Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

A summary of Concawe's '*CO_2 reduction technologies*' and '*Refinery 2050*' reports

This article summarises the results of two Concawe studies which address the potential for refineries to contribute to a future low-carbon economy. Full details of the studies are presented in Concawe reports 8/19 and 9/19, published in 2019.[2,3]

Authors

Marta Yugo
marta.yugo@concawe.eu

Alba Soler
alba.soler@concawe.eu

Introduction

In December 2015, COP21 in Paris took an important step towards addressing the risks posed by climate change through an agreement to keep the global temperature increase 'well below 2°C' and drive efforts to limit it even further to 1.5°C. To achieve these goals, the European Union (EU) is exploring different mid-century scenarios leading to a low-carbon EU economy by 2050.

In line with the EU's low-emissions strategy, Concawe's cross-sectoral Low Carbon Pathways (LCP) programme is exploring opportunities and challenges presented by different low-carbon technologies and feedstocks that have the potential to achieve a significant reduction in carbon dioxide (CO_2) emissions associated with both the manufacture and use of refined products in Europe over the 2030–2050 time frame.

Within this context, two new Concawe refining-related reports have recently been published, which focus on the transition of the European refining industry and products towards a low-CO_2 economy, and explore the technical implications of the deployment of 'Vision 2050'[1] across the EU refining system and its contribution to EU decarbonisation goals:

1) *CO_2 reduction technologies. Opportunities within the EU refining system (2030/2050)*[2] **(Step 1)**
   This report focuses on the potential of different low-CO_2 technologies and operational measures to achieve a reduction in CO_2 emissions intensity within the refinery site, towards the 2030 and 2050 time horizons.
2) *Refinery 2050: Conceptual Assessment*[3] **(Step 2)**
   Building on Step 1, this analysis expands the scope by exploring the potential introduction and processing of low fossil carbon feedstocks in European refineries with the objective of producing lower fossil carbon fuels in a 2050 demand scenario. Through some initial selected examples of key low fossil carbon technologies, it investigates the potential synergies with the existing assets as crude oil is progressively replaced, and the implications in terms of feedstock supply, key processing requirements such as hydrogen and electricity, and CO_2 emissions intensity both at the refinery and end product levels.

Articulated around refining technologies, these two key reports aim to answer some key questions, such as:

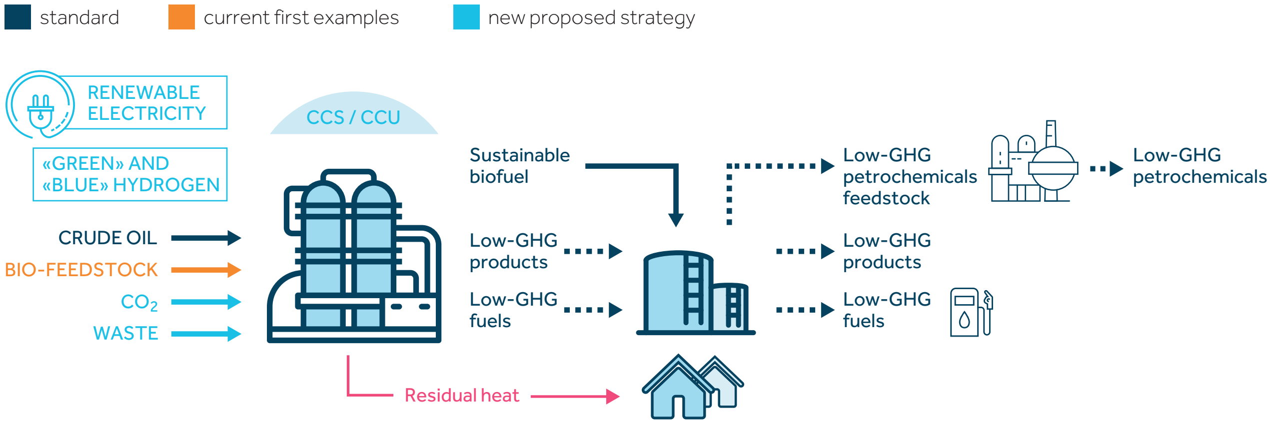
- Can the EU refining industry effectively contribute to a low-CO_2 economy?
- What kind of technologies can play a role in that future, and what is their current level of development?
- What framework conditions would be required to make this happen?

[1] https://www.fuelseurope.eu/vision-2050/
[2] https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf
[3] https://www.concawe.eu/wp-content/uploads/Rpt_19-9.pdf

Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

Figure 1: Conceptual overview of the refinery of the future—the refinery is an energy hub within an industrial cluster

Source: Vision 2050



This article is intended to serve as a brief summary of both reports, guiding the reader through the same path walked by Concawe in its aims to understand the future role for the refining industry. It highlights the main takeaways of the reports, and aims to provide the reader with an appetite to gather more information by reading the full texts of the reports.

Figure 2 (below) and Table 1 on page 31 illustrate the two-step approach and the complementary nature of the two refinery-related reports mentioned above.

Figure 2: The two-step approach of the two refinery-related Concawe LCP reports (Step 3 in elaboration)

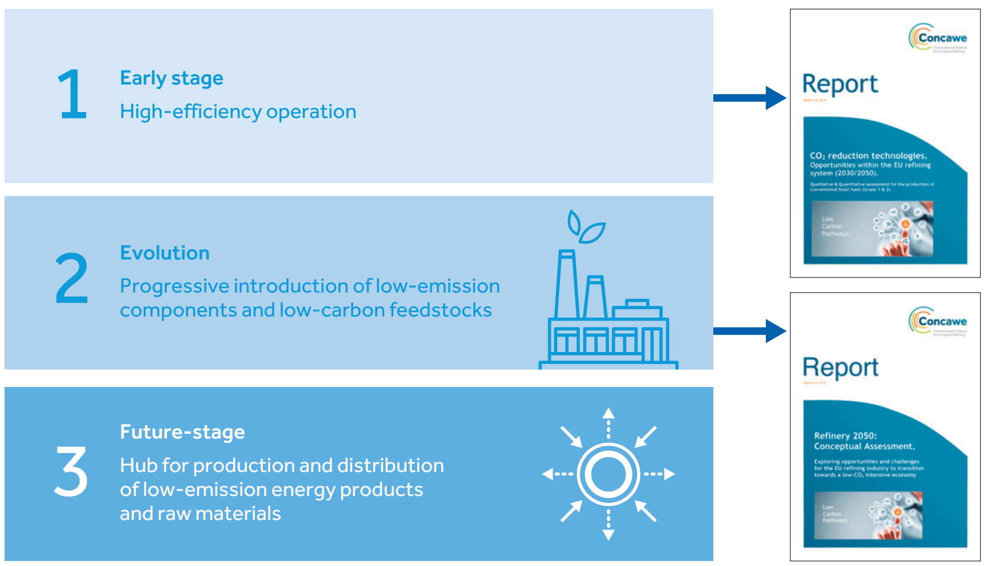


Table 1: The two-step approach and the complementary nature of the two refinery-related Concawe LCP reports

	Step 1 '*CO_2 reduction technologies*' report (Concawe report no. 8/19)	**Step 2** '*Refinery 2050*' report (Concawe report no. 9/19)
Scope (CO_2 savings)	Refinery battery limits (Scope 1 and 2 — direct and indirect emissions)	Expand scope from refinery battery limits to the final use of products (Scope 1 and 2, and a look into Scope 3).
Technologies	Technologies to reduce CO_2 emissions across the EU refining system.	Technologies which reduce the CO_2 emissions of the refinery (identified in Step 1) + low fossil carbon feedstock (co-located or co-processed within the refinery).
Time frame	What could be realistically achievable by 2030. A look into wide deployment towards 2050.	A look into the 2050 time frame (potential progressive deployment from 2030 onwards).
Demand	Based on a 2030 demand scenario (WoodMac, 2018).[a] No change in the activity level of the sector/product yields from 2030 onwards.	Exploring different routes and 2050 demand scenarios impacting both the activity level of the sector and product yields.
Feedstock	Crude oil	Crude oil progressively replaced by low fossil carbon feedstocks (e.g. biofeedstocks + e-fuel liquids).

