Concawe
Environmental Science for European Refining

Review

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Foreword

I am pleased to introduce the three articles present in this edition of the Concawe *Review*, which emanate from Concawe's Low Carbon Pathways project. We are currently faced with multiple climate-related demonstrations, and the European Parliament and Commission are defining Europe's ambition for the transition to a low-carbon economy. In such an environment, it is our mission to go beyond our usual technologies, to evaluate new ones, and to analyse their feasibility and the consequences of their implementation.

The first two articles refer to new technologies in connection with the use of renewable electricity. The first article is a literature review summarising different perspectives on e-fuels technologies, together with the respective advantages and disadvantages, costs, challenges and enablers. I find this summary highly informative on technologies for which some forecast a bright future, especially for applications like aviation and marine, for which electrification is not seen as a possibility. The second article is a literature review on batteries used in electric vehicles, reviewing different technologies and the sources and availability of metals, presenting price forecasts and outlining the challenges that need to be overcome.

Energy efficiency improvements can contribute to the reduction in greenhouse gas (GHG) emissions, as can the optimization of fuels and powertrains. High-octane gasoline enables higher compression ratios in combustion engines, which could improve gasoline engine efficiency. The third article investigates the feasibility, as well as the costs, for the European refining industry to produce fuels of such quality.

My thanks go to the authors for these valuable insights into one of the biggest challenges we face, and to the contributors to Concawe, either as a member company participating in a Concawe special task force or management group, or as a partner or collaborator with the management groups. I also take the opportunity to thank my predecessor, Dr Robin Nelson, who initiated and led Concawe's Low Carbon Pathways project.

Jean-Marc Sohier
Science Director
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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 European Union's CO_2 emissions reduction strategy, Concawe's Low Carbon Pathways (LCP) project is exploring opportunities and challenges presented by different low-carbon technologies to achieve a significant reduction in CO_2 emissions associated with both the manufacturing and use of refined products in Europe over the medium (2030) and longer term (2050).

In the scenarios considered by the Commission, e-fuels are presented as a potential cost-effective technology (with a specific scenario focused on them) that could be used to achieve the objectives of the Paris Agreement — i.e. to keep the global temperature increase to well below 2°C, and pursue efforts to limit it to 1.5°C.

This article presents a literature review of e-fuels, and aims to build a better understanding of e-fuel production technologies and implications in terms of efficiency, greenhouse gas reductions, technology readiness level, environmental impact, investment, costs and potential demand. It provides a summary of the exhaustive literature review due to be published at the end of 2019.

The main recent state-of-the-art publications have been identified and compared, covering detailed assessments, presentations, technology providers, position papers and the European Commission's long-term strategy, *A Clean Planet for all*, to help define a better picture of the potential role of e-fuels in Europe.

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Recognising that climate change represents an urgent threat to societies and the planet, the 2015 Paris Agreement set the goal of keeping global warming well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C (global warming has already reached 1°C). To build on these objectives, the EU Commission has developed its long-term strategic vision for a prosperous, modern, competitive and climate-neutral economy in Europe, which confirms Europe's commitment to be a leader in addressing global climate change. It includes an assessment, based on several scenarios, to support the EU's strategy to reduce long-term EU GHG emissions in accordance with the Paris Agreement, starting at -80% going up to -100% by 2050 compared to 1990 levels.

In all the scenarios, the electric vehicle (EV) plays an important role, creating a significant need for battery raw materials. Consequently, there are concerns about the future supply of raw materials necessary for battery production and the impact of rising prices on battery production costs.

This article is a literature review of publications from Wood Mackenzie, McKinsey & Company and Ricardo (among others), and summarises the important key messages regarding technologies, metal sources, demand, availability, prices, recycling and uncertainties/challenges of battery raw materials.

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A look into the role of e-fuels in the transport system in Europe (2030–2050)
(literature review)

As part of Concawe's Low Carbon Pathways project, this article presents a literature review on e-fuels, which aims to build a better understanding of e-fuel production technologies and implications in terms of efficiency, greenhouse gas reduction, technology readiness level, environmental impact, investment, costs and potential demand. It is a summary of the exhaustive literature review which is due to be published by the end of 2019.

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Introduction

In December 2015, Parties to the United Nations Framework Convention on Climate Change convened in Paris for the 21st Conference of Parties (COP21). The conference was an important step towards addressing the risks posed by climate change through an agreement to keep the global temperature increase 'well below 2°C above pre-industrial levels' and drive efforts to limit it to 1.5°C above pre-industrial levels. 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 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 medium (2030) and longer term (2050).

In the scenarios considered by the Commission (P2X, COMBO, 1.5 TECH and 1.5 LIFE) e-fuels are presented as a potential cost-effective technology that could be used to achieve the objectives of the Paris Agreement, i.e. to keep the global temperature increase to well below 2°C, and pursue efforts to limit it to 1.5°C.

As part of the LCP programme, this article presents a literature review of e-fuels, and aims to build a better understanding of the e-fuel production technologies and implications in terms of efficiency, contribution to reducing greenhouse gas (GHG) emissions, technology readiness level, environmental impact, investment, costs and potential demand. This is a summary of the exhaustive literature review due to be published at the end of 2019.

Recent state-of-the-art publications have been identified and compared in this literature review, covering detailed assessments, presentations, technology providers, position papers and the European Commission's long-term strategy, *A Clean Planet for all*.[1] It is intended that this will help to define a better picture of the potential role of low-carbon fuels in Europe.

E-fuels concept

E-fuels are synthetic fuels, resulting from the combination of 'green or e-hydrogen' produced by electrolysis of water with renewable electricity and CO_2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuels are also described in the literature as electrofuels, power-to-X (PtX), power-to-liquids (PtL), power-to-gas (PtG) and synthetic fuels. E-hydrogen has also been considered as part of this review.

The tables on page 5 summarise the potential primary uses of e-fuels across different transport segments (Table 1), a qualitative overview of lower heating value, storability, infrastructure and powertrain development (Table 2), and key parameters of e-fuels versus alternative options (Table 3).

[1] European Commission (2018). *A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.*
https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

Table 1: Potential primary uses of e-fuels

	E-FUELS	PASSENGER CARS	HEAVY DUTY	MARITIME	AVIATION	OTHER SECTORS (NON TRANSPORT)
Gas	e-methane (CH_4)	X	XX	XX		XXX
	e-hydrogen (H_2)	XX	XX	X		X
Liquid	e-ammonia (NH_3)	X	X	XXX		
	e-methanol (CH_3OH)	XX	X	X		
	e-DME/e-OME	X	XX	XX		
	e-gasoline	X				
	e-diesel	X	XXX	XX		
	e-jet				XXX	

'X's are an initial estimate of the relative potential role of different e-fuels in transport segments (no 'X' = no envisaged potential).
Green = primary use; blue = secondary use; yellow = minority use. 'Other sectors' include industry, building and power.

Table 2: Qualitative overview of e-fuels

	E-FUELS	LOWER HEATING VALUE (LHV), MJ/kg / MJ/litre	STORAGE	ADDITIONAL INFRASTRUCTURE	POWERTRAIN DEVELOPMENT
Gas	e-methane	46.6 / 0.04	Medium[a]	No	No
	e-hydrogen	120 / 0.01	Difficult	Yes	No[b]
Liquid	e-ammonia	18.6 / 14.1	Easy	Yes	Yes
	e-methanol	19.9 / 15.8	Easy	No	Yes
	e-DME	28.4 / 19.0	Easy	Yes	Yes
	e-OME	19.2 / 20.5	Easy	Yes	Yes
	e-gasoline[c]	41.5 / 31.0	Easy	No	No
	e-diesel[c]	44.0 / 34.3	Easy	No	No
	e-jet[c]	44.1 / 33.3	Easy	No	No

[a] E-methane could use most of the existing logistics, including transportation, storage and distribution systems of natural gas, but storability is not as easy as for liquid molecules.
[b] FCEVs (fuel cell electric vehicles) are commercially available, but are limited in number and it is difficult to assess whether they will become a mainstream option.
[c] Properties refer to conventional fossil fuels due to lack of publicly available properties for e-fuels (properties are expected to be similar although more research is needed).
Green = positive characteristics; yellow = negative characteristics.

Table 3: Different alternatives versus different key parameters

	TRANSPORT SECTORS	INFRASTRUCTURE	STORAGE	INVESTMENT	GREENHOUSE GAS REDUCTION
Fossil fuels	All	Existing	Easy	Low	Low
Electricity	LDV/HDV[a]	New	Difficult	High	High
Biofuels	All (limited by availability and cap in demand)	Existing	Easy	Medium	High
E-fuels	All	Existing[b]	Easy	High	High

[a] LDV = light-duty vehicles; HDV = heavy-duty vehicles.
[b] Existing in the case of e-methane, e-methanol, e-gasoline, e-diesel or e-jet. Not existing for e-hydrogen, e-ammonia or e-DME/OME.
Green = most positive characteristics; yellow = nominally beneficial characteristics; orange = negative characteristics.

E-fuels technology

Feedstock-related technologies

Hydrogen electrolysis

E-hydrogen (also called 'green hydrogen') is used as a feedstock for producing e-fuels. It can also be a final product in itself. It is produced by electrolysis from water.

Different electrolysis technologies can be used for producing hydrogen. These include low-temperature (50 to 80°C) technologies such as an alkaline electrolysis cell (AEC), proton exchange membrane cell (PEMC), or high-temperature (700 to 1,000°C) processes using a solid-oxide electrolysis cell (SOEC).

CO_2 capture

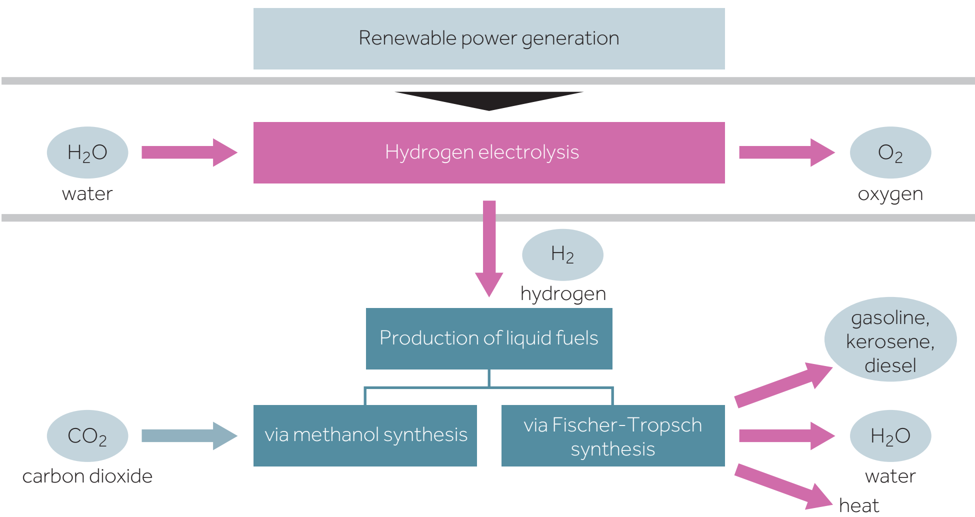
The production of e-fuels requires CO_2 (except e-ammonia), which can be obtained from various sources including biomass combustion, industrial processes (e.g. flue gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air.

E-fuels-related technologies

E-fuels production routes consist of e-hydrogen reacting with captured CO_2, followed by different conversion routes according to the final e-fuel (such as the methanisation route for e-methane; methanol synthesis for e-methanol, e-DME, e-OME or e-liquid hydrocarbons; or the reverse water-gas shift (RWGS) reaction to produce syngas + Fischer-Tropsch synthesis to produce e-liquid hydrocarbons, such as e-gasoline, e-diesel or e-jet.[2] E-ammonia does not require CO_2 and is synthesised from e-hydrogen through a Haber-Bosch reaction).

Figure 1: E-liquids production routes

Source: Frontier Economics (2018)

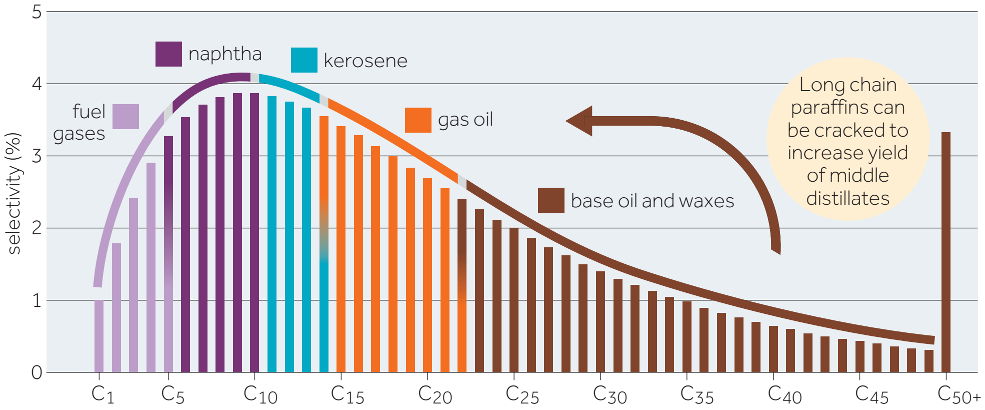


[2] Recent developments are evolving to a new technology (co-electrolysis) where CO_2 and steam are fed into a high-temperature (solid-oxide) electrolyser to produce syngas in a single step, increasing the efficiency of the process [Sunfire, 2019a].

Liquid e-fuels production via the Fischer-Tropsch reaction results in a mix of fuel gases, naphtha/gasoline, kerosene, diesel/gas oil, base oil and waxes. Figure 2 shows a typical distribution of total e-crude product leaving the Fischer-Tropsch reactors before they are separated or converted by further processing steps. The product distribution is a function of many factors, including the catalyst composition (e.g. iron versus cobalt) and the operating conditions.

Figure 2: Fischer-Tropsch liquid e-fuel products

Source: Shell (2018a)

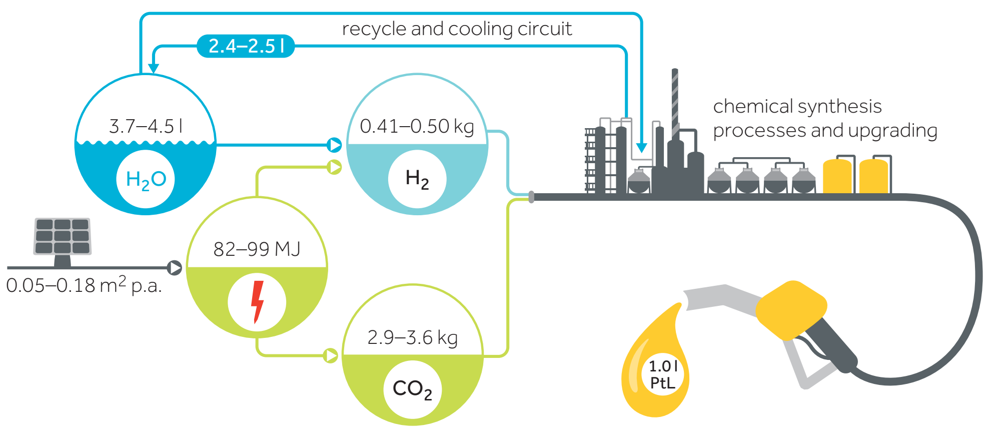


The resulting 'e-crude' from the Fischer-Tropsch reaction, which can be a single stream or several separate streams, could be fed to a hydrocracking unit. The intermediate wax molecules are hydro-processed within a hydrocracker into shorter 'middle distillate' molecules, which are then purified by distillation into naphtha, kerosene and gas oil fractions.

The mass balance to produce 1 litre of liquid e-fuel is 3.7–4.5 litres of water, 82–99 MJ of renewable electricity and 2.9–3.6 kg of CO_2 (see Figure 3).

