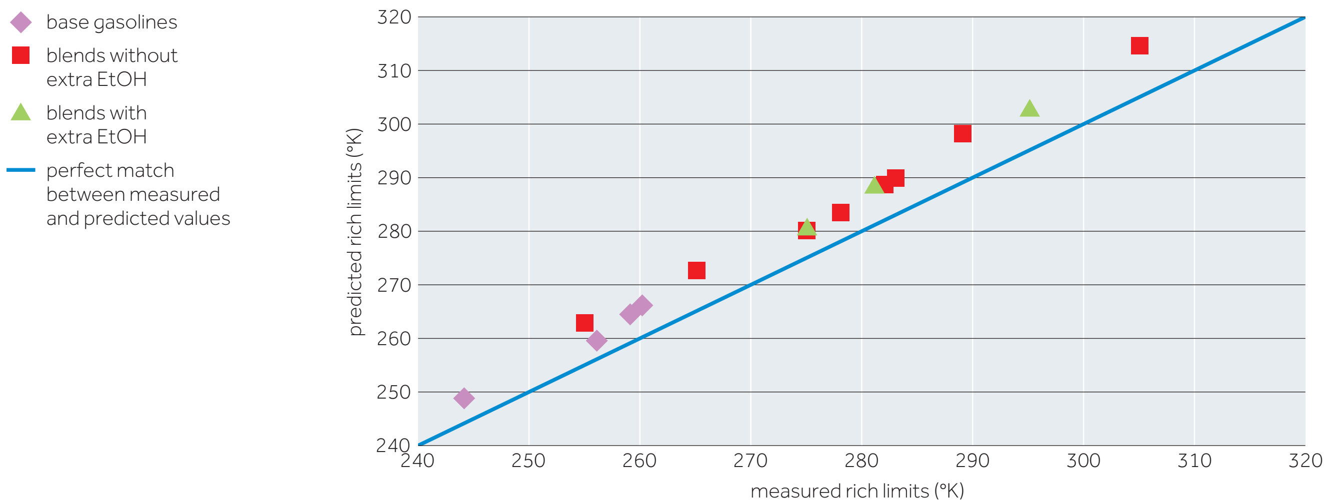


Figure 9: Comparison of measured and predicted upper flammability limits

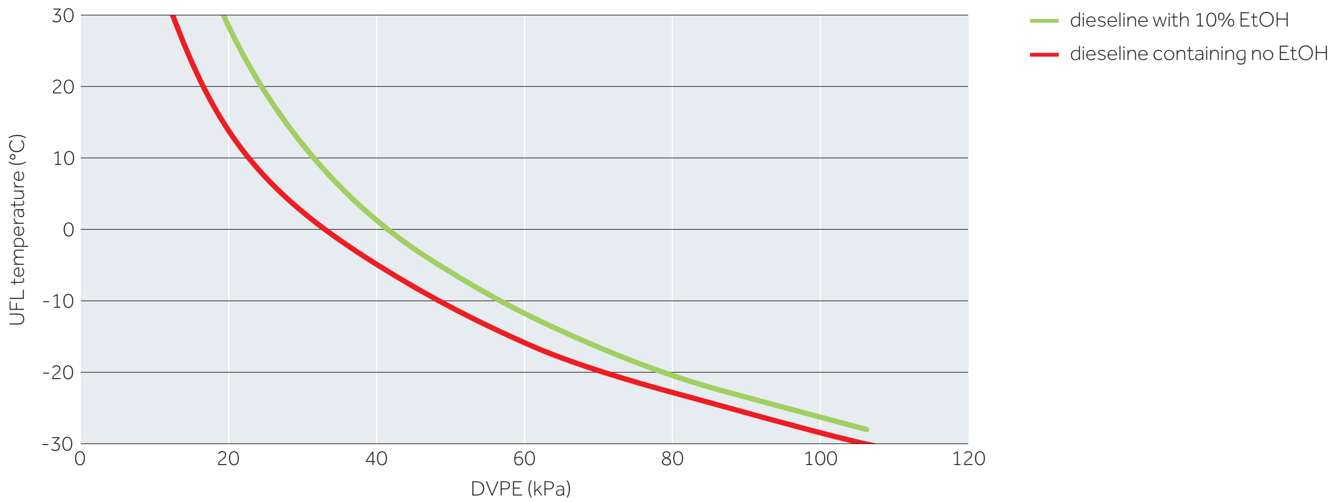


The discrepancy between measured and predicted rich flammability limit temperatures in this study were attributed to the impact of downward flame propagation in the apparatus employed in these tests, compared with upward propagation in the apparatus normally used to determine published flammability data. The model is therefore somewhat conservative.