[a] WoodMac, 2018 — data provided to Concawe

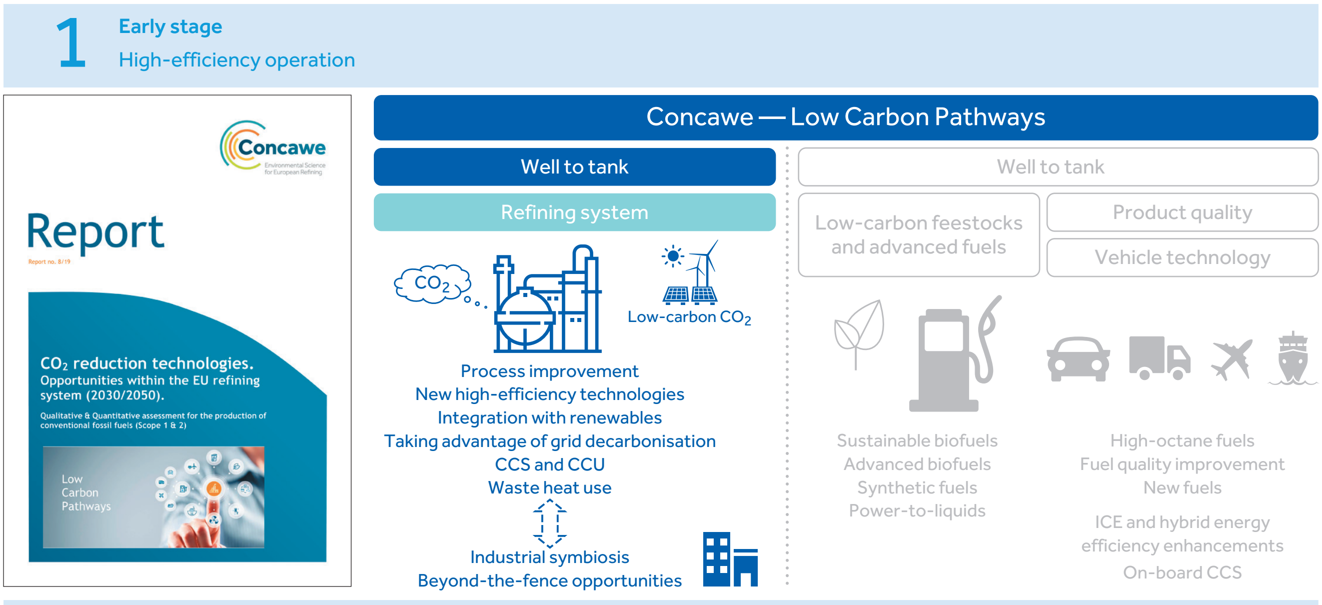
It is important to note that none of the Concawe LCP-related work is intended to be a roadmap for the whole EU refining and transport industries. Different factors coupled with local and structural constraints will determine individual companies' preferred routes to contribute to EU goals to mitigate climate change.

CO_2 reduction technologies. Opportunities within the EU refining system (2030/2050) (Step 1)

Overview: what is this report about?

This document demonstrates that the effective deployment of different technologies has the potential to achieve a significant reduction in CO_2 emissions in the EU refining sector. The starting point is the definition of a demand scenario for refinery products in 2030, followed by the modelling of different technologies and a plausible deployment rate to reduce CO_2 emissions produced at the site during the manufacturing process towards the 2030 and 2050 time horizons.

Figure 3: An overview of CO_2 reduction technologies (Step 1)



When looking at the emerging opportunities for reducing CO_2 emissions at the refinery site, different categories of opportunity become apparent:

- **Low-carbon energy carriers:** the gradual decarbonisation of the EU electricity grid or the natural gas network will offer new ways to integrate low-carbon electricity and gas into the production system.
- **Process efficiency** technologies introduced at the industrial sites can minimise energy consumption and, therefore, avoid CO_2 emissions.
- **Carbon capture** technologies will enable refineries to make CO_2 available for either storage (CCS) or use (CCU), thereby integrating the EU refining system into a circular economy.

The study was undertaken with the purpose of:

- establishing the current status of EU refineries in terms of energy intensity and CO_2 emissions intensity, including a brief historical perspective and a comparison with the situation in other world regions; and
- exploring the future of low-CO_2 technologies when deployed across the whole EU refining system towards 2030 and further to 2050, and describing plausible CO_2 reduction pathways by addressing the following questions:
  - What can realistically be achieved through continued gradual improvement?
  - What is the potential for significant new technologies to enable step changes in CO_2 intensity?
  - What is the potential for hitherto untapped synergies with other sectors?
  - What could be the impact of changes to both the quality and quantity of demand for EU petroleum products?

External factors such as future energy prices, together with more effective R&D programmes, will play a role in boosting the deployment of the key technologies identified.

What is the basis of this study?

The starting point: the 2030 demand scenario

For the purposes of this study, the demand scenario (quality and quantity) was defined as a reference for the energy consumption and CO_2 emissions at the refinery site and at EU level.

The study therefore concentrated on the impact of energy efficiency and CO_2 intensity reduction measures. In this context, the starting point for the 2030 horizon was based on actual and detailed refinery data prorated until 2030, including factors such as product demand forecasts and known changes to the configuration of the EU refinery population (see Table 2 on page 34).

In Step 1, the focus is on what the CO_2 reduction technologies could deliver in the medium/long term. It is not the intention to reflect potential changes in demand onwards (from 2030 towards 2050), hence the demand scenario was fixed in that period. Different scenarios exploring the potential evolution of demand from 2030 to 2050, and investigating the role of alternative low-carbon feedstocks to oil, are assessed in Step 2 (the *'Refinery 2050'* report).

Table 2: Demand scenarios for 2030

	MT/YEAR		CHANGE FROM 2014 ACTUAL
	2014	2030	2030
All products	**536.6**	**464.5**	**-13%**
LPG	3.0	4.4	49%
Gasoline	82.5	50.9	-38%
Jet fuel	55.3	67.6	22%
Gas oils	268.2	233.4	-13%
Road diesel	191.0	165.7	-13%
Other diesels	17.7	16.0	-9%
Heating oil	52.6	40.9	-22%
Distillate marine fuel	7.0	10.8	55%
HFO	52.1	32.8	-37%
HFO inland 0.5% sulphur	15.9	6.2	-61%
HFO marine 0.5% sulphur	1.8	16.0	806%
HFO marine high sulphur	34.4	10.6	-69%
Bitumen	17.0	16.3	-4%
Lubricants	4.8	5.4	-13%
Petrochemicals	53.7	53.7	0%
Olefins	40.9	40.9	0%
Aromatics	12.8	12.8	0%

The modelling work: the integration of low-carbon technologies within the refineries

The 2030 refining system — including the reduction in demand and, therefore, in activity as well — was incorporated into a model which could then integrate all options in a systematic and consistent way, and arrive at a range of plausible CO_2-intensity reduction figures for the whole EU refining sector.

A bottom-up approach, looking at each of the 80 refineries currently in operation in the EU, would be impractical and would raise confidentiality issues. Instead, this study adopted a top-down approach, identifying which emission-reduction technologies and external opportunities might be available to EU refiners, and what impact they might have at the 2030 and 2050 horizons on the CO_2 intensity of the whole EU refining sector.

Relevant information was collected from literature and through consultations with experts from technology providers and Concawe member companies. In addition, different rates of deployment of technology, energy prices and the degree of decarbonisation of the electricity grid were explored for both the 2030 and 2050 time horizons.