Figure 3: Resources required for liquid e-fuel production

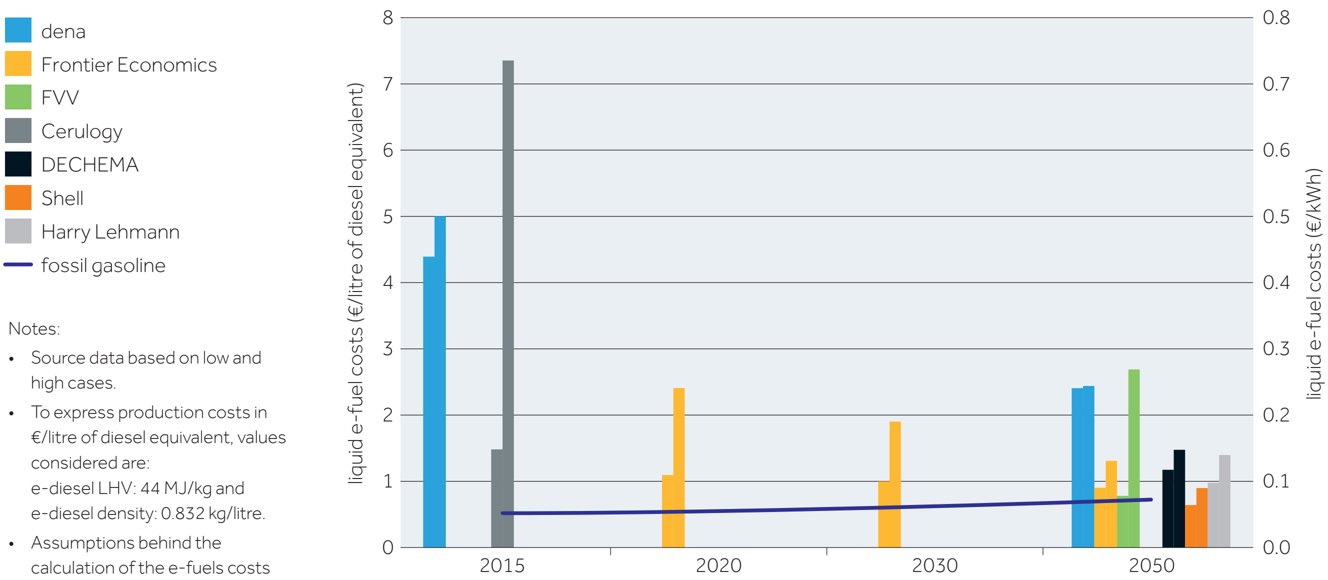
Source: Shell (2018a)



E-fuel costs

E-fuel costs are currently relatively high (up to 7 euros/litre) but are expected to decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price; this is expected to lead to a cost of 1–3 euros/litre (without taxes) in 2050.[3] The cost of e-fuels could therefore be 1–3 times higher than the cost of fossil fuels by 2050.[4]

Figure 4: Liquid hydrocarbon e-fuel costs (min/max) (€/l and €/kWh)



Notes:

- Source data based on low and high cases.
- To express production costs in €/litre of diesel equivalent, values considered are:
  e-diesel LHV: 44 MJ/kg and
  e-diesel density: 0.832 kg/litre.
- Assumptions behind the calculation of the e-fuels costs regarding the inclusion of an RWGS reaction in a separate stage or in a co-electrolysis are not defined in the original sources.

The most important drivers for the future cost of e-fuels are the costs of power generation and the capacity utilization of conversion facilities. Figure 5 on page 9 shows the breakdown of production costs for e-methane and e-liquids.

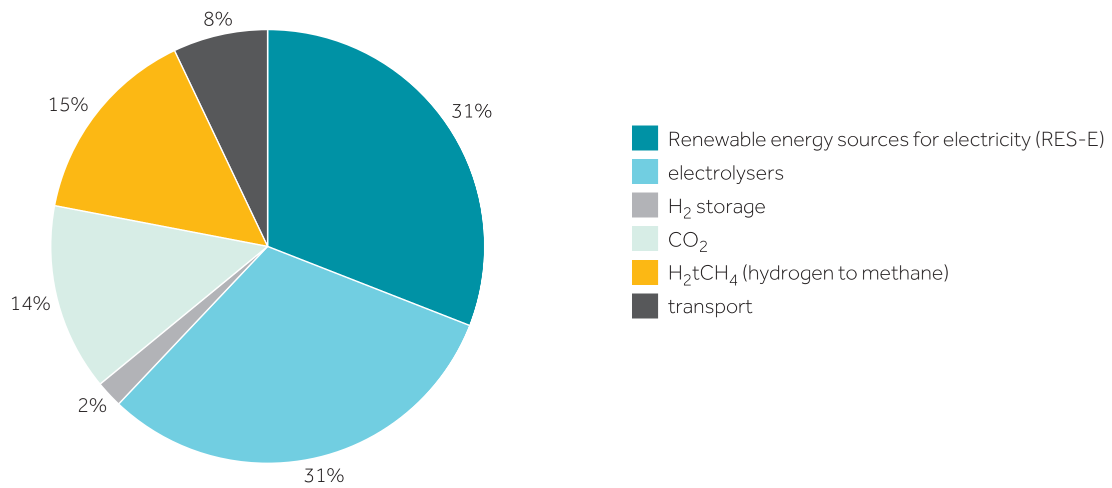
[3] Dena and Cerulogy (up to 7 euros/litre currently). Dena, Frontier Economics, FVV, DECHEMA, Shell (1–3 euros/litre in 2050).

[4] Electricity costs currently range from 4 eurocents per kilowatt hour (ct/kWh) (North Africa—photovoltaic) to 10–13 ct/kWh (North and Baltic Seas—offshore wind), and by 2050 are expected to range from 1–3 ct/kWh (North Africa—photovoltaic) to 4–8 ct/kWh (North and Baltic Seas—offshore wind). Source: Frontier Economics Calculator (2018): https://www.agora-energiewende.de/en/publications/ptgptl-calculator/

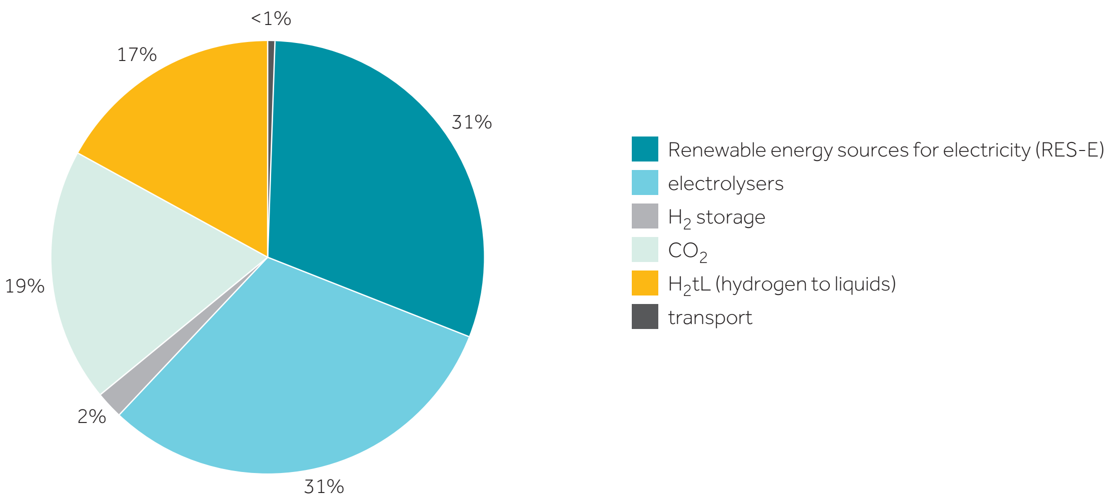
Figure 5: Cost breakdown for e-fuels

Source: Frontier Economics (2018)

a) E-methane



b) E-liquids



Note:

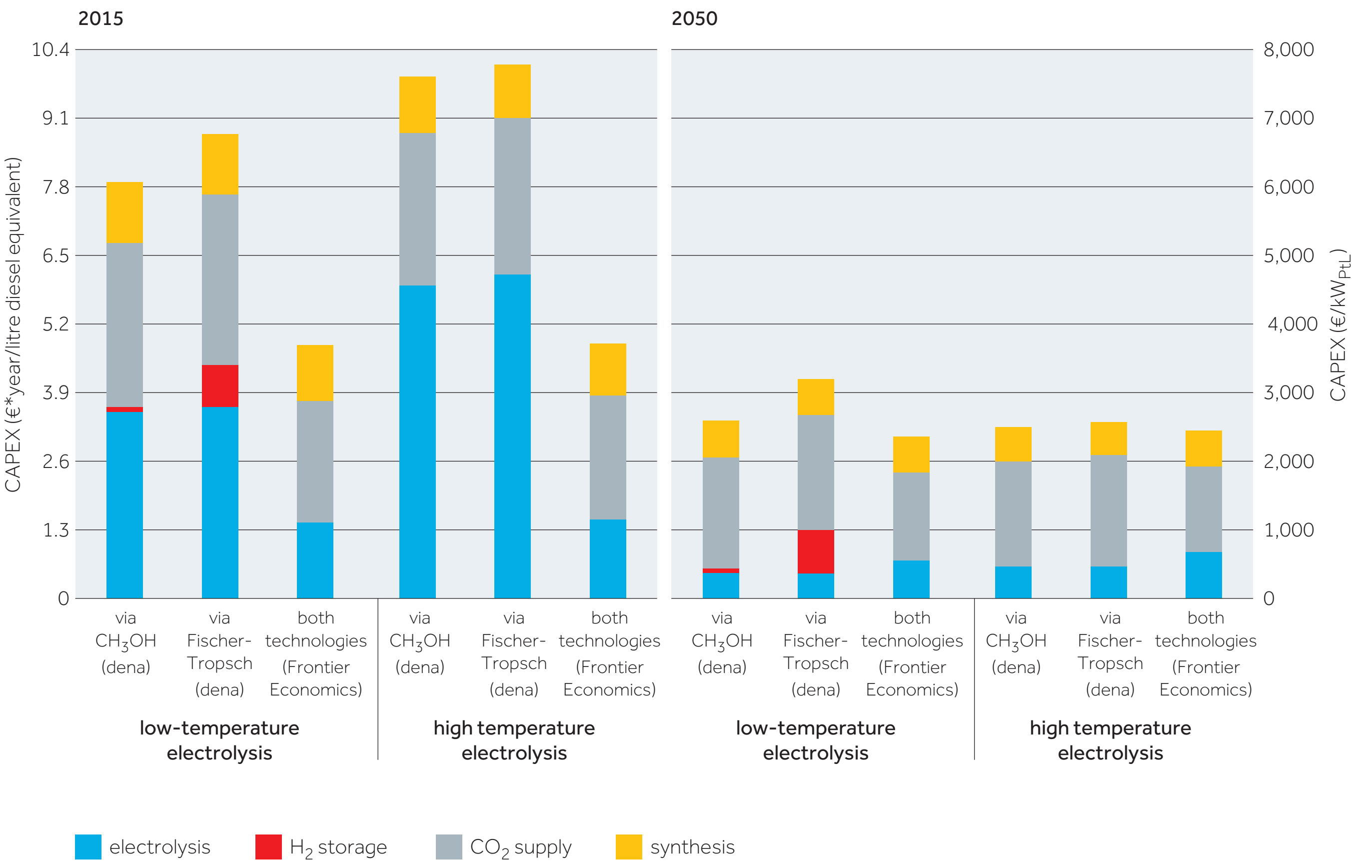
- All cost shares (%) and absolute figures (ct/kWh) are rounded and associated with the following scenario: North Africa, reference scenario 2030, PV-wind-combination, CO_2 from DAC, 6% WACC.

E-fuels investment

All references allow for a progressive reduction in investment cost per technology over time, due to economies of scale and learning effects. Figure 6 compares the capital expenditure (CAPEX) associated with different e-fuels technologies in 2015 with forecasted costs in 2050.

Figure 6: E-fuels CAPEX

Source: Frontier Economics (2018); LBST and dena (2017).



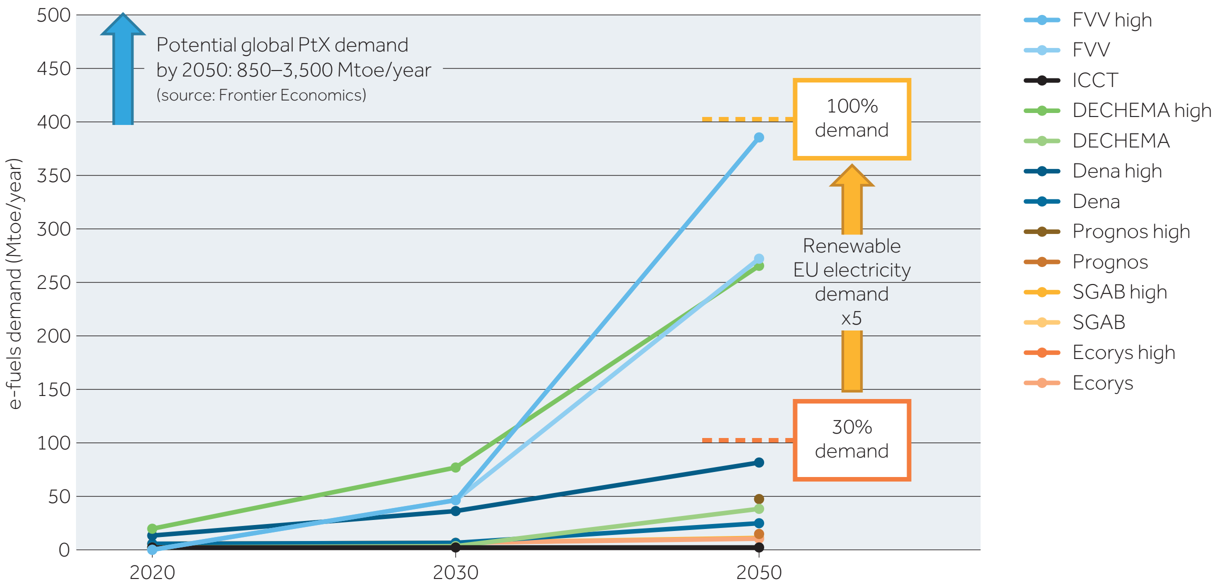
Notes:

- CO_2 capture is based on DAC in both sources.
- 8,000 €/kW$_{PtL}$ (investment in 2015 according to dena for a 70 Mt/year e-fuel plant) corresponds to ≈850 M€.
- Power generation CAPEX is not included in e-fuels plant investment. Depending on the level of deployment of e-fuels, additional power generation CAPEX could have an impact on electricity price.
- To express CAPEX in €*year/ litre of diesel equivalent, values considered are: e-diesel LHV: 44 MJ/kg and e-diesel density: 0.832 kg/litre
- Assumptions behind the calculation of the CAPEX regarding the inclusion of an RWGS reaction in a separate stage or in a co-electrolysis are not defined in the original sources.

E-fuels demand

E-fuels are not expected to play a significant role in the transport sector in the short-term (2030), and a high degree of variability is foreseen in the long term (2050). By 2050, most of the literature sources claim that the e-fuel contribution to the transport sector could range from 0 to 50–100 Mtoe/year (i.e. from 0 to 30% of the expected transport fuel demand in the EU by 2050),[5] and will mainly be focused on the aviation, maritime and long-haul road transport segments.

Figure 7: Potential EU demand for e-fuels (base and high scenarios) according to different references (2020–2050)



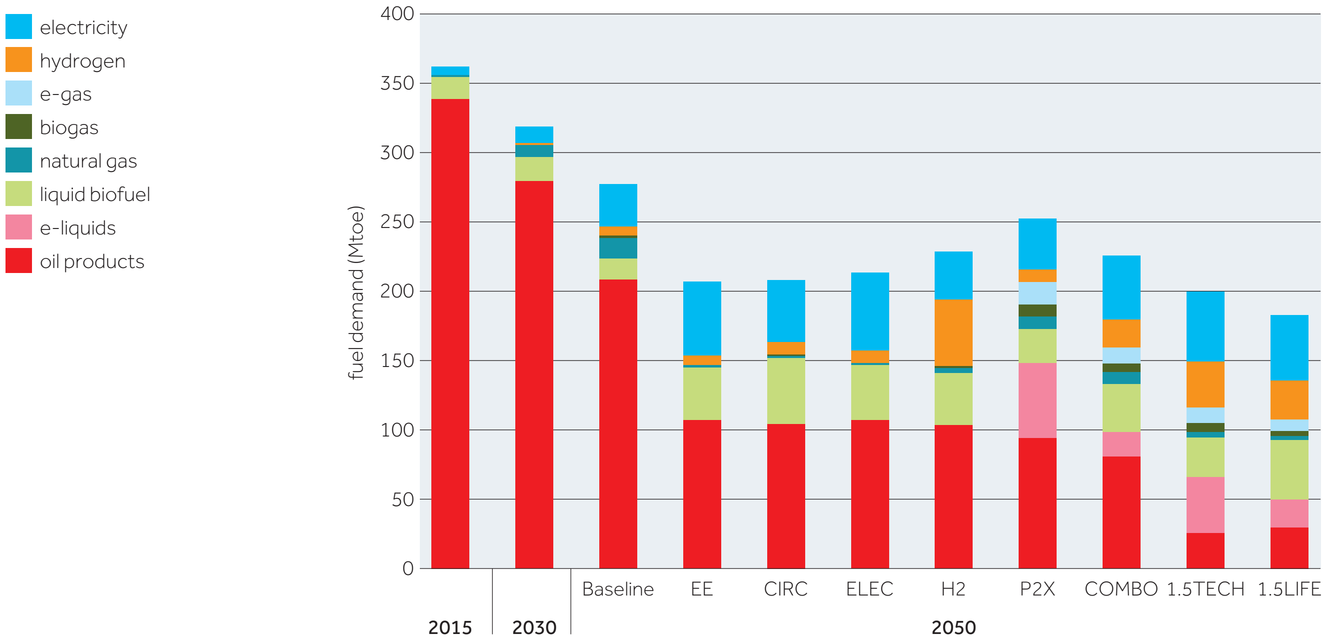
Notes:
- Energy contents: 1 toe = 41,868 GJ; 1 t = 1,051 toe
- Efficiency from electricity to e-fuel: 44% (Reference: Frontier Economics, 2018)
- Note: % of demand refers to the predicted transport demand in EU by 2050 (all transport segments). Source: EU Reference scenario.