Development of explicit formulae for the prediction of vapour space flammability

To make the model easier to use in practice, a set of explicit equations have been developed that are simple to use and allow changes in headspace flammability to be quickly assessed quantitatively as dieseline formulation is varied over any desired range. For the model, a single curve correlates the UFL temperature with DVPE for any hydrocarbon-only dieseline blend, regardless of its specific composition. All dieseline blends containing ethanol are also correlated by blend DVPE, but that correlation can differ considerably from the curve for HC-only blends (Figure 10).

Figure 10: Variation in UFL temperature with DVPE for dieseline blends with and without ethanol



The approach adopted for developing the explicit formulae is to determine the correlation between UFL and DVPE for an ethanol-free dieseline blend and then make a correction for the ethanol content:

$$T_{UFL} = f_1(DVPE_{HC}) + f_2(\%EtOH) \cdot f_3(DVPE_{HC}) \qquad (3)$$

where:

T_{UFL} = UFL temperature for the blend [°C]

$f_1(DVPE_{HC})$ is the correlating function for the curve of hydrocarbon-only blends

$f_2(\%EtOH)$ is the correction factor to account for the volume % ethanol in the blend

$f_3(DVPE_{HC})$ is a factor to adjust f_2 to account for the effect of $DVPE_{HC}$

Each of the above terms is determined from a 6th order polynomial:

$$f = C_0 + C_1 \cdot arg + C_2 \cdot arg^2 + C_3 \cdot arg^3 + C_4 \cdot arg^4 + C_5 \cdot arg^5 + C_6 \cdot arg^6 \qquad (4)$$

Table 2: Coefficients in the correlation equation

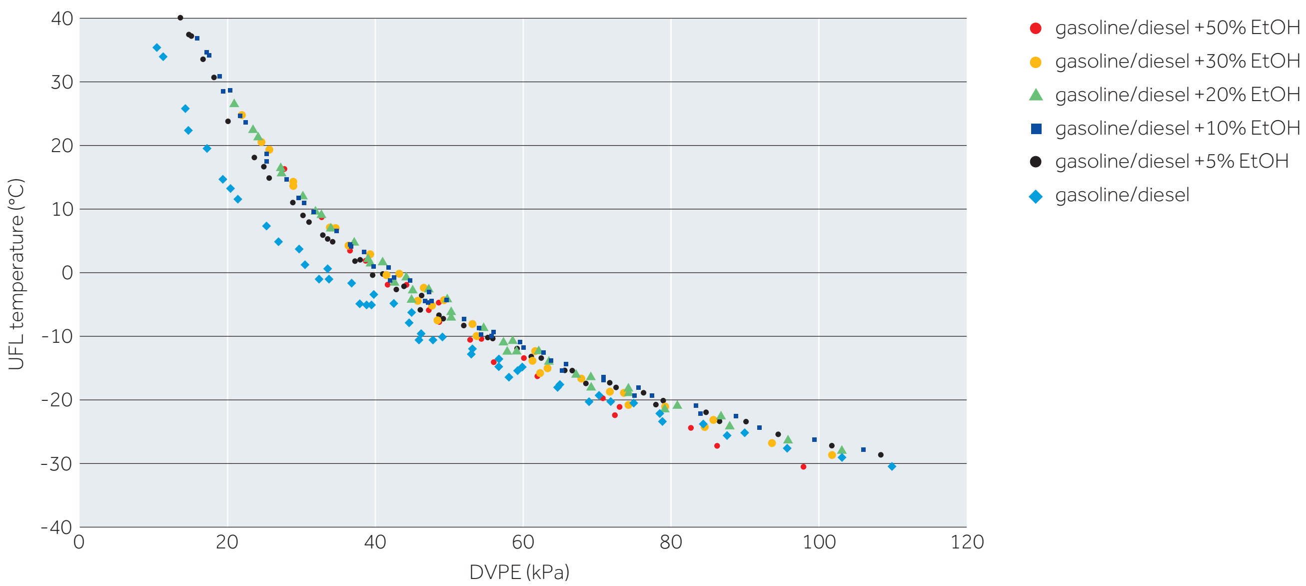
	C_0	C_1	C_2	C_3	C_4	C_5	C_6
f_1	8.95413E+01	-7.44858E+00	2.78985E-01	-6.07073E-03	7.33348E-05	-4.57018E-07	1.14437E-09
f_2 if $\%EtOH = 0$	0	0	0	0	0	0	0
f_2 if $DVPE_{HC} \leq 20$ and $0 < \%EtOH \leq 10$	0	-4.40806E+00	7.98908E-01	-7.00812E-02	2.39390E-03	0	0
f_2 if $DVPE_{HC} \leq 20$ and $\%EtOH > 10$	-9.89867E+00	-5.14490E-02	1.79400E-03	0	0	0	0
f_2 if $DVPE_{HC} > 20$ and $\%EtOH > 0$	1.04207E-01	2.90263E-01	-1.31394E-02	2.27509E-04	-1.34341E-06	0	0
f_3 if $DVPE_{HC} \leq 20$	2	-0.1	0	0	0	0	0
f_3 if $20 < DVPE_{HC} < 40$	-1.67230E+00	9.36900E-02	-6.25320E-04	0	0	0	0
f_3 if $DVPE_{HC} \geq 40$	1	0	0	0	0	0	0