The potential of each option was scrutinised in detail, taking into consideration:

- the underlying technologies, and their current and future state of development; and
- the internal and external factors (practical and financial) that might favour or constrain the adoption of such measures.

On this basis, the following assumptions were made to assess the impact of each option in a 'Median' case, and explore different sensitivities ('High' and 'Low' cases), for each of the 2030 and 2050 horizons:

- a specific set of energy and CO_2 prices, consistent with authoritative studies; and
- a maximum rate of uptake for certain options, consistent with the economic environment that we considered to be practical and plausible at the time horizon.

In addition, in the 2050 'Median' and 'High' cases, three alternative routes to achieve deep decarbonisation are considered, namely electric boilers and heaters (Max-e), electrolytic hydrogen (Max-h) and CCS (Max-c). Each of these options have different implications in terms of both the use of electricity and the technologies applied to achieve significant CO_2 reductions (these are also detailed in the report).

What can be learnt from the report?

Potential CO_2 savings

A variety of opportunities to implement CO_2 reduction technologies in the EU refining system are identified and clustered into three main categories as listed on page 32: low-carbon energy carriers; process efficiency; and CO_2 capture.

Figure 4 on page 36 shows the cumulative total emissions savings (i.e. including emissions from production of imported electricity and hydrogen production), the total electricity consumption and the associated refinery CAPEX for the main opportunities identified above. Each column shows the cumulated potential for a specific category for the 2030 horizon with increasing deployment towards the 2050 horizon.

Assuming that EU refining activity is maintained at the 2030 level,[4] when all options are exercised in the 'Median' case, the total EU refinery CO_2 emissions (direct and indirect[5]) can potentially be reduced by approximately 25% by 2030 and up to 60% by 2050 in the high-uptake cases compared to the 2030 reference case. It is worth noting that the 2030 reference case already considers a CO_2 reduction of approximately 30% (direct emissions) and 5% (direct and indirect) as compared to 2008.[6]

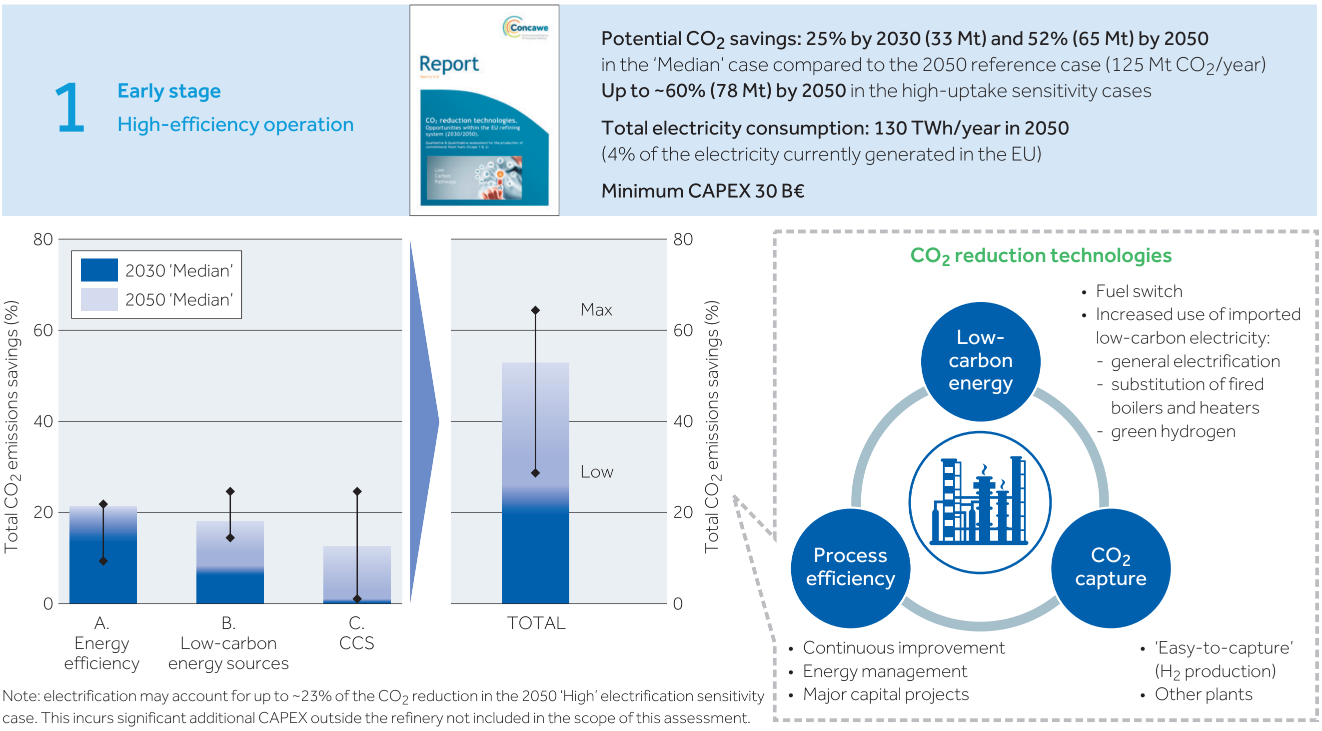
[4] Total CO_2 emissions in the 2030 reference case are ~125 Mt CO_2/year.

[5] Direct emissions considers emissions produced by the refinery. Indirect emissions includes emissions from sources not owned or directly controlled by the refinery but which are related to the activities of the refinery, such as emissions from off-site generation of electricity, steam or hydrogen.

[6] The smaller reduction in direct and indirect emissions compared to the reduction in direct emissions is due to the fossil component of the electricity grid and the fossil footprint associated with the biofeedstocks considered in 2030. Achieving complete renewability of feedstocks (using renewable energy in their production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

This is equivalent to an annual total CO_2 emissions saving of 33 Mt (2030) to 65 Mt (2050) with the potential to increase this by up to 78 Mt by 2050 in the high-uptake sensitivity cases.

Figure 4: CO_2 reduction technologies and potential CO_2 savings



Investment level (CAPEX)

Figure 5 on page 37 shows that the CAPEX required to achieve these potential savings for the whole EU refining system is estimated at a minimum of ~30,000 M€ (2050 'Median' case). This estimated cost represents the generic cost of the different technologies and opportunities identified within the battery limits of the refinery. For example, it does not include fixed OPEX (operational costs), which would account for 25–40% of the total annual fixed costs, and would be highest for cases involving CO_2 capture. The actual cost of implementation would be determined by the specific conditions of each individual asset.

Abatement cost (€/t CO_2)

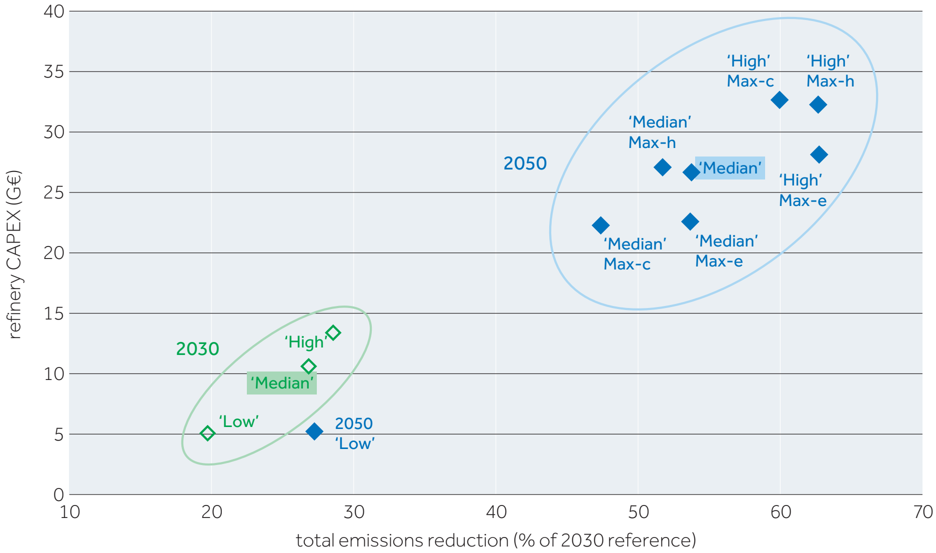
The abatement cost is a useful tool that enables the comparison of the cost of different options to reduce emissions by 1 tonne of CO_2. It is determined partly by the CAPEX (investment) and fixed OPEX required to implement a particular option. The abatement cost and the CO_2 CAPEX intensity are often used interchangeably (and commonly expressed in the same units, €/t CO_2, with no differentiation between them), but whereas the abatement cost provides a clear view of the real cost and is heavily affected by the energy prices (included in the OPEX), the CAPEX intensity is a fixed value which represents the level of investment needed.