The above findings align with the scenarios for the transport sector in 2050 as reported by the European Commission in its long-term strategy, *A Clean Planet for all*, in which e-fuels (e-liquids and e-gas) are projected to represent about 28% of the energy demand in 2050 in the P2X scenario (around 71 Mtoe (see Figure 8 on page 12).

[5] EU Reference scenario: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

Figure 8: Transport sector fuel demand in 2050

Source: European Commission (2018)



E-fuels advantages

The main advantages of these low-carbon fuels are detailed below:

- E-fuels achieve a significant CO_2 reduction versus their equivalent fossil-based fuels (see Figure 9 on page 13), offering a compelling complementary alternative for low-CO_2 mobility in Europe.
- The main CO_2 abatement potential is ≈ 85–96% (WTT basis) or 70% (life-cycle analysis).[6] The CO_2 abatement potential (WTT basis) can be similar if CO_2 comes from DAC or from a concentrated fossil source when CO_2 is considered as a waste.[7]
- E-fuels have a higher energy density compared to electricity, and can thus be used in the aviation and shipping sectors where no electricity-based alternatives can be found.[8]
- Liquid e-fuels are easier (and relatively inexpensive) to store and transport compared to electricity. They can be kept in large-scale stationary storage over extended periods, and mobile storage in vehicle tanks, which can compensate for seasonal supply fluctuations and contribute to enhancing energy security[9] (see Figure 10 on page 13).

[6] Sources: Audi; Sunfire; JEC (2019); German Environment Agency (2016).

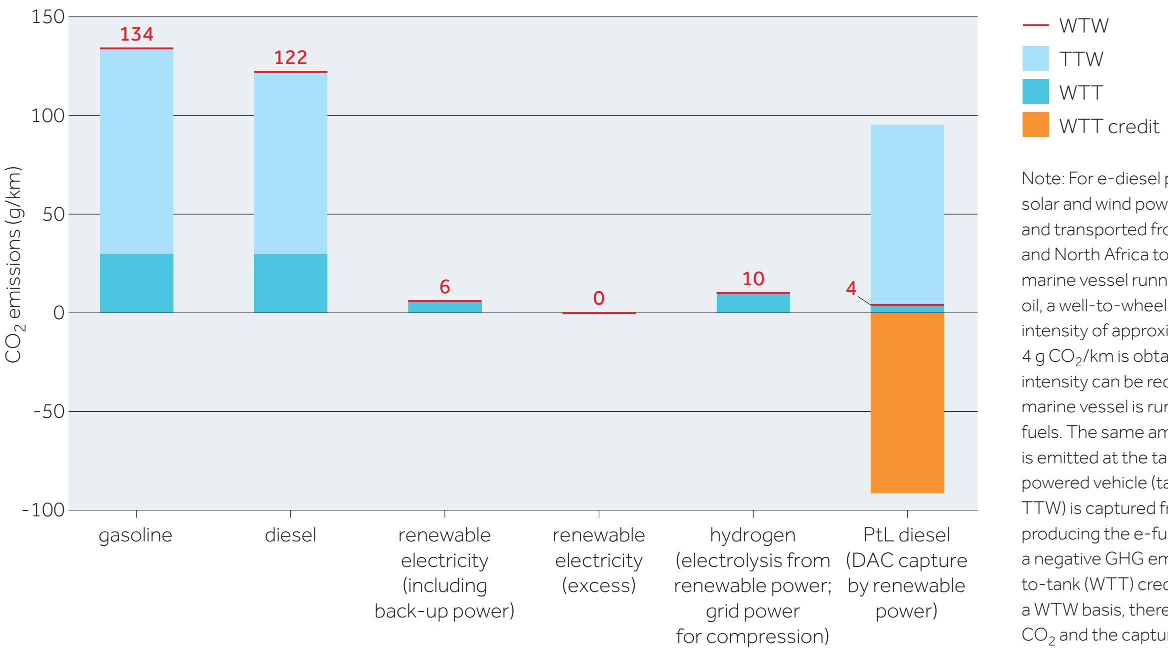
[7] There are, however, controversial opinions about the total 'carbon-neutrality' of the CO_2.

[8] There may be small sectors of both where electric options might find a place (e.g. some ferries).

[9] Strategic petroleum reserves within the territory of the EU are equal to at least 90 days of average domestic consumption.

Figure 9: GHG intensity (g CO_2/km) of different light-duty fuel-powertrain combinations

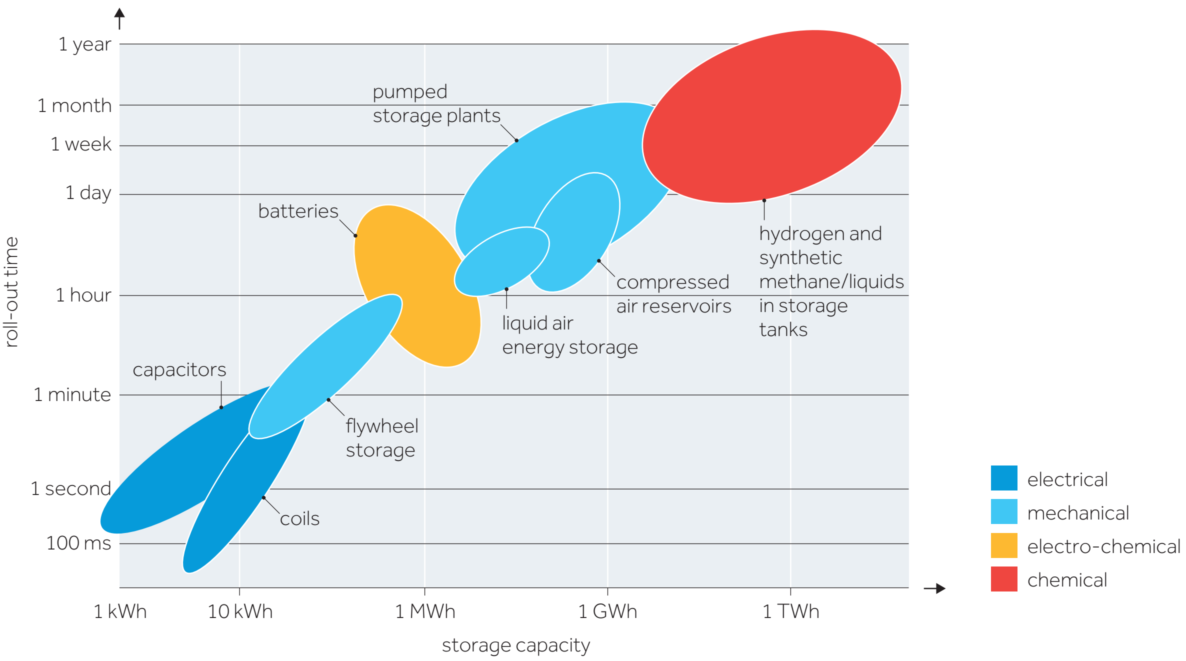
Source: Shell (2018a)



Note: For e-diesel produced from solar and wind power sources only, and transported from the Middle East and North Africa to Europe on a marine vessel running on heavy fuel oil, a well-to-wheel (WTW) GHG intensity of approximately 4 g CO_2/km is obtained. This GHG intensity can be reduced further if the marine vessel is run on low-carbon fuels. The same amount of CO_2 that is emitted at the tailpipe of the e-fuel powered vehicle (tank-to-wheel, TTW) is captured from air while producing the e-fuel. This is shown as a negative GHG emission, or a well-to-tank (WTT) credit, on Figure 9. On a WTW basis, therefore, the tailpipe CO_2 and the captured CO_2 cancel each other out.

Figure 10: E-fuels can be stored economically, in large volumes and over long periods

Source: Frontier Economics (2018)



- Existing infrastructure can remain in use for transportation and storage (for example, gas transport networks, liquid fuels distribution infrastructure (pipelines), filling stations, energy storage facilities, and the entire rolling stock and fuel-based vehicle fleets).
- Some e-fuels could be deployed immediately across the whole transport fleet without any major changes in engine design. Liquid e-fuels are an alternative technology for reducing GHG emissions in both existing and new vehicles without requiring the renewal of the fleet.
- A high blending ratio is potentially possible when adding methane to natural gas, and liquid e-fuels to conventional fossil fuels, provided they meet the corresponding specifications.
- E-fuels would likely have positive impacts on environmental air quality because of the favourable combustion characteristics of the molecules produced.

E-fuels disadvantages/barriers

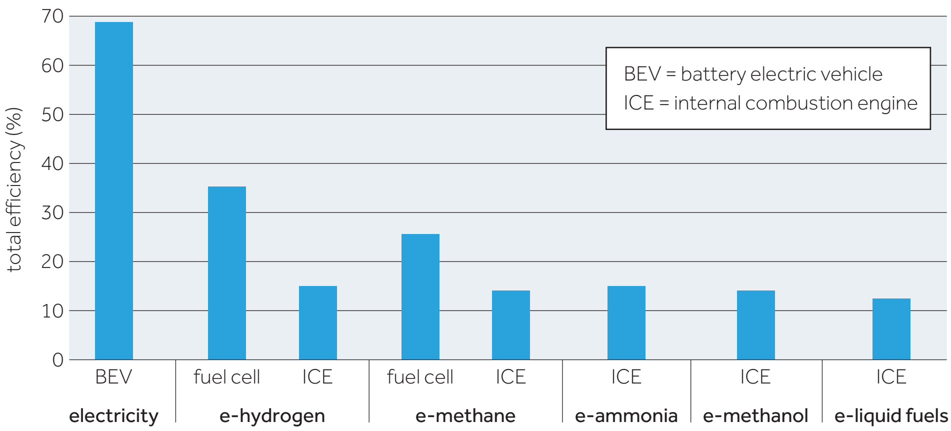
The main disadvantages or barriers of these low-carbon fuels are detailed below:

- The inherent thermodynamic conversion losses that occur when producing e-fuels will result in the need for a significant number of new renewable generation plants.[10]

  The overall energy efficiency of electricity use in battery electric vehicles (BEVs) is 4–6 times higher than for e-fuels in combustion engines (see Figure 11). It can be seen from the figure that the battery electric vehicle has a total overall efficiency (from the power generation point to the final user) of around 69%, while a fuel cell vehicle has an efficiency of around 26–35%, and a liquid e-fuel car has an efficiency of around 13–15% (Frontier Economics, 2018).

Figure 11: E-fuels final efficiency in engines (WTW approach)

Source: Concawe assessment based on Frontier Economics (2018)



[10] For example, to supply 1% of the total EU expected demand for transport by 2050 with e-fuels (Fischer-Tropsch route) will require 6% of the total EU-28 currently installed wind power capacity (178 GW), or 100% of, for example, the Netherlands + Sweden currently installed wind power capacity (11.88 GW). (Source: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf)

The whole efficiency of production of e-diesel, including its use in an internal combustion engine (ICE), is only 15%, meaning that for 1 MJ of renewable power, only 0.15 MJ is effectively used to power the vehicle (including losses in electricity transmission, conversion process, internal combustion engine and mechanical losses in the powertrain).

WTW energy efficiency is the basis for some of the negative claims in relation to e-fuels (e.g. Bellona (2017) or Transport & Environment (2017)). However, other sources, such as Cerulogy (2017), claim that even if the production of e-fuels is not as energy efficient as the direct supply of electricity for BEVs, it still offers an important opportunity to produce very low-CO_2 fuels with a significant opportunity to reduce GHG emissions in transport. Electrification is not an effective solution for all transport sectors. Even within the light-duty segment, e-fuels can offer an alternative route to decarbonisation and has the advantage that it can be deployed across the whole existing fleet without modifications to the engine, using much of the current distribution infrastructure.

- The current technology for producing e-fuels is still at the demonstration scale. Overcoming some of the more profound challenges faced in the development of large-scale commercial plant[11] would require that facilities are scaled up by a factor of 100,000 times compared to what has been demonstrated so far [12]—or by 100 times compared to a project recently announced in Norway[13] which is scheduled to start in 2021.
- The amount of capital-intensive equipment necessary to deploy the technology.
- Renewable electricity is a prerequisite for low-carbon e-fuels to contribute to reducing GHG emissions. As such, there is a need for a substantial increase in renewable electricity production.
- Production costs for e-fuels remain high compared with conventional fossil fuels.

[11] Shell's Pearl GTL facility based in Qatar is the largest synthetic liquids plant in the world. Only the gas-to-liquids part of the e-fuels route has been commercialised, which is producing fuels at a scale comparable to conventional refining.

[12] Sunfire 1 bbl/day e-fuel pilot plan currently under way in Germany.

[13] Nordic Blue Crude is planning to scale-up e-fuel technology, starting in 2021 in Heroya (Norway). The Sunfire-Synlink multipliable co-electrolysis module is to be used. It will be the first commercial plant, and will produce 10 million litres or 8,000 tonnes of the synthetic crude oil substitute e-Crude annually on the basis of 20 megawatts of input power. According to Sunfire, if the plant goes into operation, about 21,000 tonnes of CO_2 emissions will be avoided per year, given the use of both waste heat from industrial processes and environmentally friendly hydroelectric energy. This could fully power 13,000 passenger cars with synthetic eco-fuel. https://www.sunfire.de/en/company/news/detail/breakthrough-for-power-to-x-sunfire-puts-first-co-electrolysis-into-operation-and-starts-scaling

Key enablers

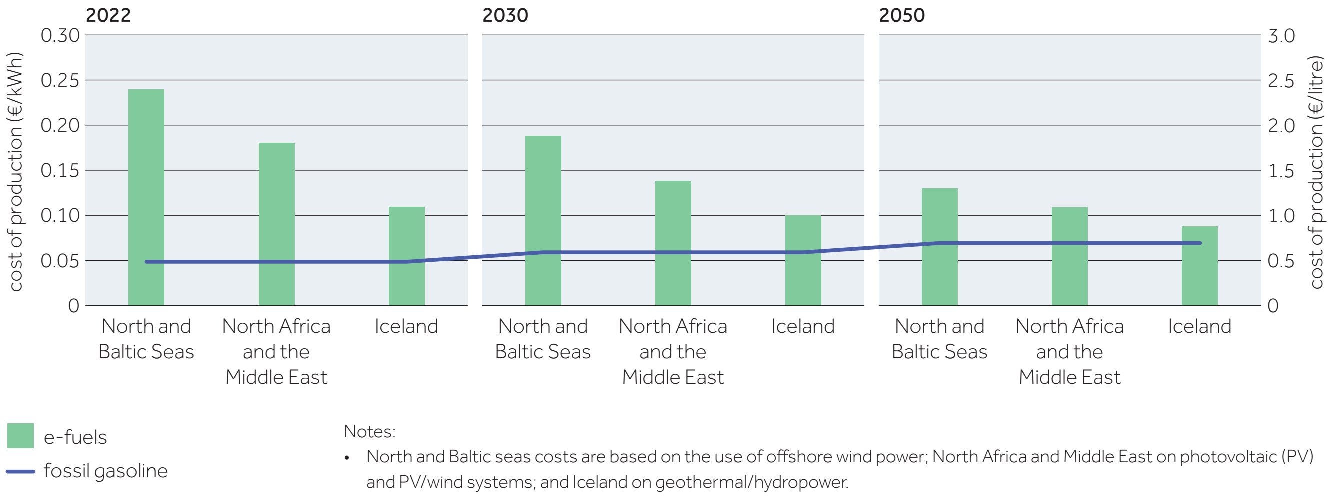
The main key enablers for the deployment of e-fuels on a commercial scale are listed below:

- Technical development and scale-up: the need to scale up the current demonstration-scale technology to a commercial plant level highlights the magnitude of the assets and investment needed in a new value chain (electrolysers, carbon capture, syngas and e-fuels conversion facilities).
- Operational full-load hours: to function in a manageable and economically efficient manner, e-fuel facilities need to have capacity for sustained operation over a high number of full-load hours despite the likely intermittency of a renewable power supply.
- Accessibility of affordable renewable energy: due to conversion losses, the price of electricity is the major determinant of the variable costs of e-fuels production. Access to a sustainable and affordable source of renewable power is therefore essential for the economically viable operation of an e-fuels production facility.