Each of the coefficients for equation 4 are given in Table 2, enabling f_1, f_2 and f_3 to be calculated for any situation, and the UFL temperature determined. Specific examples of the calculation in different circumstances are given in Pellegrini, L. *et al.* (2020).[8]

Selected results

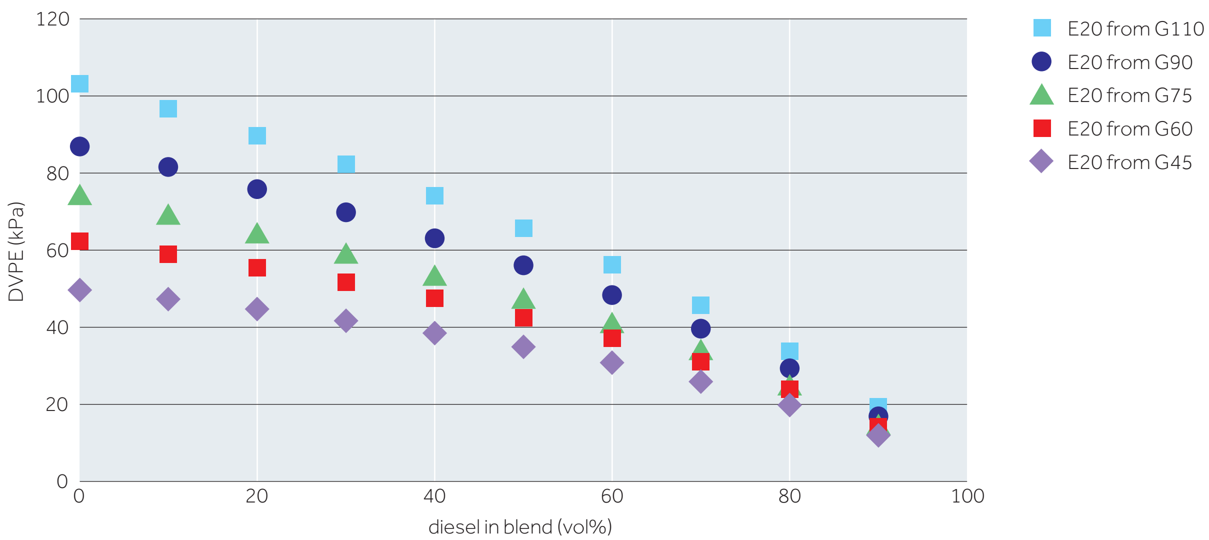
Figure 11 on page 53 shows the relationship between DVPE and UFL temperature for dieseline blends containing differing amounts of ethanol. For DVPEs up to 60 kPa, the curve for blends containing ethanol have a higher UFL temperature for a given DVPE than is the case of the pure hydrocarbon blends. For DVPEs above 60 kPa, blends with a high ethanol content can have a lower UFL temperature than the pure hydrocarbon. The reason for this is that while ethanol has an intrinsically higher UFL temperature than hydrocarbons it tends to raise the mixture vapour pressure because of deviations from Raoult's law, and the effect is more significant if the HC fraction has a low vapour pressure.

Figure 11: The impact of DVPE on the UFL temperature of dieseline comprising various ethanol levels



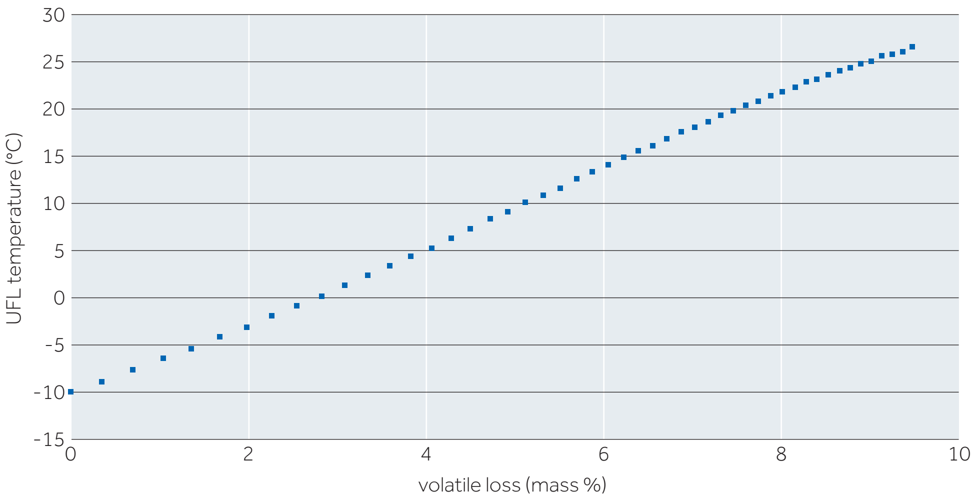
Another important perspective of the study is to understand exactly how the relative gasoline/diesel content affects the DVPE, and hence the UFL temperature. Figure 12 shows the impact of the addition of diesel to various E20 gasolines with different volatilities. The blend DVPE is principally determined by the DVPE of the gasoline. If an E20 gasoline with a DVPE of 75 kPa is mixed with 50% diesel, the dieseline can be seen to have a DVPE of about 45 kPa.