Figure 5: Refinery CAPEX vs total emissions reduction, and a breakdown of the different low-carbon technologies

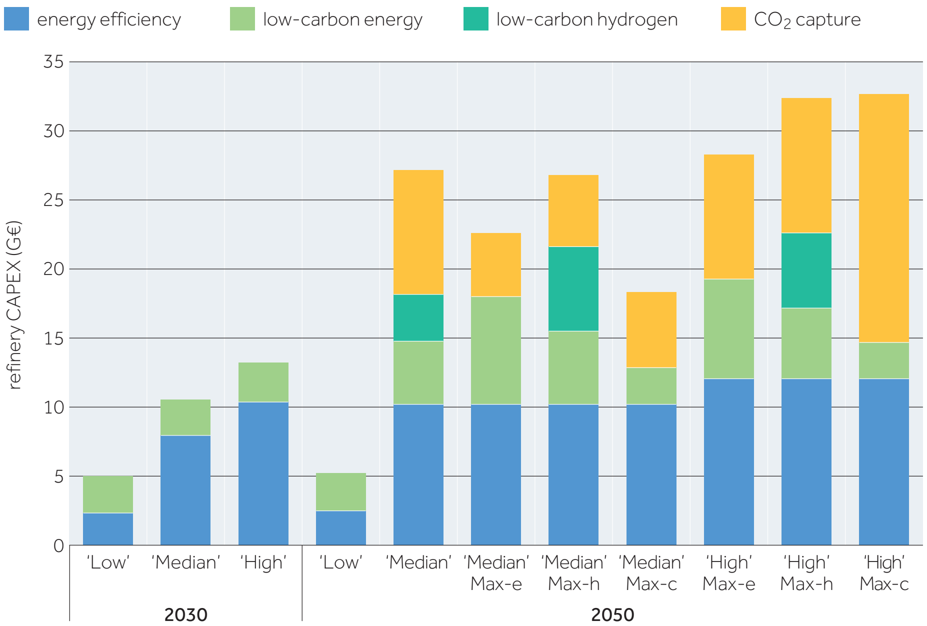
a) CAPEX vs emissions reduction

Max-h = Maximum hydrogen **Max-e** = Maximum electricity **Max-c** = Maximum CCS

Note: the 'Median' cases are highlighted as the main cases explored in the report



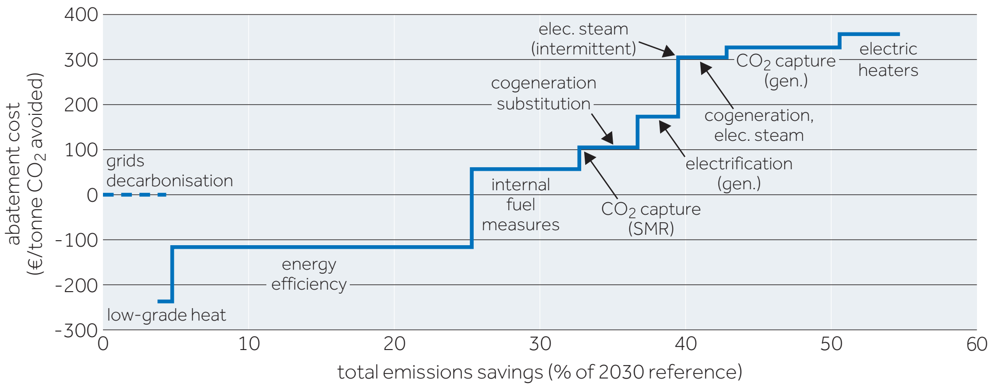
b) A breakdown of the low-carbon technologies



Therefore, there is no single CO_2 abatement cost per technology (Figure 6b). Figure 6a plots the abatement cost of each measure, as an example, ranked from low to high, versus the cumulative CO_2 emissions savings for the 2050 'Median' case.

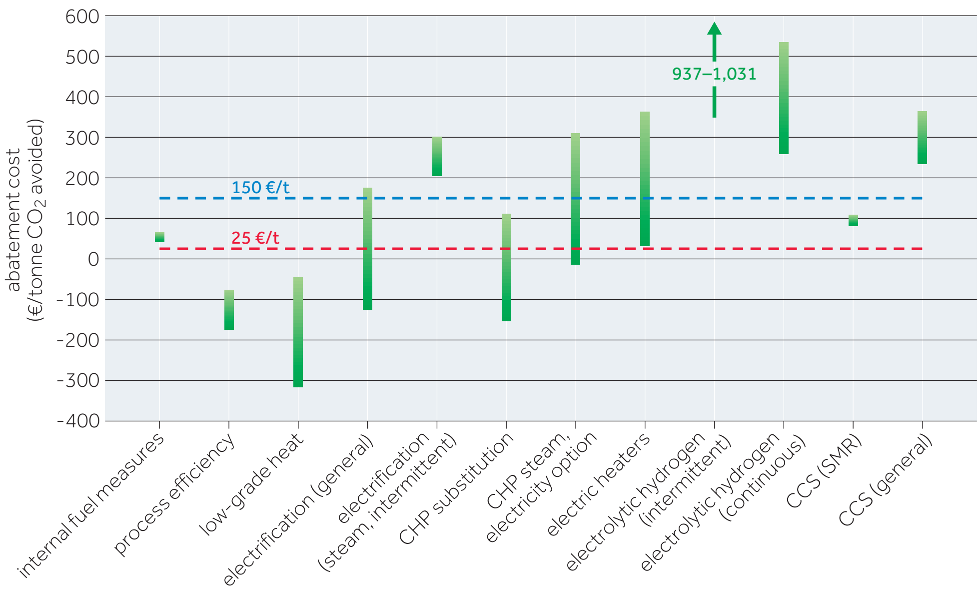
Figure 6: CO_2 abatement cost curve (2050 'Median' case), and example CO_2 abatement costs for different technologies

a) CO_2 abatement cost curve for the 2050 'Median' case



	2030			2050		
Case	**'Low'**	**'Median'**	**'High'**	**'Low'**	**'Median'**	**'High'**
Prices:						
Natural gas (€/GJ)	8	11	15	8	13	17
Electricity (€/MWh)	150	98	60	160	100	60
CO_2 (€/tonne)	25	35	75	25	90	150

b) Example CO_2 abatement cost per technology



Note: the horizontal dashed lines indicate the range of CO_2 prices considered in the different cases.