  Importing e-fuels could become an important element, allowing the use of highly favourable locations for generating renewable electricity, which can have a positive impact on the cost of e-fuel production. Figure 12 shows how importing e-fuels from regions around the world where electricity prices are low could reduce costs by up to 20–50%.

Figure 12: Cost of e-methane and liquid fuels produced in different world regions (€/kWh e-fuel)

Source: Frontier Economics (2018)



Notes:

- North and Baltic seas costs are based on the use of offshore wind power; North Africa and Middle East on photovoltaic (PV) and PV/wind systems; and Iceland on geothermal/hydropower.
- Costs do not include network charges and distribution costs.
- Gasoline price is based on average values from scenarios by the World Bank and the IEA.
- DAC is considered.
- Potential e-fuels cost reduction in the North and Baltic Seas with the use of concentrated sources of CO_2 instead of direct air capture (DAC).
- Electricity prices considered (ct/kWh):[14]

	2020	2030	2050
North and Baltic seas (offshore wind)	7–12	5–11	4–8
North Africa and Middle East (PV)	3–4	2–3	1.1–2.7
Iceland (geothermal/hydropower)	2.8	2.7	2.6

[14] https://www.agora-energiewende.de/en/publications/ptgptl-calculator/

- Policy framework: policymakers at the EU and national levels will need to create an appropriate regulatory framework, both to encourage and enable investments, so that private companies will recognise the business case for investing in e-fuels technologies.

  As an example, e-fuels have an expanded role in the regulatory framework proposed by the Renewable Energy Directive (RED II).[15] However, the proposed framework raises some important questions. Flexibility is provided in the regulation, such that there is no requirement for a direct connection between renewable electricity and the renewable fuel production site, but the modalities of such flexibilities still need to be defined (via a delegated act, by the end of 2021 at the latest). Another example is the current transport regulation, based on a TTW methodology, that gives fuel manufacturers no incentive to invest in e-fuels, as their contribution to emissions reduction in transport does not count (Vision 2050).[16]

Opportunities/synergies

Some opportunities/synergies that e-fuels could benefit from are listed below:

- Industrial clusters linking industrial producers of CO_2 (as a concentrated source) to produce e-fuels:
  - In the future, it is likely that some industrial processes will continue to emit large amounts of CO_2 for process-related reasons (energy-intensive industries such as refineries, steel, cement or biogas).
  - A notional refinery in the EU would require 3,000 kt/year of CO_2 to produce 1,000 kt/year of e-fuel. Only around 15% of this CO_2 would be produced within the refinery, with 85% having to be imported from another CO_2 producer.
  - The expected CO_2 generation from large point sources is expected to exceed the amount of CO_2 required to meet the demand for e-fuels.
- Alliances between industry and original equipment manufacturers (OEMs) will provide significant opportunities:
  - Some OEMs, such as Audi AG, are exploring an e-fuels strategy to provide a compliance pathway for their vehicles.
- Business models can be based on regions with large and cheap renewable energy sources:
  - The transportation and import of e-fuels from geographically privileged regions is relatively simple.

[15] European Union (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG

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Outlook for battery raw materials
(literature review)

In all the scenarios defined by the EU Commission's long-term strategy to address climate change, the electric vehicle has a big role to play. The long-term supply of battery raw materials will therefore be a necessity. There are concerns regarding the future availability of raw material supply and the impact of rising prices on battery production costs. This article is a literature review which aims to summarize the important key messages regarding technologies, metal sources, demand, availability, prices, recycling, and the uncertainties and challenges associated with battery raw materials.

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Introduction

Recognising that climate change represents an urgent threat to societies and the planet, the 2015 Paris Agreement set the goal of keeping global warming well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C (global warming has already reached 1°C).

To build on these objectives, the EU Commission has developed its long-term strategic vision[1] for a prosperous, modern, competitive and climate neutral economy in Europe, which confirms Europe's commitment to be a leader in addressing global climate change. It includes an assessment, based on several scenarios, to support the EU's strategy to reduce long-term EU GHG emissions in accordance with the Paris Agreement, starting at -80% going up to -100% by 2050 compared to 1990 levels. In all the scenarios, the electric vehicle (EV) plays an important role, creating a significant need for battery raw materials. Consequently, there are concerns about the future supply of raw materials necessary for battery production and the impact of rising prices on battery production costs.

This article is a literature review of publications from Wood Mackenzie, McKinsey & Company and Ricardo (among others), and summarises the important key messages regarding technologies, metal sources, demand, availability, prices, recycling and uncertainties/challenges of battery raw materials.

Back to the future

Electric cars were a common sight in the city streets of Europe and the United States (US) more than one hundred years ago. An American, Thomas Davenport, is credited with building the first EV in 1835. When Henry Ford introduced the mass-produced gasoline-powered Model T in 1908, it symbolised the end of the age of the EV until its recent revival. This technological 'rediscovery' is already having a revolutionary impact on the automotive industry as manufacturers revise their business strategies, develop new technologies and reconfigure global supply chains while trying to secure access to battery raw materials.

Technologies

Automotive battery technology roadmaps identify lithium-ion (Li-ion) batteries as being the dominant battery type used from now to 2050. Lithium-ion is a term applied to a group of battery chemistries that contain various different materials, however they all contain lithium in the cell cathode. Currently, there are six Li-ion battery technologies, the main difference between them being the cathode composition:

- lithium cobalt oxide (LCO)
- lithium nickel manganese cobalt (NMC)
- lithium nickel cobalt aluminium (NCA)
- lithium iron phosphate (LFP)
- lithium manganese oxide (LMO)
- lithium titanate (LTO).[2]

[1] European Commission (2018). *A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.*

[2] Mascot AS (2018).

With the exception of LCO, each of the Li-ion technologies mentioned above are used in the automotive industry today. China has been responsible for the largest growth in EV batteries, predominantly using LFP technology.

Beyond 2030 these types of Li-ion battery are expected to be superseded by next-generation battery types such as lithium-air and lithium-sulphur, which may contain very different active materials but will still require lithium, according to Ricardo (2018).

Li-ion technology has been successful for EVs because it offers a good balance of power and energy density. The key performance parameters of these battery technologies are presented in Figure 1.

Figure 1: Key performance metrics of battery technologies by chemistry

Source: Yoshio *et al.* (2009) and McKinsey & Company (2018)

strong moderate weak

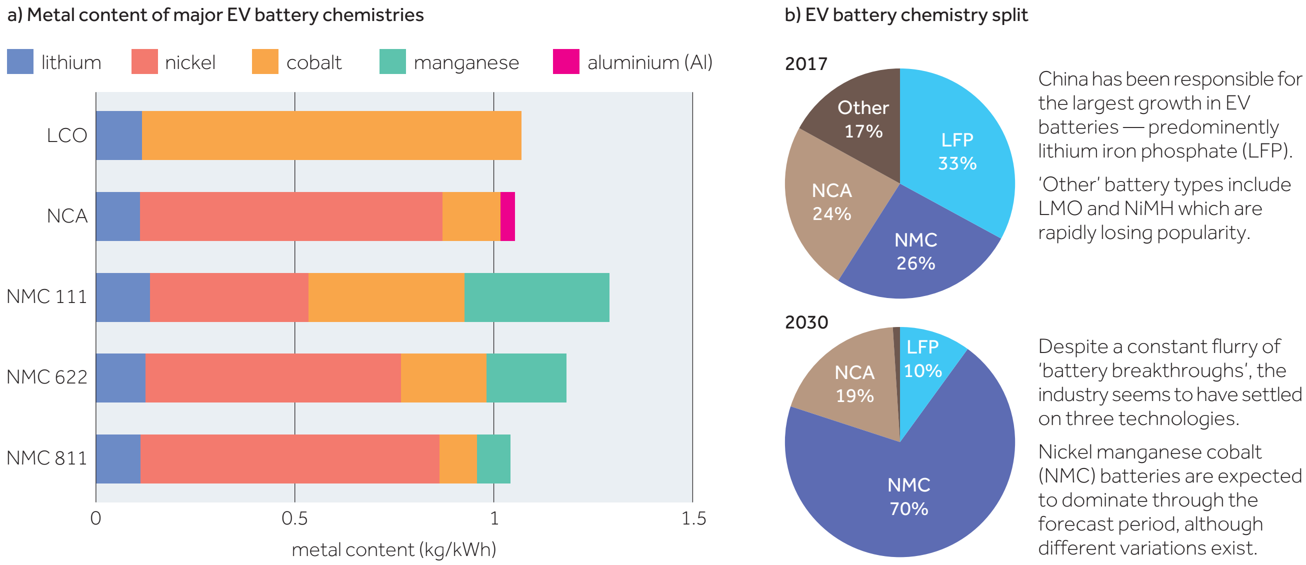
Material	Description	Safety	Cost (US$/kWh)	Energy density (kWh/kg)	Cycle life[d] (times)	Ni content (kg/kWh)
LCO ($LiCoO_2$)	Mostly used in consumer electronics. Limited application for xEVs[b] (e.g. Tesla).	Low	Low	0.58	1,500–2,000	0.0
NMC[a] ($LiNi_xCo_xMn_xO_2$)	Used mainly in consumer electronics but increasingly used in xEVs.	Mid	Mid	0.60	2,000–3,000	0.69 51 wt%
LMO ($LiMn_2O_4$)	Relatively mature technology. Used in xEVs by Japanese OEMs (e.g. Nissan Leaf, Mitsubishi i-MiEV, Chevrolet Volt).	High	High	0.41	1,500–3,000	0.0
LFP ($LiFePO_4$)	Relatively new technology used in xEVs and ESS.[c] Driven by A123 Systems and Chinese manufacturers (e.g. BYD, STL).	Very high	High	0.53	5,000–10,000	0.0
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	Used mostly in consumer electronics (often blended with other chemistries) and e-vehicles (e.g. Tesla)	Mid	Mid	0.72	n/a	0.68 (49 wt%)

[a] For 811 configuration (i.e. cathode material is 80 percent nickel, 10 percent manganese and 10 percent cobalt, by weight).
[b] xEVs = hybrid and electric vehicles
[c] ESS = energy storage solution
[d] The cycle life is the number of complete charge/discharge cycles that the battery is able to support before its capacity falls below 80% of its original capacity.

Among all the Li-ion technologies, nickel manganese cobalt (NMC) chemistries have become the automotive OEMs' preferred technology in recent years. According to Wood Mackenzie, NMC batteries could potentially dominate by 2030 (70% of EV batteries—see Figure 2 on page 25). Other battery materials (graphene, solid-state electrolyte) are not expected to have an impact on cathode chemistry in the foreseeable future, according to McKinsey & Company.

Figure 2: Metal content of NMC (vs LCO and NCA) batteries (2017 vs 2030)

Source: Research Interfaces (2018)/Wood Mackenzie



Note: All of the NMC lithium technologies utilise different proportions of nickel, cobalt and manganese.

Natural sources of metals

Where are these metals located around the world?

- Lithium
  - More than 95% of the world's lithium supply occurs as a primary product in the form of brines (from Argentina, Chile, Bolivia and China) or hard rock sources (from Australia and China):
    - Lithium brine deposits are found in salt lakes or salt flats (salars), and form in basins where water has leached the lithium out from the surrounding rock. The brines are captured and transferred to evaporation ponds, where they are concentrated by solar and wind evaporation, after which the lithium recovery takes place. Lithium from brines is the most suitable for battery manufacture.
    - Hard rock sources of lithium consist of granitic pegmatites, most prevalently those containing the mineral spodumene.
  - Lithium is sold and used in two main forms: lithium carbonate (19% Li), which is largely produced from brines; and lithium hydroxide (29% Li) produced from hard rock sources. Lithium hydroxide is currently the preferred form of lithium for use in longer-range EV batteries.

- Cobalt
  - Less than 10% of cobalt supply occurs as a primary product. The remainder is a by-product, primarily from copper and nickel mining. Cobalt expansion projects will therefore not only be dependent on the future demand, supply and price dynamics for cobalt, but also on future nickel and copper dynamics.
  - The total cobalt supply is split between mined cobalt and a recycle contribution.

- Nickel
  - Pure native nickel is found in the Earth's crust only in tiny amounts, usually in ultramafic rocks and in the interiors of larger nickel-iron meteorites that were not exposed to oxygen when outside the Earth's atmosphere.
  - An important source of nickel is the iron ore limonite, which contains 1–2% nickel.
  - Major production sites include Indonesia, Canada (which is thought to be of meteoric origin), New Caledonia, Russia and Madagascar.

Demand

What is the expected demand for these metals?

The lithium and cobalt markets have historically been driven by the demand for batteries used primarily in consumer electronics, which represented 40% and 25% of lithium and cobalt demand, respectively, in 2017. In the case of nickel, the global market has traditionally been driven by stainless steel production using both high-purity class 1 and lower-purity class 2 nickel products. The growing adoption of EVs (particularly in China) and the need for EV batteries with higher energy densities (increasing battery sizes and raw material intensities) could potentially see the demand for these metals increase dramatically.

According to the McKinsey & Company analysis (see Figure 3 on page 27), the global demand for each of these metals could potentially increase as follows:

- **Lithium:** demand could increase by more than 300%, from 214 to 669 kt LCE[3] (in the base case) and to 893 kt LCE (in the aggressive case), between 2017 and 2025.
- **Cobalt:** demand could increase by 60%, from 136 to 222 kt (in the base case) and to 272 kt LCE (in the aggressive case), between 2017 and 2025.
- **Nickel:** demand could increase by 25%, from 2,000 to 2,500 kt Ni between 2016 and 2025.
  - Although stainless steel production is likely to remain the largest use of nickel, its share will decrease from 70% to 60% as the EV revolution accelerates the demand for nickel for use in battery production.
  - The demand for high-purity class 1 nickel (suitable for battery manufacturing due to its high purity and dissolvability) may increase from 33 kt in 2017 to 570 kt in 2025 (more than 10 times the current demand).

Wood Mackenzie's demand forecast aligns with the McKinsey & Company aggressive scenario (see Figure 4 on page 27). According to Wood Mackenzie, by 2030, we could potentially need at least:

- six more Greenbushes mines (the biggest lithium mine in Australia);
- three more Katanga mines (the biggest cobalt mine in the Congo); and
- six more Ambatovy mines (the biggest nickel mine in Madagascar).

[3] Lithium carbonate equivalent — the industry standard for measuring lithium volumes.