Figure 12: DVPE of E20/diesel blends using gasolines of different volatility
(G110 refers a gasoline BOB with a DVPE of 110 kPa)



Loss of volatile material in the tank (e.g. from evaporative emissions) can increase the likelihood of having a flammable mixture: this is something that the model can be used to assess. Figure 13 shows an example scenario — the temperature needs to be lower than -10°C for a flammable mixture to exist, but if 5% of the fuel evaporates and is able to escape the tank, the temperature only needs to be lower than +10°C for a flammable mixture to exist.

Figure 13: The effect of volatile loss on headspace flammability for a blend of 60% diesel, 30% G110 and 10% EtOH



Conclusions

A mathematical model has been developed that predicts the flammability of the headspace vapours in a tank that contains mixtures of diesel fuel and gasoline containing various amounts of ethanol. The non-ideality of the blends of hydrocarbons and ethanol is accounted for using activity coefficients.

It was found that the UFL temperature is correlated with the DVPE of the mixture, with the exact correlation being sensitive to the amount of ethanol in the blend.

The model has been validated against vapour space compositions measured by gas chromatography, and against ignition in a constant volume chamber. The UFLs predicted by the model were consistently 5–10°C higher than measured in this apparatus. The discrepancy was attributed mainly to the impact of downward flame propagation in the apparatus, compared to upward propagation used in flammability data found in the literature and used in the model.

Explicit correlation equations have been derived from the full mathematical model that enable the UFL temperature to be estimated for dieseline blends with or without ethanol. The equations can be readily incorporated into spreadsheets or programs to assess the UFL temperatures of a wide variety of dieseline formulations, and for evaluating practical issues arising in-service.

The minimum value for the DVPE required to ensure a non-flammable headspace mixture depends on the ambient conditions. The DVPE of a dieseline mixture is largely influenced by the DVPE of the gasoline, and winter-grade gasolines have higher DVPEs. Provided that the dieseline mixture contains at least 40% gasoline, it would be unlikely that the headspace of a dieseline mixture would be in the flammable region.

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Abbreviations and terms

AFOLU	Agriculture, Forestry and Other Land Use
BECCS	Bioenergy with Carbon Capture and Storage
BOB	Basestock for Oxygenate Blending
BTL	Biomass To Liquids
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DG RTD	European Commission's Directorate General for Research and Innovation
DGS	Distillers' Grain and Solubles
DVPE	Dry Vapour Pressure Equivalent
E20	Petroleum fuel blend containing 20% ethanol
EC	European Commission
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol (or ethyl alcohol)
EU	European Union
EV	Electrified Vehicle
FAD	Fatty Acid Distillate
FC	Fuel Cell
GC	Gas Chromatography
GHG	Greenhouse Gas
Gt	Gigatonne
GTL	Gas-to-Liquid
GW	Gigawatt
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
HNV	High Nature Value
HVO	Hydrotreated Vegetable Oils
HyPE	Hydrogen Pathway Exploration
ICE	Internal Combustion Engine
ILUC	Indirect Land-Use Change
JEC	Consortium of the EU Commission's Joint Research Centre (JRC), EUCAR and Concawe
JRC	European Commission's Joint Research Centre
kPa	Kilopascal
LCF	Low Carbon (liquid) Fuel
LFL	Lower Flammability Limit
MSW	Municipal Solid Waste
Mt	Megatonne
Mtoe	Megatonnes of oil equivalent
O_2	Oxygen
OPEX	Operating Expenditure
PPC	Partially Premixed Combustion
PV	PhotoVoltaic
R&D	Research and Development
R&I	Research and Innovation
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuel
SGAB	Sub-Group on Advanced Biofuels
TRL	Technology Readiness Level
UFL	Upper Flammability Limit
ULSD	Ultra-Low Sulphur Diesel
UK	United Kingdom
WTW	Well to Wheels

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