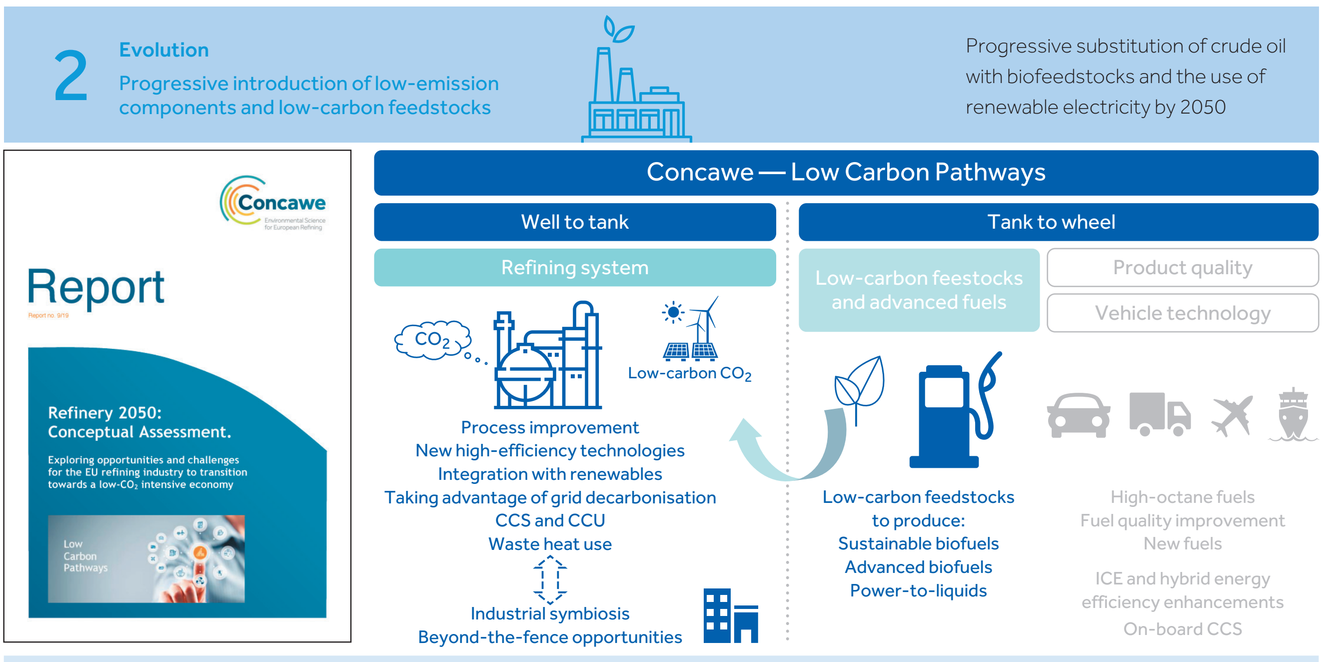
Internal measures and process efficiency improvements show close to zero or negative abatement costs under the energy price scenario considered. The historical profitability of the underlying investments, and the pay-back time threshold assumed for such projects, along with the discount rate (@ 15% capital charge) is used for consistency between all technologies shown on Figure 6.

Refinery 2050: Conceptual Assessment — alternative feedstocks (Step 2)

Overview: what is this report about?

As explained on page 29, this report builds on Step 1, and explores opportunities and challenges for the EU refining system to progressively integrate different low-carbon feedstocks in a mid-century demand scenario. Through a conceptual modelling exercise, some initial figures have been calculated and a range of potential implications have been identified in terms of utilisation and synergies with existing refinery assets, as well as additional electricity, hydrogen and feedstock requirements. It also provides the first estimate of the capital cost that would be required.

Figure 7: Overview of the ‘Refinery 2050’ concept (Step 2)



Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

What is the basis of this study?

The starting point: exploring the 2050 demand scenario

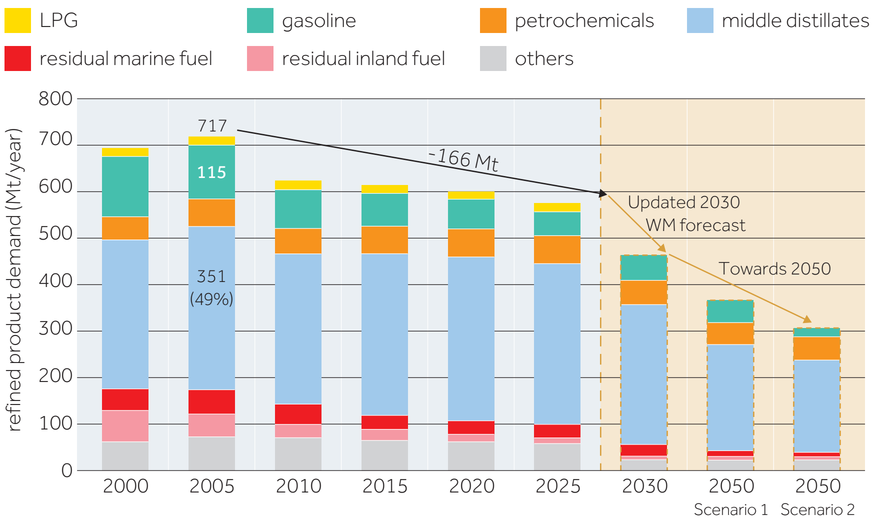
For the 2050 time frame, the main assumption for the demand scenarios is that the demand for most of the products that are currently produced by the refining industry will still be present in lower quantities due to competition with other technologies, and in sectors where no other alternatives are envisaged. In this context, the key question is how to ensure that the demand from the final customer (for end products or intermediate products supplied as feedstocks to other industries) is met in a low-CO_2 intensive manner.

In this context, two different demand scenarios have been explored with changes in the distribution of refining products. These scenarios:

- were initially inspired by the IEA scenarios (IEO, 2017)[7] and adapted to include Concawe's view on specific issues, including different levels of vehicle efficiency improvements and electrification of passenger cars, and reductions in the demand for heating oil and heavy fuel oil;
- define the basis for the modelling exercise which aims to explore the resilience of the refining scheme in the face of these changes as crude oil is progressively replaced by alternative low-carbon feedstocks; and
- provide the basis for the scale and range of both feedstocks and external requirements (e.g. electricity) at the EU level.

> The 2050 scenarios lead to a reduction in the refining throughput ranging from ~-20% (Scenario 1) to ~-35% (Scenario 2) versus the 2030 baseline.
> (Reduction in 2030 versus 2014 is -13%, as shown in Table 2 on page 34.)

Figure 8: Evolution of total demand for refined products in the EU-27+2 (including Norway and Switzerland)



Two different 2050 demand scenarios were explored, inspired by the IEA scenarios (IEA, 2017),[7] and adapted to include Concawe's view, for example:

- energy efficiency across all means of transport;
- a deep reduction in the demand for road diesel and gasoline due to penetration of alternative powertrains; and
- a reduction in marine fuel demand and a shift to middle distillates linked to the 0.5% sulphur limit.

Both scenarios lead to a reduction in refining throughput, ranging from -20% (Scenario 1) to -35% (Scenario 2) vs 2030.

Note: Scenario 2 was used as the main reference in the study.

[7] IEA (2017). *World Energy Outlook 2017:* 'New Policies Scenario' and 'Sustainable Development Scenario'. International Energy Agency.

Scenario 2 is used as the main reference in the study as an ambitious long-term scenario in terms of greenhouse gas (GHG) reduction.

The modelling work: the replacement of oil by low-carbon alternative feedstocks (an example of potential routes)

The modelling exercise explores fossil fuel cases as well as examples of the deployment of the low fossil carbon feedstocks through two different cases:

a) a limited case, where the intake of alternative feedstocks in the notional refinery is limited to the equivalent of 1 Mt/year liquid products; and

b) a maximum case, where alternative feedstocks provide the bulk of the intake (up to ~81% of crude oil replacement), the residual crude oil intake being determined by the need to satisfy the demand for bitumen.