Figure 3: Expected demand for lithium and cobalt by 2025

Source: McKinsey & Company (2018)

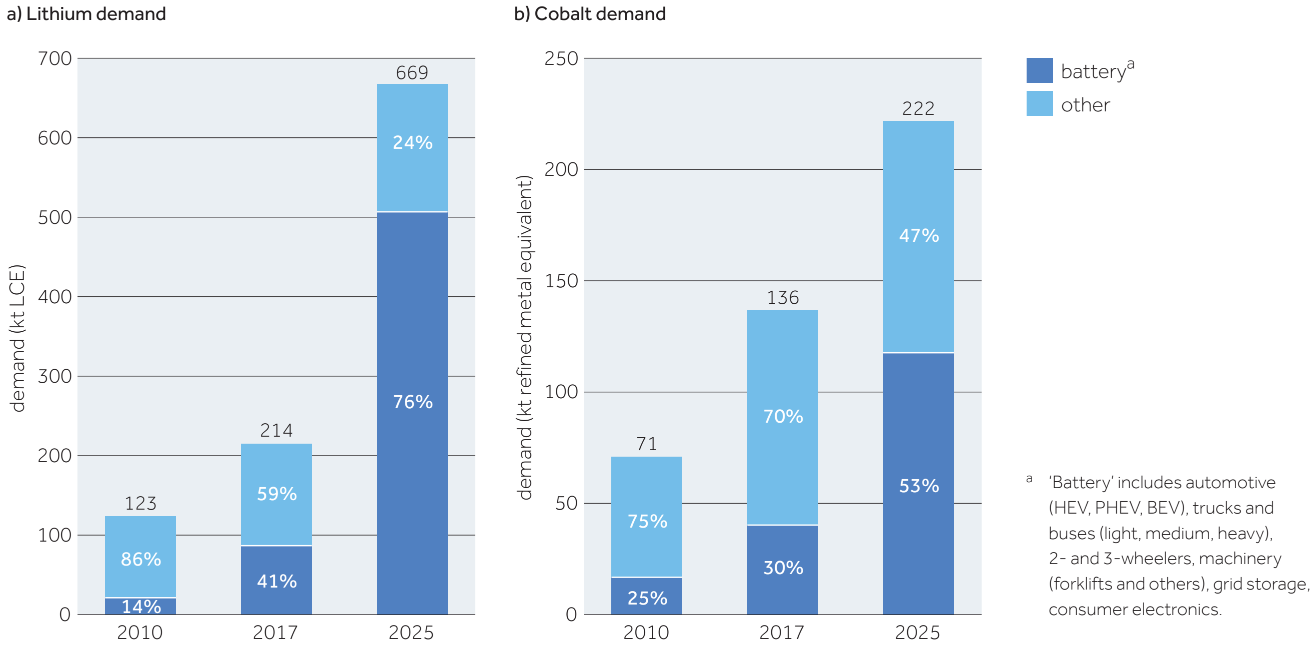
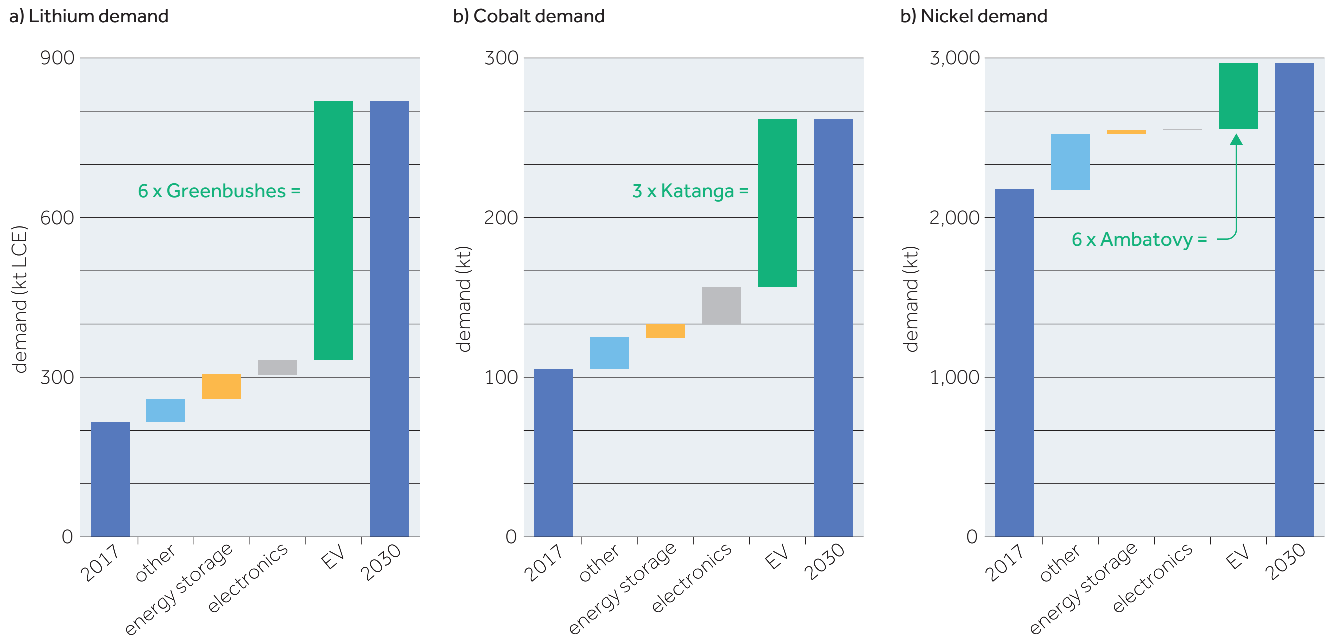


Figure 4: Lithium, cobalt and nickel expected demand by 2030

Source: Wood Mackenzie



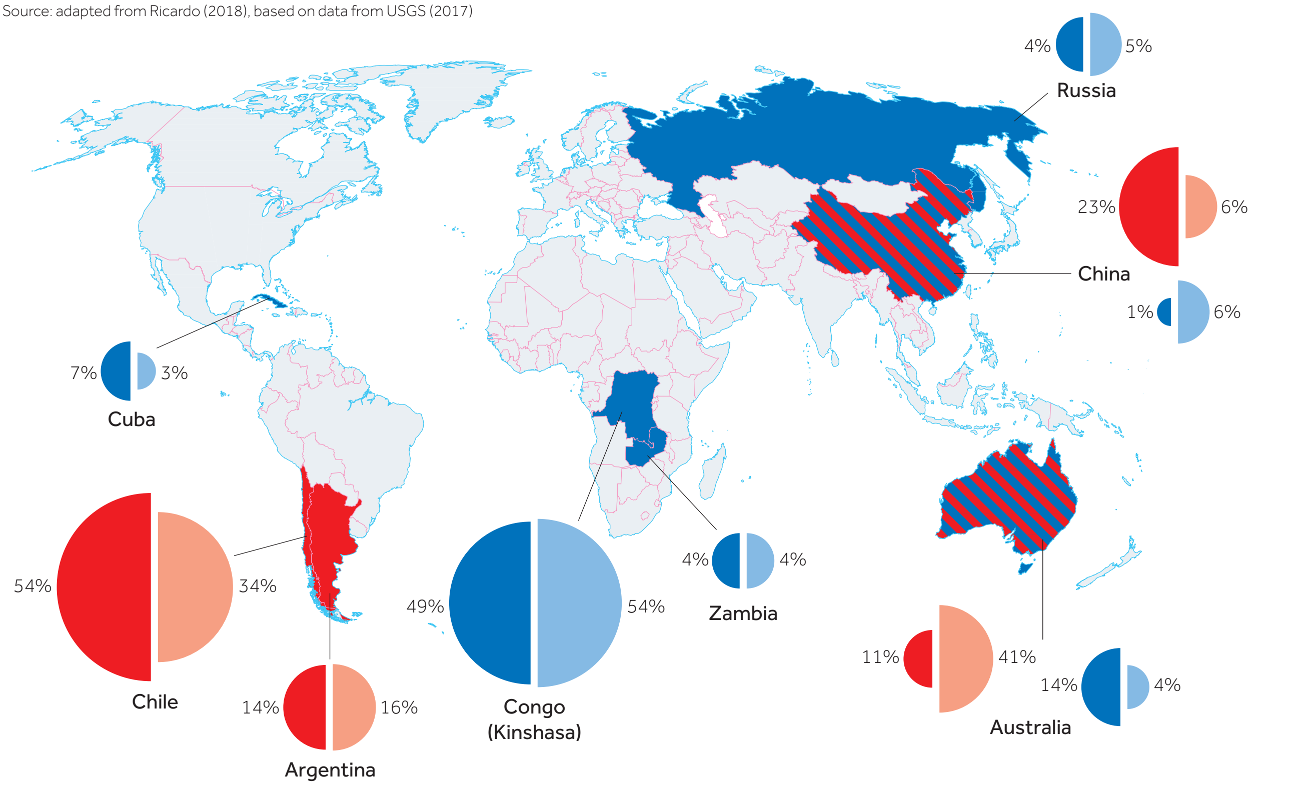
Availability

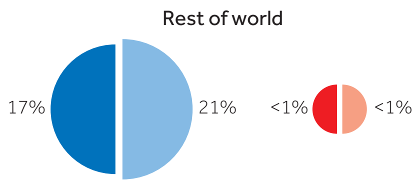
Is there sufficient availability to cover the expected demand?

The majority of these metals are located in a few countries around the world (see Figure 5).

Figure 5: Worldwide availability of lithium and cobalt

Source: adapted from Ricardo (2018), based on data from USGS (2017)





3 **Li** Lithium — Share of global lithium **reserves** | Share of global lithium **production (2016)**

- The majority of lithium reserves are located in South America; Chile has more than half of the global lithium reserves.
- Lithium production and prices could depend heavily on the policies of the Chilean government.

27 **Co** Cobalt — Share of global cobalt **reserves** | Share of global cobalt **production (2016)**

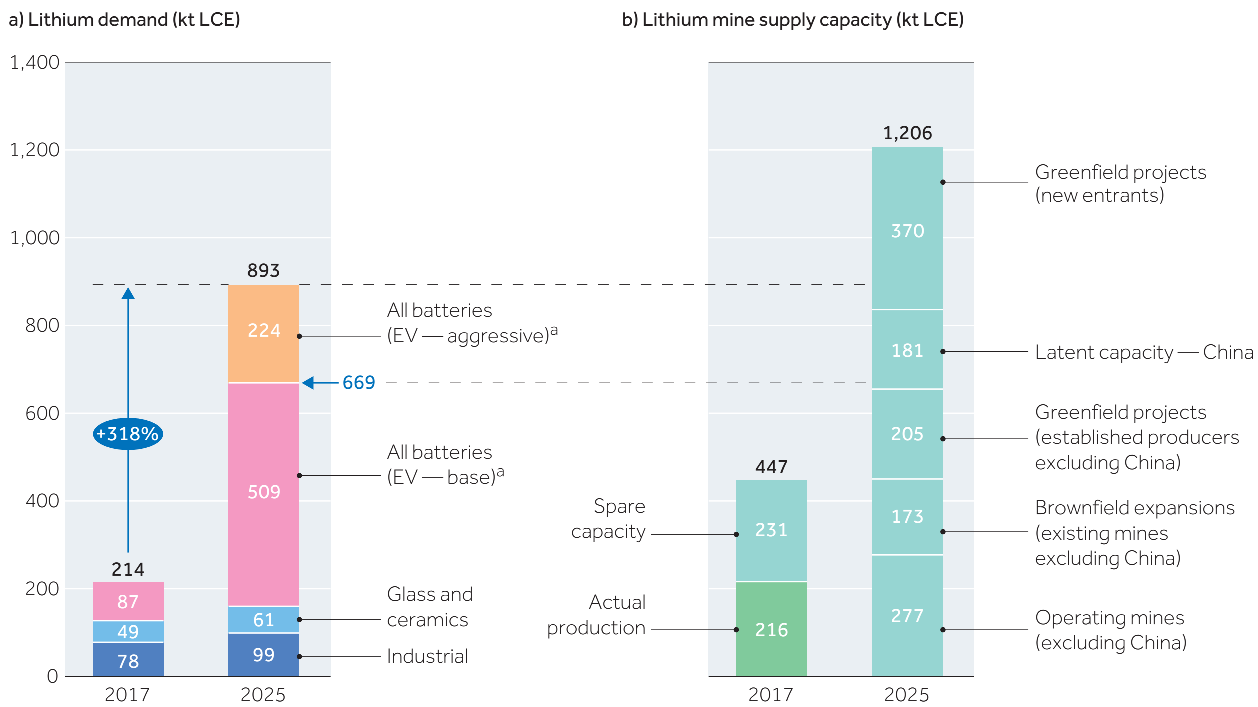
- Although cobalt reserves are present in many countries, the largest reserves and current production are located in the Congo (Kinshasa).
- Instability in this region is a factor in the 128% increase in the price of cobalt in 12 months (London Metal Exchange, September 2016–September 2017 values).

Lithium

- Only eight countries are currently producing lithium, of which three countries—Chile, Australia and China—accounted for 85% of global production (216 kt LCE) in 2017. Chile has more than half of the global lithium reserves.
- Within Europe, only Portugal has a (small) lithium industry, amounting to 0.6% and 0.4% of global production and reserves, respectively.
- Currently, four companies (Talison, SQM, Albemarle and FMC) control most of the mined product.
- Currently, there are no structural constraints on supply, with global production being well below industry capacity (450 kt LCE). For example, the world's largest miner, Talison, is operating at barely 60% of its capacity. Talison's announcement that it plans to expand its lithium production over the next few years suggests that there is ample capacity to meet the foreseen growth in demand, which is estimated to reach 669 kt LCE by 2025 (see Figure 6).

Figure 6: Lithium supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2018)



[a] 'Batteries' include automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics.

- There is therefore no concern about global lithium availability, according to McKinsey & Company. However, according to Ricardo, the annual lithium demand could be the greater challenge:
  - Global lithium extraction investment is limited by the low cost of lithium from the Salar de Atacama in Chile. To supply the peak annual lithium demand for European BEVs, roughly half of the surface of the salar would need to be covered in evaporation ponds, with potential impacts on wildlife and tourism.
  - Other large lithium resources, such as the Salar de Uyuni in Bolivia — estimated to be the largest or second largest lithium resource globally — are limited in their potential annual output. In the case of the Salar de Uyuni, an extraction rate of only 10 kt/year would exceed the water replenishment rate of the basin and would have an adverse impact on local agriculture.

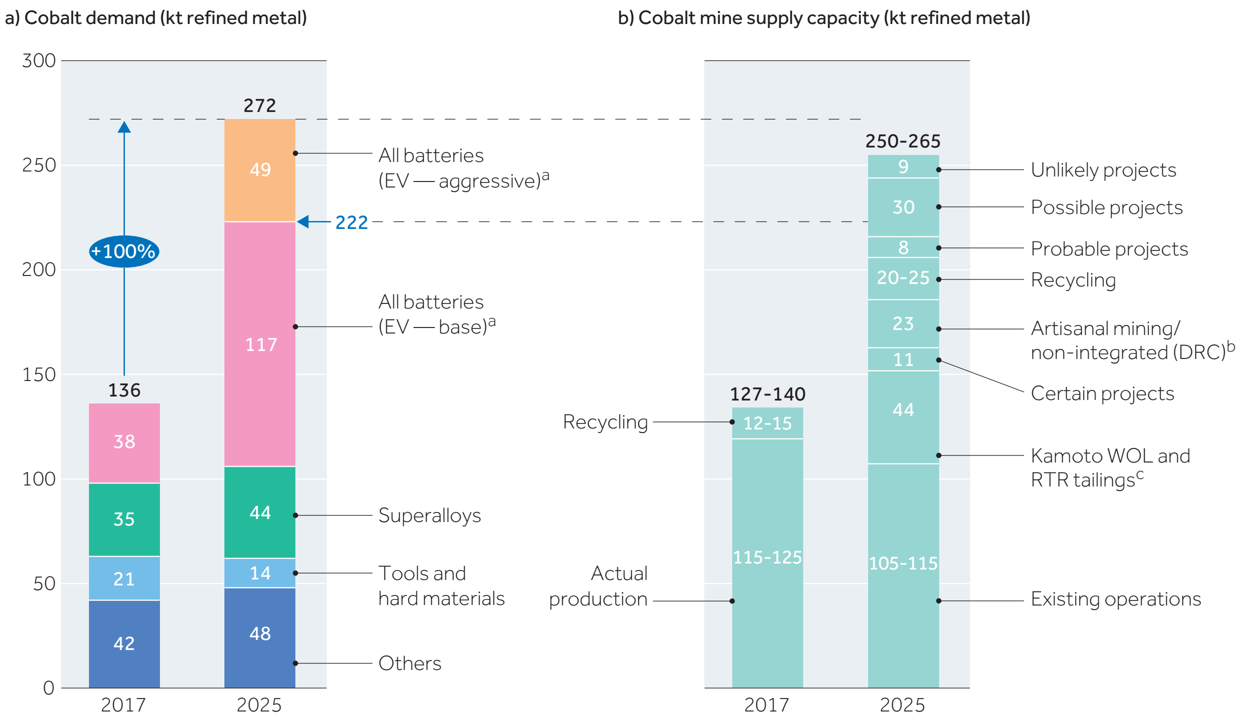
  The feasibility of meeting the increased lithium demand by 2040 is therefore uncertain. There may be sufficient lithium, however the rate of lithium production could be the limiting factor. Furthermore, so few countries control the majority of lithium that supply issues could occur.

Cobalt

- More than half of global production is concentrated in Kinshasa in the Democratic Republic of Congo (DRC), with Russia, Cuba, Australia and Zambia accounting for the other half of global supply, according to Ricardo. By 2025, nearly 100% of the global cobalt supply will come from the Congo, according to Wood Mackenzie.
- The cobalt mine supply is currently fragmented in terms of producers, and the top three players account for 40% of global mine supply — Glencore (22%); DRC state miner Gecamines (9%); and China Molybdenum (7%).
- According to McKinsey & Company (see Figure 7 on page 31), the industry could add capacity expansions of between 110–120 kt by 2025, bringing the total potential mine supply to 225–235 kt. Additionally, recycling could provide an additional 25 kt of supply by 2025, bringing the total refined cobalt supply to around 255 kt by 2025.
  - 45 kt of cobalt mine capacity additions by 2025 are expected to come from two expansion projects, both in the DRC (DRC will then represent 75% of global cobalt mine supply).
- There are concerns about whether the supply of cobalt will be able to meet the growth in demand, given:
  - the uncertainty about announced projects;
  - the lack of transparency in the value chain;
  - DRC country risk; and
  - concern for child labour.
- These concerns are increasing the focus on low-cobalt NMC batteries. According to Ricardo, in the long term, alternatives to cobalt-containing batteries will be available, although some of these may not achieve the same level of performance.

Figure 7: Cobalt supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2018)



[a] 'Batteries' include automotive (HEV, PHEV, BEV), trucks and buses (light, medium, heavy), 2- and 3-wheelers, machinery (forklifts and others), grid storage, consumer electronics.

[b] Includes non-integrated capacity which is reliant on purchased ore and/or preconcentrate from smaller and/or artisanal operations. This capacity is not tracked on a mine-by-mine basis, but tracked on a processing plant level, assumed to be fed by mines not tracked individually in the other buckets.

[c] Large increase explained largely by ramp-up of WOL (whole ore leach) operations by Glencore (commissioned in 2017) and ERG's Metalkol Roan Tailings Recovery (RTR) project (commissioned in 2018). Together, these projects account for ~41 kt.

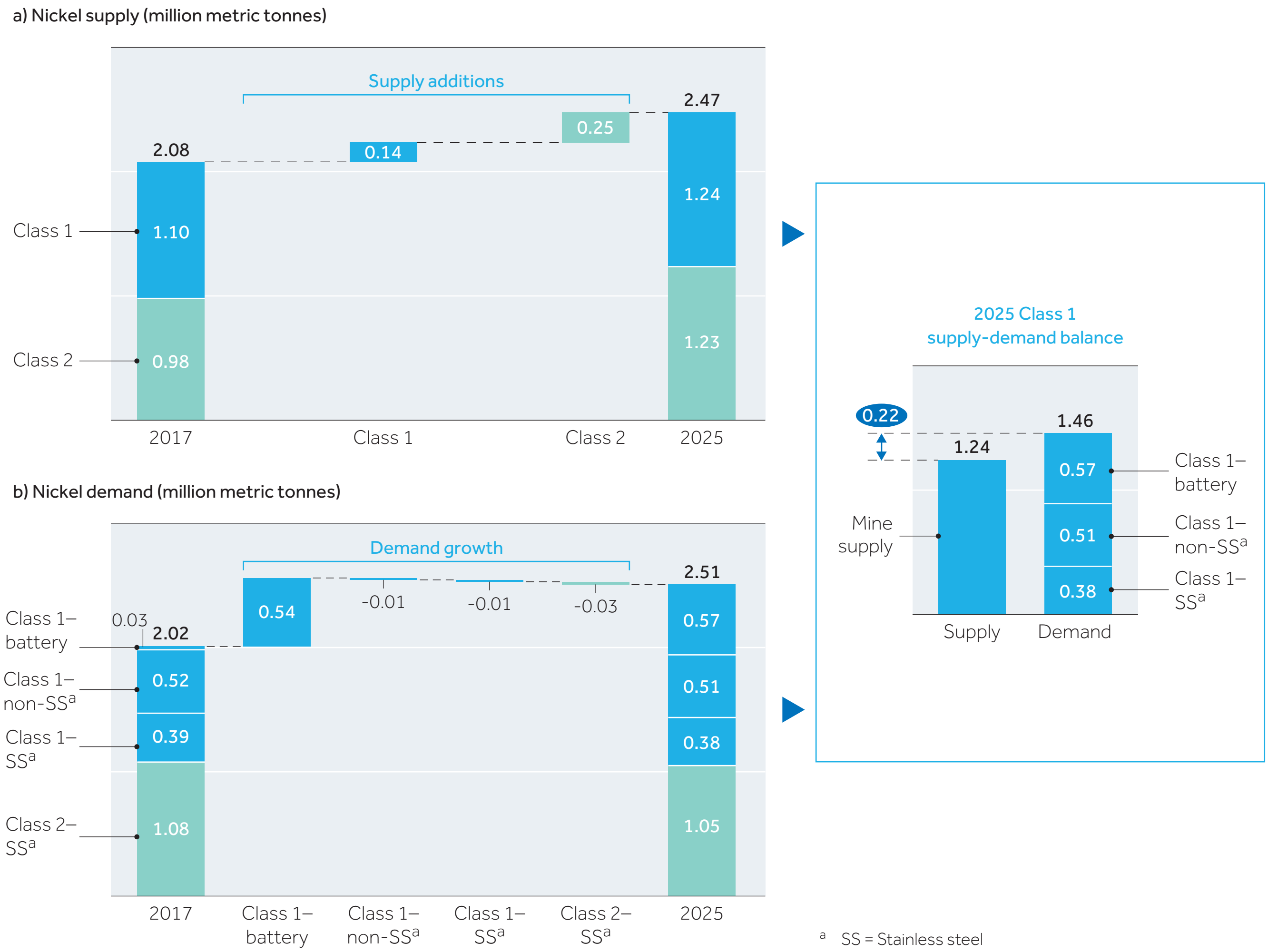
Outlook for battery raw materials (literature review)

Nickel

- Major production sites include Indonesia, Canada (meteoric origin), New Caledonia, Russia and Madagascar.
- The nickel market has been driven by stainless steel production using both high-purity class 1 and lower-purity class 2 nickel.
- High-purity class 1 nickel is required for battery manufacture.
- The industry faces a major challenge in the lack of an easy and sustainable way to increase the supply of class 1 nickel. According to McKinsey & Company, class 1 supply will lag demand by 2025, with only 1.2 Mt of supply available to meet a demand of 1.5 Mt.
- A shortfall in class 1 nickel seems likely.

Figure 8: Nickel supply versus demand, 2017 vs 2025

Source: McKinsey & Company (2017)



[a] SS = Stainless steel

Prices

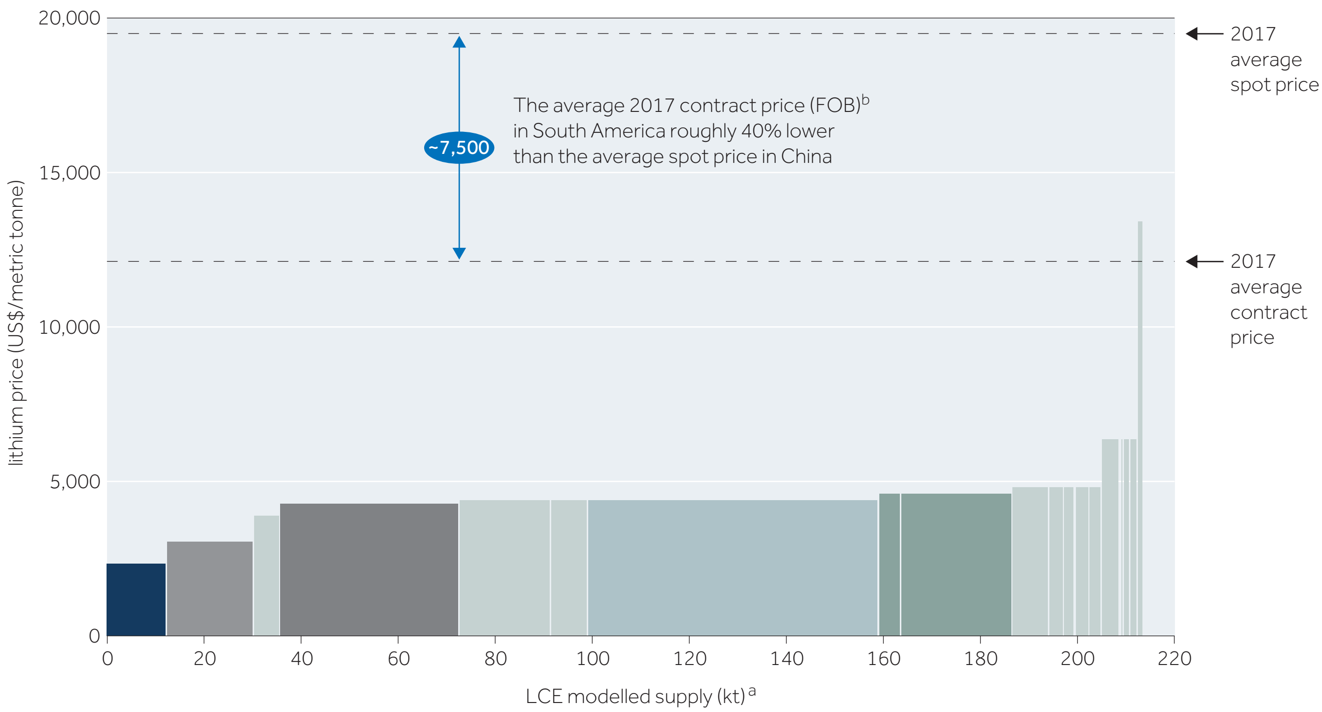
The EV revolution is reflected in the dramatic increase in the price of lithium and cobalt that has taken place over the past two years.

In terms of the pricing mechanism, lithium and cobalt have been seen in the past as 'minor metals', and, unlike copper, aluminium and steel, there is little transparency or liquidity in relation to pricing.

Lithium contract prices can be 60% below the spot price inside China (see Figure 9). The spot price is used predominantly in China for speculation rather than for large-scale negotiations. Furthermore, lithium prices could depend heavily on the policies of the Chilean government, which is currently planning large mining policy changes.

Figure 9: 2017 lithium cost curve and 2017 average price (USD/t LCE, kt LCE of modelled supply)

Source: McKinsey & Company (2018)

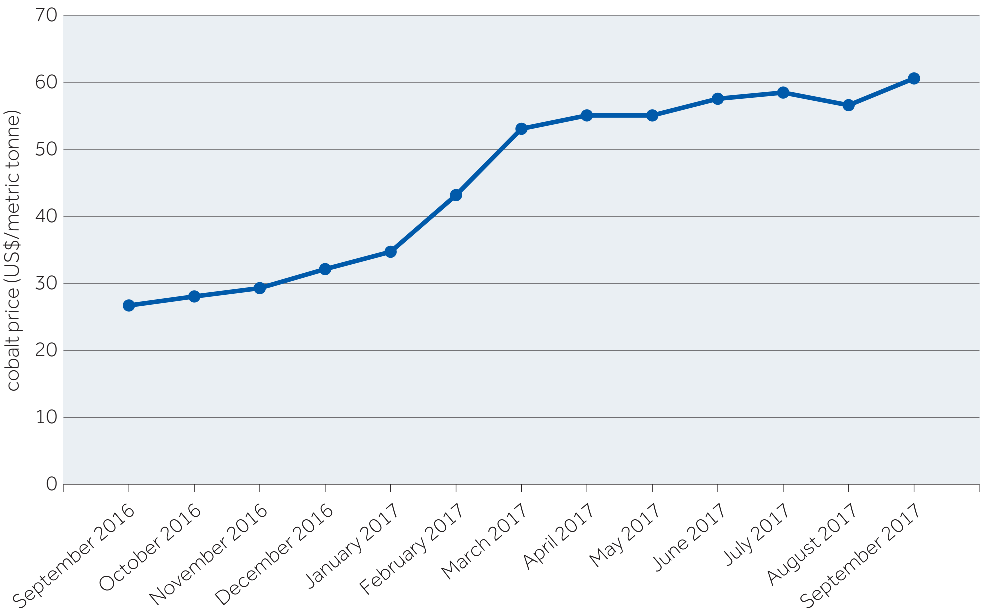


[a] kt of LCE modelled supply; Chinese capacity utilisation is modelled at 30% and rest of world at 90%.

[b] FOB = free on board.

Trading in cobalt is much less transparent, with deals structured well below the spot price and not publicly announced. This instability in Congo (Kinshasa) is a factor in the 128% increase in the price of cobalt in 12 months (see Figure 10). Over time, liquidity and transparency are expected to increase as the markets increase in size.

Figure 10: Trend in global cobalt prices in the 12 months to September 2017



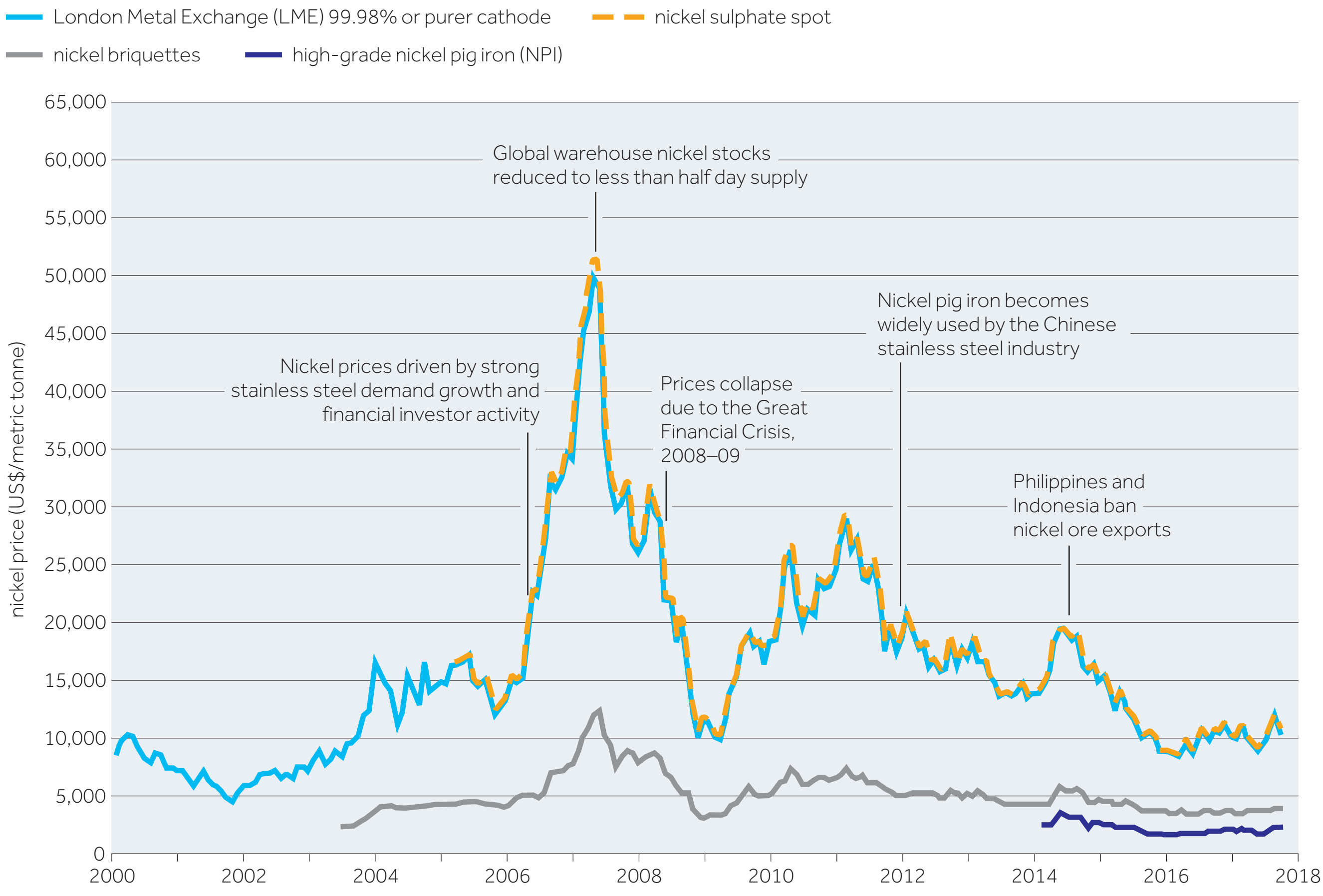
The price of nickel has fallen over the past decade due to the expansion of low-cost class 2 nickel capacity (see Figure 11).