The key basis for the modelling exercise is as follows:

- The modelling exercise is based on a Concawe-based refinery simulation tool (RafXL) calibrated against 2008 data.
- An average mid-range refinery was simulated (160,000 bbl/day of crude oil intake), consistent with the European average refinery configuration. This is a hypothetical refinery used for illustration and is not intended to represent a 'typical' refinery but to serve as the basis for a refining site being able to produce the required demand.
- Energy efficiency improvement rates of 19% and 22% in 2030 and 2050, respectively (from the 2008 reference), broadly representing the average between the 'Median' and 'High' cases detailed in the '*CO_2 reduction technologies*' report discussed on pages 32–39.
- Carbon capture (and storage) applied in selected cases. Waste heat from Fischer-Tropsch (FT) synthesis provided up to 80% of the capture energy demand.
- For alternative low fossil carbon feedstocks product yields, utilities requirements and basic product properties were derived from literature data.
- For each case, the capacity of the various process plants was adjusted (allowing extra new capacity where required) to best match the demand for all major products.
- Pathway scalability has been considered at two-levels, i.e. at an individual production facility and at the EU refining industry level.

What can be learnt from the report?

Low-carbon feedstocks: description and product yields for selected examples

This study investigates the potential for substantial replacement of crude oil with three main categories of selected low fossil carbon feedstocks (lipids, lignocellulosic biomass and e-fuels), each with different processing pathways (and associated yields), i.e.:

1) lipids hydrotreatment;
2) lignocellulosic biomass (e.g. wood):
   - gasification of lignocellulosic biomass, followed by Fischer-Tropsch synthesis and hydrocracking;
   - hydrotreatment/hydrocracking of pyrolysis or hydrothermal liquefaction oils made from lignocellulosic/woody biomass; and
3) e-fuels production from the conversion of captured CO_2 and electrolytic hydrogen into syngas by the reverse-water gas shift reaction, and then into hydrocarbons by Fischer-Tropsch synthesis with subsequent hydrocracking to produce fuels with a suitable boiling range.

A summary of the selected pathways explored in the report, and synergies with existing assets, is presented in Table 3.

Table 3: Summary of selected pathways explored in the report, and synergies with existing assets

		LIGNOCELLULOSIC BIOMASS		
	LIPIDS	GASIFICATION AND FISCHER TROPSCH ROUTE	PYROLYSIS ROUTE	E-FUELS
Illustrative pathway	Commercial lipid hydrotreatment has recently become well-established with a few stand-alone operations of up to 1 million tonnes/year.	Biomass-to-liquids (BTL). Gasification of woody biomass, followed by Fischer-Tropsch (FT) synthesis and hydrocracking.	Fast-pyrolysis or hydro-thermal liquefaction of lignocellulosic biomass or wastes, followed by hydrotreating to remove oxygen.	E-fuel from FT synthesis/hydrocracking of syngas derived from CO_2 capture + electrolytic H_2 using renewable electricity.
Product	Primarily paraffinic diesel and jet fuel.	Primarily paraffinic diesel and jet fuel, possibly with co-products such as chemical naphtha or wax.	Mix of biogasoline and biodiesel (relatively aromatic).	Primarily paraffinic diesel and jet fuel, possibly with co-products such as chemical naphtha or wax.
Feedstock	Typical feeds today: vegetable oil, animal fats or cooking oil; future expansion likely to rely on microbial/algal oils.	Lignocellulosic biomass including wood and residues from forestry, waste wood from industry, agricultural residues (straw and stover) and energy-crops. Potentially, municipal waste as well.		Captured CO_2 and renewable electricity.

Table 3 continues on next page ...

Table 3 (continued): Summary of selected pathways explored in the report, and synergies with existing assets

		LIGNOCELLULOSIC BIOMASS		
	LIPIDS	**GASIFICATION AND FISCHER TROPSCH ROUTE**	**PYROLYSIS ROUTE**	**E-FUELS**
Synergy with refining assets	**Very high** Lipid co-processing with fossil gas oil (5% up to 30% in suitable units with technology stretch). Potential for hydroprocessing refinery units to be adapted as dedicated lipids hydrotreater units (100%). Simplification by integration with refinery utilities, especially H_2 and LPG handling (significant capital saving).	**Moderate** New gasification/FT system; raw FT product is converted to fuel by co-processing in the refinery hydrocracker or by transformation of refinery unit to 100% biofeed. Integration with refinery utilities, especially power and LPG handling.	**Significant** Pyrolysis oil made 'in-field' simplifies biomass logistics. Pyrolysis oil is deoxygenated/upgraded to fuels by co-processing in the refinery unit. Raw oil may need treatment in a new stabiliser. Potential for unit transformation to 100% biofeed. Integration with utilities, especially H_2 (from co-processing to dedicated units).	**Moderate** New electrolysers and FT system. Raw FT product is converted to fuel by co-processing in the refinery hydrocracker or by transformation of the refinery unit to 100% biofeed. Refinery can use its own CO_2 emissions as feed for integrated e-fuel plants.
Technology and supply-chain readiness	Existing conversion technology and conventional supply chain. Future expansion requires development of new algae technology and the establishment of a significant new agricultural industry.	Conversion technologies have been commercialised separately in other sectors (power, natural gas) but have not been demonstrated at scale as an integrated process. A few forestry supply chains exist at >1 Mt/year scale, but significant replication would be needed.	Pyrolysis technologies have been demonstrated in a few small commercial operations, mainly in the heat/power sector. Upgrading to transport fuel is still at the developmental scale; refinery trials have been inconclusive. A few forestry/waste supply chains have been established (power sector), but would need significant replication.	Conversion technologies have been commercialised separately in other sectors (power, natural gas) but at very different scales. Integrated process still at pilot-scale. Potential for CO_2 utilisation at sites without CO_2 storage options or logistics.
External requirements	**High** (Sustainable feedstock availability)	**Very high** (Low-carbon electricity)		

Two series of cases were modelled in the study:

1. Limited low fossil carbon feedstock cases

In the first series of cases, after decreasing the throughput of the notional/average refinery to meet the 2050 demand scenario, the remaining crude oil intake was reduced by just under a quarter. The shortfall (about 1 Mt/year) was provided by one of the alternative feedstocks under consideration.

Table 4: A summary of the limited low fossil carbon feedstock cases (2050, average refinery)

KT/YEAR	FOSSIL CASE (2050) 50/2 FOS[a]	LIPIDS ROUTE (L1)	BIOMASS/FT ROUTE (BFT1[b])	BIOMASS/HTL (PYROLYSIS) ROUTE (BPY1)	E-FUELS ROUTE (FOE1)
Crude intake	4,300	3,280	3,280	3,280	3,300
Crude replacement (%)		24%	24%	24%	23%
Lipids	0	1,000	-	-	-
Biomass	0	-	4,250	2,250	
HT oil				970	
CO_2 capture					3,166
E-fuels	0	-	-	-	1,020
Hydrogen production	29.8	60	21	82	464
Electricity imports (GWh/year)	2,414	3,344	-1,536[c]	4,545	22,739
Direct fossil CO_2 emissions per refinery (fossil from site) (% reduction versus 2050 fossil case)	-	-54%	x 1.8[b]	-31%	-92%
Direct fossil CO_2 emissions EU-wide (fossil from site) (Mt/year)	42	18	76	28	4[d]

[a] 50/2 FOS relates to the 2050 demand scenario 2 assuming the 2050 level of energy efficiency with CO_2 emissions reduction through limited electrification, and no electrolytic hydrogen and CO_2 capture.

[b] The biomass FT (BFT1) route could increase the direct fossil emissions versus the base fossil case due to the partially fossil footprint associated with the biofeedstocks. Achieving complete renewability of feedstocks (using renewable energy in the production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

[c] Due to the biomass gasification process and its associated surplus of heat, the refinery will end up exporting electricity.

[d] The EU electricity mix remaining fossil component has been assumed for the e-fuel production to be 40 t CO_2/GWh by 2050. Ensuring access to fully renewable electricity would have the potential to reduce the CO_2 emissions even further.

2. Maximum low fossil carbon feedstock cases

A second series of cases illustrated a hypothetical extreme situation where alternative feedstocks provided the bulk of the intake, the residual crude oil intake being determined by the need to satisfy the demand for bitumen.