Currently, nickel is priced in relation to the London Metal Exchange (LME) reference grade (98.8% or higher). The need for additional class 1 capacity driven by the demand for EV batteries would influence both future nickel prices and the pricing mechanism.

With regard to the impact on EV battery costs, McKinsey & Company estimates that raw materials represent 10% of the cost of a battery pack in 2018 (around 22$ of the total 200$/kWh), increasing from 3% in 2010.

Figure 11: Evolution of nickel prices by product

Source: McKinsey & Company (2017)



Notes:

- Pure nickel is traded on the LME with premiums/penalties for different nickel products.
- Briquettes are traded at a premium; nickel pig iron is traded at a penalty to reflect its lower quality.
- Nickel sulphate is based on the London Metal Exchange price adjusted for nickel content in the salt.

Although lithium prices influence the EV battery cost, battery economics are more sensitive to cobalt prices, as shown in Figure 12.

Figure 12: Battery costs for NMC in different lithium and cobalt price scenarios (US$/kWh)

Source: McKinsey & Company (2018)

2018 NMC 622 cathode

Li_2CO_3* price (US$/t)	Cobalt price (US$/lb) 15	25	40
5,000	-6% 196	-2% 205	+2% 213
10,000	-3% 201	~ 208	+5% 218
14,600	-1% 206	+2% 213	+7% 223

2018 NMC 811 cathode

Li_2CO_3* price (US$/t)	Cobalt price (US$/lb) 15	25	40
5,000	-4% 121	-2% 123	0% 126
10,000	-2% 124	~ 126	+2% 129
14,600	+1% 127	+2% 129	+5% 132

NMC 622 is more sensitive to changes in cobalt price compared to NMC 811

Δ, percent to base

Δ, US$ to base

* Li_2CO_3 = lithium carbonate

Recycling

Currently, the industry is focusing on recycling as a way to extract valuable battery raw materials at a low cost. Until now, the industry has been more concerned with the disposal of potentially hazardous used consumer electronic products than with the potential for extracting materials for reuse.

Lithium recycling is still in its infancy. In 2017, no lithium was recovered, and no well-defined routes are currently available for the recycling of Li-ion batteries; however, numerous techniques exist at the prototype stage, which utilise pyrometallurgical and hydrometallurgical processes to attempt to extract the valuable metals. According to Ricardo, battery recycling to recover lithium could become a large industry by 2050. However, lithium recovery may not be economically feasible for all battery types (for example, LFP batteries have little recyclable material of value). Furthermore, lithium recovered from recycled batteries will have a limited impact on the total virgin lithium required by 2050.

Cobalt has, historically, been recycled because of its high value application in alloys. In 2017, 12–15 kt of cobalt was recovered through recycling.

In 2017, approximately 90 kt of nickel was recovered from purchased scrap in the US. This represented about 39% of consumption for the year. Processes now exist for recycling nickel from spent rechargeable batteries.

Environmental impacts of material production

Environmental impacts from material extraction are being reduced in some regions. However, there is a risk that large-scale exploitation of lithium, cobalt and nickel resources could lead to significant environmental impacts, according to Ricardo.

Impacts of lithium production

- Lithium for battery production is typically extracted from brines in South American salars with an evaporative beneficiation process carried out in a series of pools. Lithium ore is extracted using open-cut mining.
- The water requirement for the lithium extraction is significant and puts pressure on local water supplies, which in some cases is heavily relied upon for local agriculture.
- Tourism in the salar areas is a major source of employment, and could be affected by increased lithium production.

Impacts of cobalt production

- Cobalt is extracted using open-cut or underground mining.
- Exposure to cobalt can impact human health. In addition, mining for cobalt (where cobalt is the intended product rather than a by-product of nickel or copper mining) often targets arsenide ores, which can have further environmental and human health impacts.
- Additional environmental impacts can occur that are similar to those associated with nickel production. In the Congo (Kinshasa) cobalt region it is suggested that there is little control of pollutants from cobalt mining.

Impacts of nickel production

- Nickel extraction typically uses open-cut mining.
- Historically, nickel mining has caused significant emissions of SO_2, as well as soil contamination and water acidification, although process improvements are reducing all of these effects.

Summary

As a summary, some of the challenges and uncertainties related to EV battery raw materials reviewed in this article are listed below:

Challenges

- Capacity of supply
- Sensitive regions (e.g. the Congo)[4]
- Risk of disruption to supply
- Lack of transparency in prices
- Metals recycling
- Environmental impacts of material production.

Uncertainties

- Extent and speed of EV adoption
- The preferred standard for battery technology in the future
- Many players: mining companies, battery producers, automotive OEMs, financial players and consumers.

[4] In contrast with oil production, where the largest share of oil reserves or production in any country is 18% of the global supply, the shares of lithium in Chile or cobalt in Congo (Kinshasa) amount to ~50%. The oil supply is therefore less dominated by any one country, which may be beneficial considering the uncertainties associated with some countries that have large oil reserves or production capacities. However, as Ricardo claims, there is a key difference between oil and battery materials:

- Oil is required to *operate* an ICE vehicle: the price effects the *running costs*.
- Battery materials are required to *manufacture* an EV: the price effects the *capital costs*.

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High-octane petrol (HOP) study: making gasoline relevant for the future of road transport

Improvements in vehicle efficiency will be a key factor in ensuring that liquid fuels remain a vital partner in the future of road transport. This article looks at the role of high-octane petrol (HOP) in improving engine efficiency, and summarises the findings of a modelling study designed to assess the impact of HOP on the refining system and the positive effect of HOP on CO_2 emissions.

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Introduction

Gasoline is a complex mixture of hydrocarbons and other chemical compounds used as fuel for spark-ignition internal combustion engines (ICEs), primarily in passenger cars and other light-duty transportation vehicles (LDVs). Gasoline in the European Union (EU) has to meet more than a dozen individual specifications, for which the technical standards and analytical methods are specified under EN 228, the European Standard for unleaded petrol.

The European Commission (EC) also sets limits on other components of finished gasoline. Mandatory environmental regulations for several fuel properties were first introduced in 1998 (Directive 98/70/EC), and were revised in 2003 (Directive 2003/17/EC) and 2009 (Directive 2009/30/EC[1]). Other industry specifications limit the tendency and ability of the gasoline blend to foul, damage or corrode gasoline storage facilities as well as the components of vehicle combustion and exhaust systems. These specifications include gum deposition, oxidation stability, colour, NACE corrosion and phosphorous levels.

Petroleum refineries are the main source of finished gasoline and blendstocks for oxygenate blending (BOBs). Ethanol represents approximately 5 volume percent (vol%) of the finished gasoline consumed in the EU.

To burn, liquid gasoline must be vaporised and mixed with oxygen (air). Since gasoline is a blend of hundreds of molecules with different characteristics, gasoline boils (vaporises) over a range of temperatures and must be blended in a way that vaporisation will occur over the entire range of engine operating temperatures. Specifications which measure and control the vaporisation performance of gasoline include:

- Reid vapour pressure (RVP);
- distillation;
- drivability index; and
- vapour-liquid ratio.

Apart from the volatility characteristics mentioned above, the other important fuel quality to be considered is ignition quality. The octane number of a fuel is a measure of its resistance to auto-ignition. Gasoline spark-ignited engines need a high-octane fuel to avoid knocking; this contrasts with diesel engines which rely on auto-ignition and therefore require a low-octane (or high cetane number) fuel. The octane number of a fuel is measured in a special test engine known as a CFR engine, which is a single-cylinder test engine with variable compression ratio dating from 1928. Although the test has been progressively improved over the years, the basic engine configuration and test conditions remain the same. Tests in the early 1930s demonstrated that the knocking behaviour of fuels in vehicles of that era did not correlate with the measured Research Octane Number (RON), therefore a new, more severe Motor Octane Number (MON) was developed. Both methods are still in use today, although in modern passenger cars the relevance of MON is more questionable. A fuel's octane number is determined by comparing and extrapolating its performance in the engine with blends of pure compounds: iso-octane, defined as 100 octane; and n-heptane, defined as having a zero octane number.

[1] See Annex 1: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF

Gasoline octane, particularly the RON, is a critical consideration in the design of today's engines which are optimised for particular octane numbers. A number of studies carried out over the years by the engine manufacturers as well as Concawe members have suggested that engines with higher compression ratios realise improvements in engine performance and efficiency, but they require gasoline with higher octane ratings. A more recent modelling and vehicle study carried out by Concawe has confirmed the results of previous studies and will be the subject of a separate article in the next Concawe *Review*.

Background

The long-term goal of the EU is the decarbonisation of transport.[2] To achieve this, vehicle efficiency targets for passenger cars and light commercial vehicles have been put in place for 2020/21 and were extended until the 2030 horizon at the end of 2018. Early in 2019, Europe agreed to introduce vehicle CO_2 efficiency targets for the heavy-duty vehicle (HDV) segment for the first time. Additionally, the Renewable Energy Directive II extends the requirement to use sustainable renewable fuels or energies in the transport sector until 2030.

To ensure that liquid fuels can continue to play their vital roles in the future of road transport, FuelsEurope has developed the 'Vision 2050'[3] with the objective of demonstrating that the carbon intensity of liquid fuels can be reduced, and therefore, together with vehicle efficiency improvements, contribute to a reduction in GHG emissions from transport. In this context, high-octane petrol (HOP) is one of the many possible improvements that could play a role.

Although vehicle efficiency targets are formulated in a technology-neutral manner, manufacturers do not have many options to ensure compliance, in particular for passenger cars. This is mainly due to the inflexibility in the CO_2 vehicle standards methodology (tank-to-wheels), based on type approval regulations, which do not recognise the fuel contribution. Neither bio-components nor other fuel improvements can count towards the efficiency target.

[2] European Commission (2018). *A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.*
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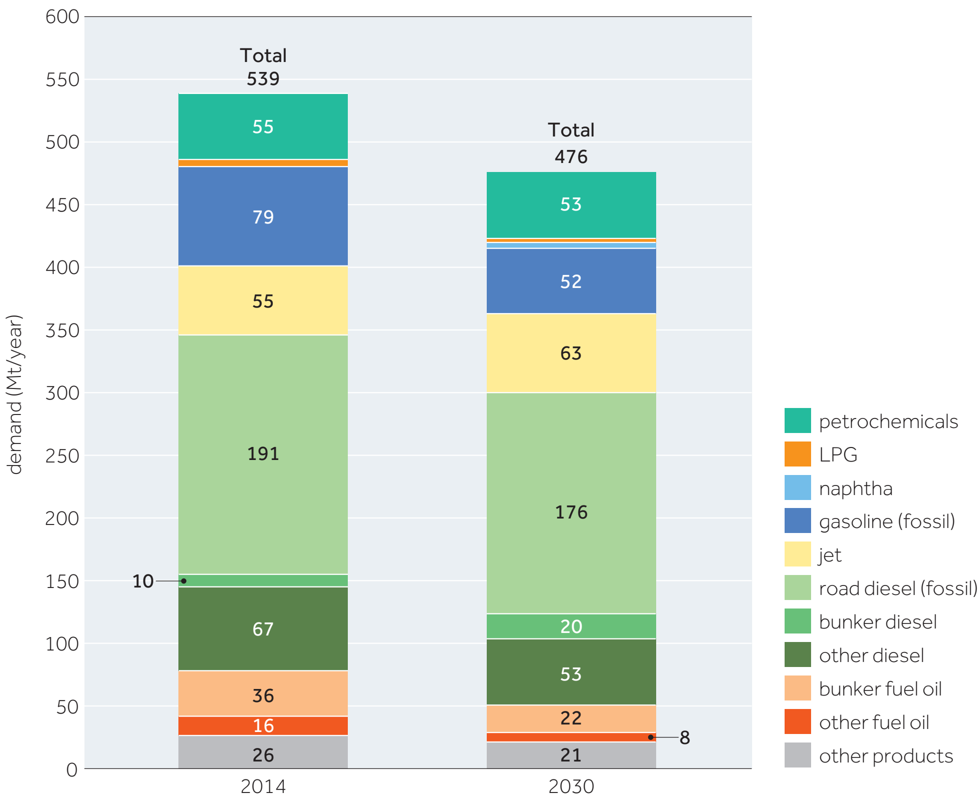
[3] FuelsEurope (2019). *Vision 2050. A pathway for the evolution of the refining industry and liquid fuels.*
https://www.fuelseurope.eu/wp-content/uploads/DEF_2018_V2050_Narratives_EN_digital.pdf

Gasoline demand and EU trade balance

EU-28 gasoline demand (consumption) is around 79 Mt/y (2014 data as used for this study) for the fossil content (the ethanol added after the refinery fence being ~5% of the finished grade on average in the EU-28). This demand is expected to decrease significantly towards 2030.

As can be seen from Figure 1, gasoline demand is anticipated to fall from 79 Mt to 52 Mt — a decrease of 34%. This is partly due to the lower efficiency, leading to higher CO_2 emissions, compared to diesel engines. Therefore, every effort to improve gasoline quality needs to be considered from the perspective of an inevitable decline in demand. This decline may be minimised/reduced by quality improvements required to enable an increase in gasoline engine efficiency, which should provide a potential reduction in CO_2 emissions compared to using standard 95 and 98 grade gasoline fuels. Any cost assessment will be a challenge, since it should not be based on a constant demand for fossil fuel, and an accurate assessment of the impact on demand over a long period (to 2030 as for this study[4]) following a product quality change is not rationally possible.

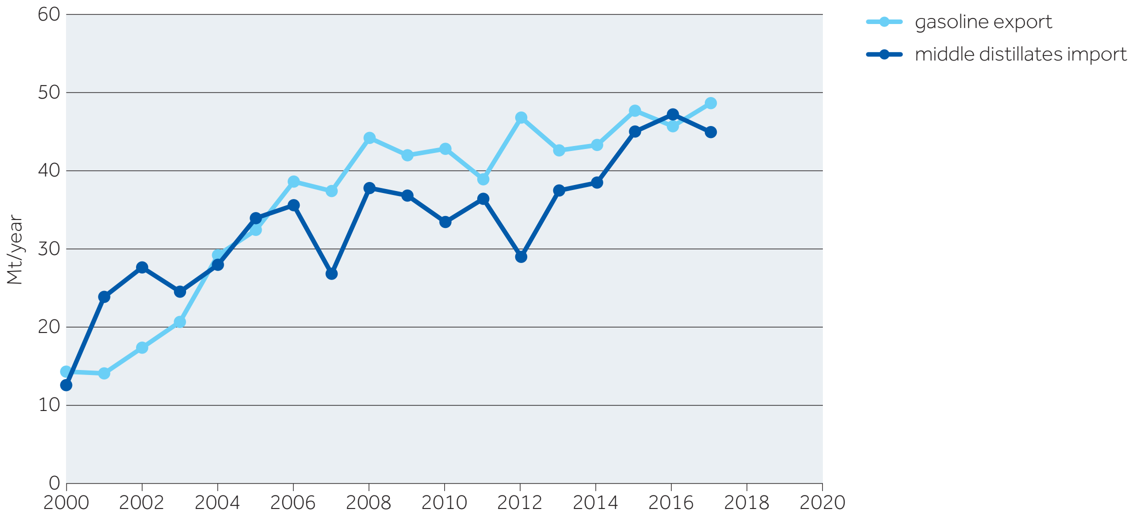
Figure 1: Reconciliated demand for petroleum products in the EU-28, 2014 and 2030 (Mt/year)



[4] 2030 demand scenario from Wood Mackenzie forecast

The overall net trade in transportation fuels is somewhat unbalanced, with a large amount of the gasoline produced in Europe being exported (nearly 50 Mt) and an equivalent quantity of middle distillates (diesel and jet fuels) being imported. Gasoline and gasoline components are global commodities that are frequently traded between regions and countries. The EU market is particularly integrated with other markets in the US Gulf Coast and in West and North Africa.

Figure 2: EU-28 net trade balance
Source: Wood Mackenzie, European Union database



Study objective and main assumptions

The objective of this study was to assess the feasibility and impact of a HOP fuel grade in the European (EU-28 + 3) refining system as a contribution to improvements in vehicle efficiency. The work was undertaken using Concawe's modelling tools and capabilities, and attempted to answer the following questions:

- What is the overall feasibility for the refining system, and at which RON?
- What would be the impact on CO_2 emissions from refining and cars (well-to-wheels)?
- What would be the cost impact for refining?