Table 5: A summary of the maximum low fossil carbon feedstock cases (2050, average refinery)

KT/YEAR	LIPIDS + BIOMASS (LB)	LIPIDS + BIOMASS + CCS (LB-c)	BIOMASS + BIOMASS + E-FUELS (LBE)	BIOMASS + LIPIDS + E-FUELS (LBPE) [a]
Crude intake	810	810	810	810
Crude replacement (%)	81%	81%	81%	81%
Lipids	2,910	2,910	2,150	2,410
Biomass	3,810	3,810	2,800	3,640
HT oil				784
CO_2 capture			2,729	459
E-fuels			879	148
Hydrogen production	84.6		448.3	181.3
Electricity imports (GWh/year)	149	1,764	19,977	6,051
Direct fossil CO_2 emissions per refinery (fossil from site) (% reduction versus 2050 fossil case)	x 1.3 [b]	-200 % [c]	-70%	-30%
Direct fossil CO_2 emissions EU-wide (fossil from site) (Mt/year)	56	-90	13	29

[a] As LBE but limited e-fuels (16% capture) and with biomass 50/50 FT and pyrolysis oil (HTL process).

[b] The Lipids + Biomass (LB) route could increase the direct fossil emissions versus the base fossil case due to the partially fossil footprint associated with the biofeedstocks. Achieving complete renewability of feedstocks (using renewable energy in the production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

[c] Negative emissions considered due to the CCS + biomass technologies coupling.

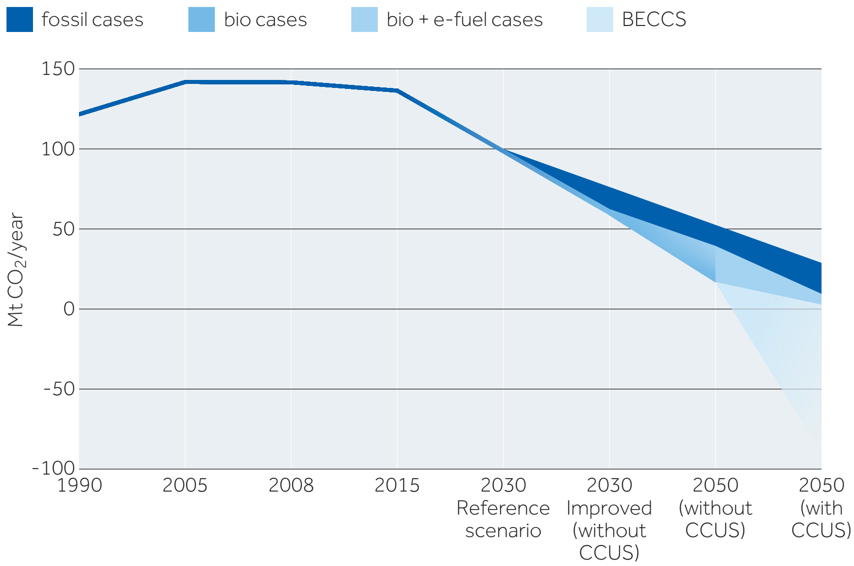
Potential CO_2 savings, electricity and hydrogen consumption, and CAPEX

Figure 9 shows potential evolution of CO_2 emissions at EU refinery sites resulting from the combination of measures identified in the '*Refinery 2050*' report.

The figure illustrates that, compared to the 1990 level, the CO_2 emissions from EU refinery sites (hence EU-wide) could be reduced by between 50% and 90%. When CCS solutions are combined with biomass feedstocks in BECCS (bioenergy with carbon capture and storage) schemes, net negative emissions could be achieved (compatible with the European Commission's long-term strategy, *A Clean Planet for all* [7]).

It also shows the total electricity and hydrogen consumption EU-wide, and the estimated CAPEX for a notional refinery.

Figure 9: EU-wide CO_2 emissions at refinery sites (direct fossil emissions; results from the '*Refinery 2050*' report)



EU wide:

- Potential CO_2 savings range from **50–90%** vs 1990, **and 85%** vs the 2030 improved scenario.
  Pathways enable negative emissions through biomass + CCS.
- **Total electricity consumption ranges from 150–550 TWh/year in 2050.**
  Consumption increases by 5 to 18 times vs the 2030 improved scenario.
- **Total hydrogen consumption ranges from 7–15 Mtoe/year in 2050.**
  Consumption increases by 2 to 5 times vs the 2030 improved scenario.

For a notional refinery (160 kbbl/day):

- **Estimated CAPEX could range from 1–10 G€** for the limited penetration cases, **and from 6–15 G€** for the extreme cases.

Impact beyond the refining boundary limits—an example:

In extreme cases the fossil carbon intensity of the main fuels could be reduced by 60–80% (diesel).

Feedstocks to petrochemicals also benefit from the renewable carbon intake—in extreme cases, up to around 60% non-fossil carbon.

Notes on Figure 9:

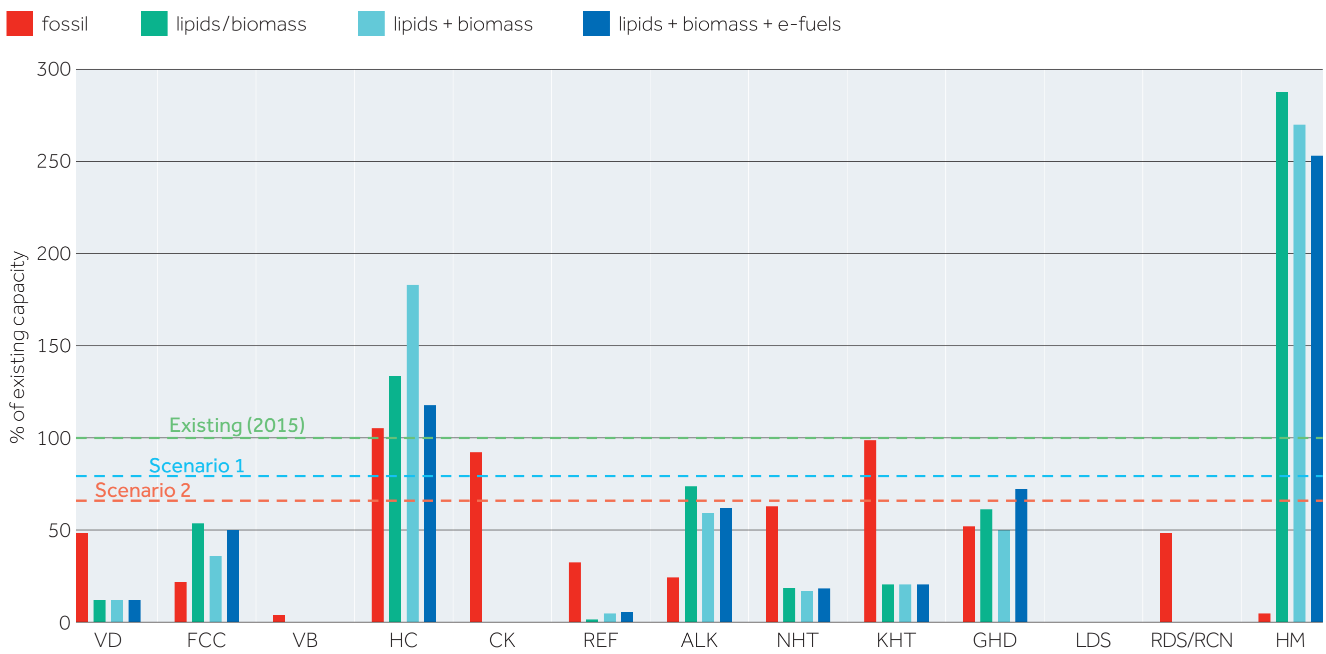
- The dark blue colour on Figure 9 relates to fossil cases where, once the demand reduction is taken into account, the upper and lower limits depend on the different penetration of CO_2 technologies identified in the '*CO_2 reduction technologies*' report (Step 1).
- The mid-blue colours relate to bio cases (lipids + biomass) and e-fuel cases.
- The very light blue relates to BECCS (bioenergy with carbon capture and storage); this technology is able to achieve negative emissions.

[7] https://ec.europa.eu/clima/policies/strategies/2050_en

Refinery utilisation level

Within this conceptual assessment, Concawe also looked at the potential utilisation levels of the existing process units within an average refinery when the selected alternative feedstocks are progressively processed instead of crude oil. The modelling work conducted shows that, due to the different composition and upgrade requirements necessary for the alternative feedstocks to meet the defined demand, some units could be operating well below their minimum operational rates. As a result, some rationalisation/downsizing may be required across the EU refining system to make these scenarios realistic from an operational point of view.

Figure 10: Refinery process plant utilisation



Process plants abbreviation key:

VD	vacuum distillation	REF	catalytic reforming	LDS	atmospheric residue desulphurisation
FCC	fluid catalytic cracking	ALK	alkylation	RDS/RCN	vacuum residue desulphurisation/conversion
VB	visbreaking	NHT	naphtha hydrotreating	HM	hydrogen manufacturing
HC	hydrocracking	KHT	kerosene hydrotreating		
CK	coking	GHD	gas oil hydrodesulphurisation		

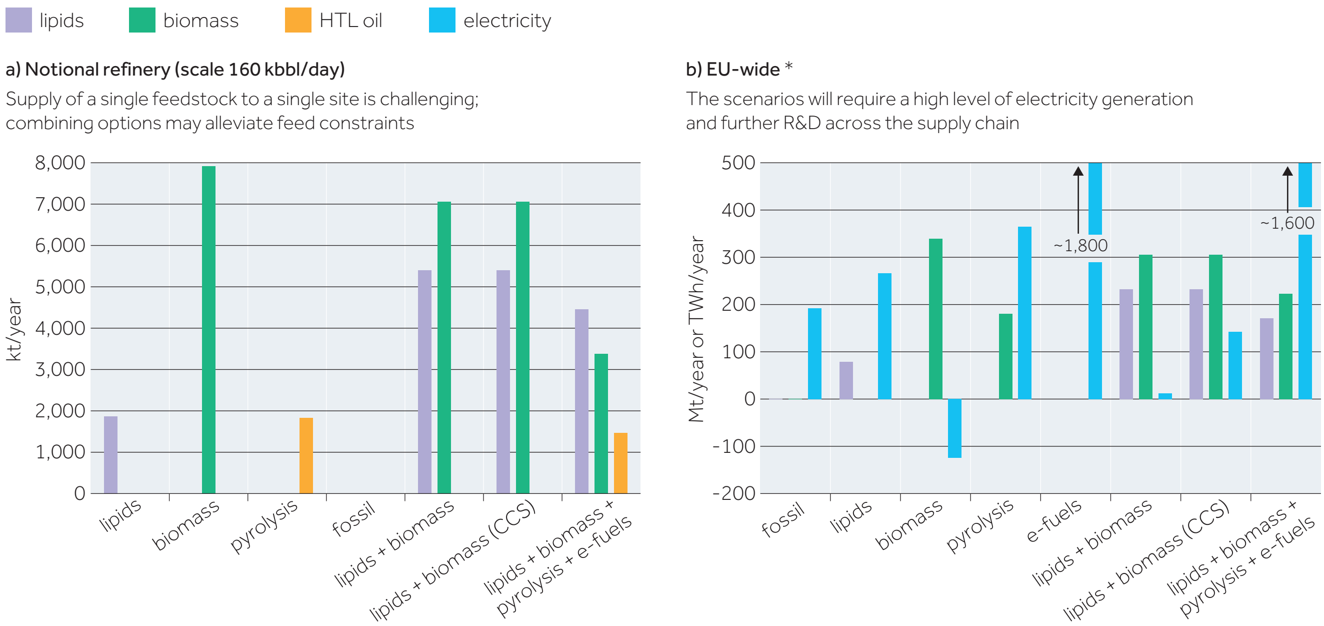
Generally speaking, the selected examples involve maximizing the hydrocracking and middle distillate hydrotreating routes, meaning that more capacity would be required than that which is currently defined for the average refinery. Consequently, the hydrogen requirements for processing these feedstocks also increases, and more hydrogen capacity would therefore also be required. On the other hand, the activity levels of some of the other units which usually operate at high levels of activity with current fossil crude oil—such as the coking unit—would not be minimised when fossil oil is largely replaced.

Furthermore, it is important to highlight that this first assessment is not intended to represent the future utilisation of all refineries in Europe; rather, its aim is to help us explore some initial examples of how alternative pathways can be combined in an average refinery, and assess the impacts that may occur in an average asset. Different refineries with different configurations may adopt a different combination of one or more of the pathways explored, among others, depending on factors such as their specific schemes or the proximity to a specific feedstock.

Alternative feedstock supply requirement

When looking at the feedstock requirements and other utilities (such as electricity), the different cases explored show different profiles—see Figure 11.

Figure 11: Alternative feedstock supply requirement



* Note: as a reference, net electricity generation in the EU-28 was ~3,100 TWh in 2016 (Source: Eurostat)

The study predicts that, in all cases, the scenarios will require high levels of renewable electricity (up to 1,800 TWh/year at the EU level) and an increase in the low-carbon feedstocks availability (up to 200 Mt/year for lipids and 300 Mt/year for wood at the EU level).

A literature review on the maximum potential availability and demand for low-carbon feedstocks in Europe in the 2020–2050 time frame was published in the Concawe *Review*, Vol. 27, No. 2.[8] According to references such as DG R&I and Ecorys (2017),[9] the maximum sustainable low-carbon feedstock availability in Europe would be 500–600 Mt/year by 2030 (and up to 700 Mt/year in the 2050 'High' R&D scenario).

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

[9] https://op.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1

Research and development framework

When the technology readiness level (TRL) of each of the different technologies explored is assessed (see Figures 12 and 13), it can be seen that the different opportunities identified in these studies are at different stages of development. Therefore, to reduce the CO_2 intensity of refinery sites and products, and for the identified potential to become a reality at reasonable cost for each time horizon (2030 and 2050), some key enablers would be required:

- Some technologies are ready or almost ready for deployment, and the industry is taking steps in this regard (e.g. CCS, hydrotreating vegetable oils).
- Further technological development across the whole value chain is key to increasing the availability and mobilisation of sustainable low-carbon feedstocks as key enablers to minimise CO_2 emissions at both the site and end-product levels.
- Boosting efforts in R&D/scaling-up of technologies common to different pathways, such as low-carbon hydrogen and CCS/CCU, are considered to be key building blocks for reaching deep decarbonisation levels.
- A number of key R&D challenges associated with the low-carbon feedstock technologies will need to be met; some of these identified in Table 6.
- Cross-sectoral and collaborative R&D efforts with stakeholders across the value chain (specially the supply chain) are expected to accelerate the development and scale-up of the key technologies.

Beyond this, refineries will need to attract the investment required to revamp existing plant, or build new plant and the required infrastructure to facilitate the integration of developing low-CO_2 technologies. A supporting regulatory framework and economic environment are envisaged to play a key role in this regard.

Table 6: Key R&D challenges for low-carbon alternative feedstocks

FEEDSTOCK	KEY R&D CHALLENGES
Lipid	• Alternative feedstocks development (e.g. waste, algae); biology still in early stages of R&D.
BTL	• Technology not yet commercially available. • How to ensure continuous operation when processing different feedstocks is still an issue. • Conversion efficiency/increasing resource availability are key factors. • Establishment of large lignocellulosic/residue supply chain in line with new plants start-up needed.
Pyrolysis	• Technology needs to be scaled up. • Processing of pyrolysis in refineries requires further R&D.
E-fuels	• Technology needs to be scaled up. • Efficiency improvements are required to reduce electricity requirement and improve CO_2 capture ratio → cost reduction.