Many different cases were investigated, but for simplicity, only the main case is presented in this article. The simulated HOP is RON 102. For the demand structure, across the EU, the current share is 90% RON 95 grade and 10% RON 98. The results are shown for an estimated 2030 demand structure with 50% HOP (the remaining 50% being RON 95). The biofuel content remains constant at the current level of 3.4% energy (equivalent to an average E5 grade).

As the engine is tuned for a dedicated higher octane, efficiency improves. For this study, and based on previous Concawe research, a 1% efficiency increase per 1 point of RON increase is assumed. The demand for travel being constant decreases the demand for HOP (i.e. for the same passenger-km or weight-km, less energy is required by the transport system, and hence the 'domestic' demand decreases). For the case developed in this article, the decrease in demand is 6.4% (this results in a 40% switch in demand from RON 95 to RON 102 HOP, and a 10% demand switch from RON 98 to RON 102 HOP). Fossil gasoline production remains constant, and domestic volume reduction due to increased engine efficiency can be compensated by additional exports to other markets.

2030 scenario modelling results

Linear programming (LP) is a mathematical tool that helps the decision-making process. LP consists of an optimization driven by an economic objective function (profit maximization or cost minimization), where variables involved are constrained by means of linear equations. Concawe has a unique LP model which includes all the individual process unit capacities of the EU refining system. With more than 25 years' experience in modelling, this is the most relevant tool for assessing refinery operations.

Overall gasoline pool results

To meet the new quality demand, the model increases the octane rating of the gasoline pool. This is done by a combination of factors, including increasing oxygenate imports (MTBE), decreasing naphtha blending to gasoline (low octane component, more exports of petrochemicals), and increasing the use of alkylate (unit optimisation). For the reformer, the model increases severity, resulting in lower reformate yield but with a higher octane. To avoid a result based on the economic incentive to incorporate oxygenate (which is an unknown factor for 2030) in the gasoline pool, the data are shown for a 'high oxygenate case' (imported component) and a 'low oxygenate case' (more octane coming from the refinery).

Table 1: Overall gasoline pool results

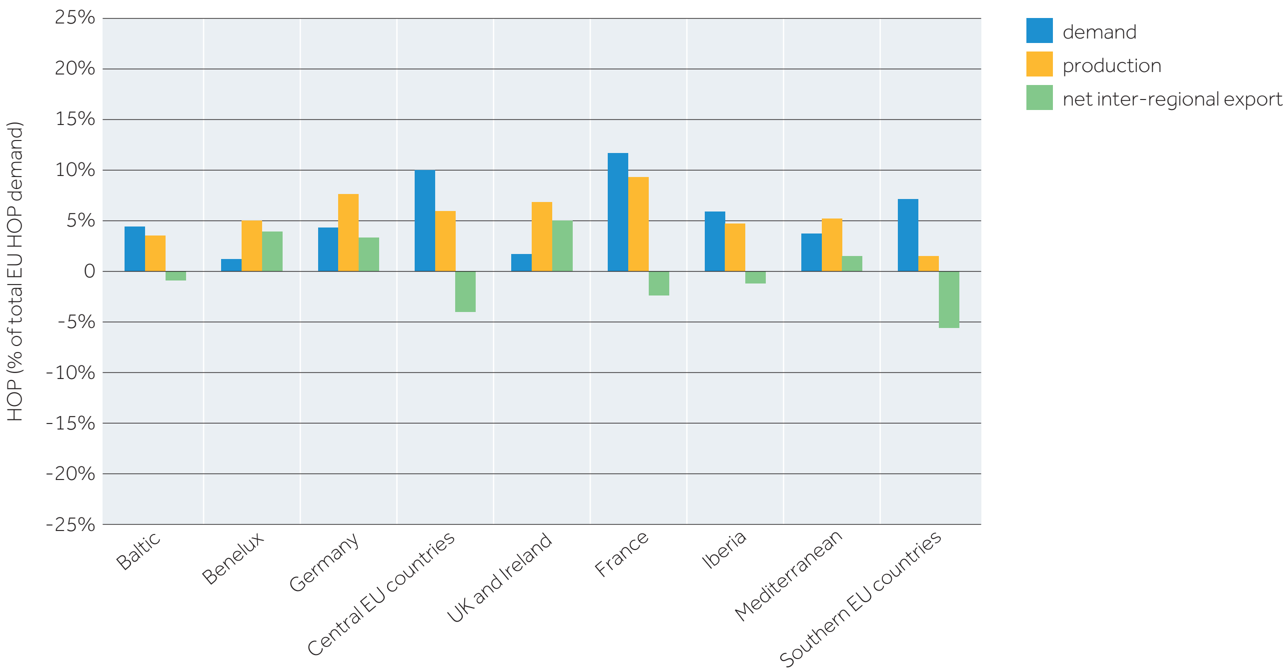
	HOP RATIO	POOL RON[5]	MTBE	ALKYLATE	NAPHTHA
Base case	10% (98)	94.6	1.1%	9.3%	5.4%
HOP RON 102					
High oxygenate case	50%	95.8	5.9%	13.5%	1.3%
Low oxygenate case	50%	95.8	4.4%	14.9%	1.0%

[5] The gasoline pool produced by the model consists of RON 95, RON 98 (base case) and low-octane export grade (RON 91).

Regional balances

To understand the behaviour of different refinery configurations, the results were extracted for the nine regions embedded in the LP model. The purpose was not to forecast or predict actual future local trade flows, but to provide a view on how different refinery configurations may react to a higher octane demand for EU gasoline. Figure 3 shows the evolution for each region, for the 2030 HOP RON 102 case for the light oxygenate pathway compared with the 2030 base. The regions have a different behaviour, some of them importing and others exporting HOP. However, in comparison to the total demand, these inter-regional trade flows remain limited. Each of the simulated refineries manage to adapt and produce some of the HOP demand.

Figure 3: Regional balances for the 2030 HOP RON 102 case (light oxygenate pathway) vs 2030 base case



The Central and Southern EU model refinery configurations show the highest imbalance between demand and production. However, if the constraints on intermediate trade flows and blending of oxygenates were to be relaxed, this would lead to a more closely balanced situation for these sections of the model.

Sensitivity case

In the standard cases, increasing unit capacities through investment was not allowed as the choice was to push the refining system based on existing capacities. However, in a clear and foreseeable environment, investing to adapt refinery yields to local demand is a strategic opportunity that some refiners may chose. In this case, giving the freedom to the model to invest and increase process units capacities results in a significant evolution, including an increase in alkylation units, and reformer and isomerisation recycling. The direct impact is on MTBE imports, which go back down to the level in the base case (1.1%).

Direct CO_2 emission balance

Table 2 shows the CO_2 balance taking into account the refinery, the vehicle emissions from cars and the oxygenate well-to-tank (WTT) impact. The key hypothesis for the impact on 'cars' is a 1% efficiency increase per 1 point of RON increase. Different engine testings are currently ongoing. In the case of a lower value, the impact on 'cars' is proportional. For example, at 0.50% efficiency/point of RON, the CO_2 balance goes from -5.1 Mt/y to -2.55 Mt/y.

Table 2: CO_2 balance vs 2030 base case (Mt/year)

	REFINING	CARS	OXYGENATE IMPACT (WTT)	TOTAL CO_2
Base case	Base	Base	Base	-
HOP RON 102				
High oxygenate case	-0.9	-5.1	+1.6	-4.4
Low oxygenate case	-0.5	-5.4	+1.0	-4.9

Looking at Table 2 in more detail, the evolution of 'Refining' + 'Oxygenate impact (WTT)' is +0.7 and +0.5 $MtCO_2$/year for the 'high' and 'low' oxygenate cases, respectively. It could be deduced that the octane from the refinery system is less CO_2-intensive than oxygenate production; however, the change vs base case is quite small (~1 Mt versus a total ~140 Mt for the refining system), hence it is more reasonable to consider that both pathways (refinery and oxygenate) are equivalent in terms of their CO_2 intensities.

The refining system is under higher constraints with regard to the gasoline units, but importing oxygenates allows a slight decrease in crude processing and hence lower CO_2 emissions. This decrease is compensated for by the carbon content of the oxygenate on a WTT basis.

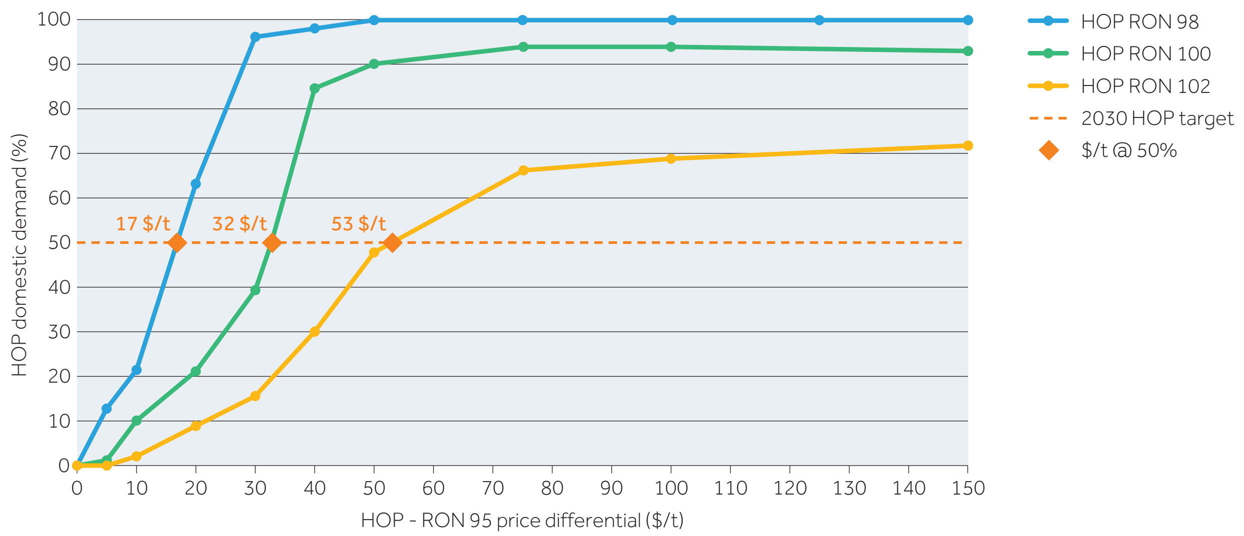
Economics

To run HOP cost sensitivity cases, step changes in the HOP price differential versus the current RON 95 price are modelled. Two historical price sets were considered, one at a high Brent value (100 $/bbl, 2014) and the second at low Brent (43 $/bbl, 2016). This assessment was undertaken without process investment (this was only allowed in a sensitivity case as mentioned on page 45). For a better understanding and to provide confidence in the behaviour of the model, Figures 4 and 5 on page 47 show the curves for HOP RON 98 and RON 100. However, in this discussion, comment is only made on the RON 102 curve and results as this is the main case for the study.

HOP cost sensitivity — 2014 price set, Brent @ 100 $/bbl

To reach 50% of the market demand (2030 hypothesis), the model needs an incentive of 17 $/t and 53 $/t for a RON of 98 and 102, respectively (see Figure 4). As expected, with the study being undertaken without process investment, the model reaches a plateau at different levels of domestic demand depending on the RON increase. Investments or innovative solutions/technologies would allow the model to reach 100% of domestic demand even for RON 102. Our estimation shows that the HOP RON 95 price differential is driven by the MTBE value for one third, and the remaining two thirds by other components.

Figure 4: HOP domestic demand % vs HOP-RON 95 price differential (2014 price set, Brent at 100 $/bbl)

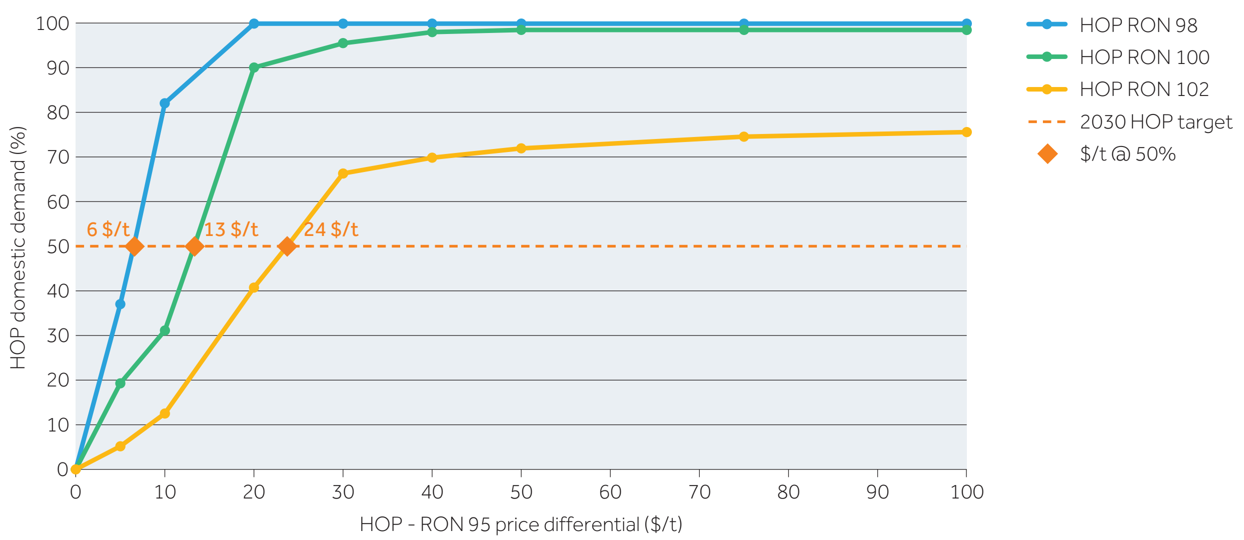


HOP cost sensitivity — 2016 price set, Brent @ 43 $/bbl

At a lower Brent value, the incentives are quite different, being only 24 $/t for HOP RON 102 (see Figure 5). In this case, the MTBE contribution to this price differential increased to about 50%.

For RON 102, at 50% of domestic demand, the break-even point (above RON 95) is worth between 7.5 and 3.5 $/t/point of RON (2014 and 2016 price scenarios, respectively—see Figures 4 and 5, HOP RON 102 curve at 50% of domestic demand). Being a cost for refiners, this has to be compared to the octane value on the market, as the cost could potentially be recovered via market price differentials.

Figure 5: HOP domestic demand % vs HOP-RON 95 price differential (2016 price set, Brent at 43 $/bbl)



To appreciate the order of magnitude, it can be noted that the average historical octane value in the US Gulf Coast is estimated at around 12 $/t/point of RON (2010–2017). Since gasoline is a commodity traded in a free and open market with multiple competing companies, the market price and product differential are the result of a supply/demand equilibrium. In this context, refiners cannot always pass their costs on to their clients, as there is no direct correlation between refinery costs and market value. Therefore, historical figures may be considered as an indication but in no way as a forecast.

Conclusion

This study recommends the endorsement of RON 102 as a pragmatic way forward for high-octane petrol in discussions with industry stakeholders.

The main takeaways from the HOP study are as follows:

- The set of assumptions in the LP modelling study demonstrate the feasibility of producing a HOP in the EU refining system, requiring either more oxygenates or investments in gasoline units.
- The evolution of the LP economical function is in the same order of magnitude as the historical octane value (USGC quotation).
- A significant reduction in CO_2 emissions is expected (refining process + combustion in ICEs at high compression ratio + oxygenate WTT).

Refiners have been improving fuel quality for decades and will continue to do so into the long-term future. The demand for cleaner and more efficient fuels is increasing, and the successful implementation of HOP would represent a significant contribution to climate change mitigation.

Abbreviations and terms

AEC	Alkaline Electrolysis Cell
BEV	Battery Electric Vehicle
BOB	Blendstocks for Oxygenate Blending
CAPEX	Capital Expenditure
CEN	European Committee for Standardization
CFR	Cooperative Fuel Research
CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon dioxide
COP21	21^{st} Conference of the Parties to the United Nations Framework Convention on Climate Change
DAC	Direct Air Capture
DME	Dimethyl Ether
DRC	Democratic Republic of Congo
E5	Grade of fuel consisting of 5% ethanol and 95% gasoline
EC	European Commission
EN 228	European Union standards for gasoline as specified by the European Committee for Standardization (CEN)
ESS	Energy Storage Solution
EU	European Union
EU28 + 3	The 28 countries of the European Union plus Iceland, Liechtenstein and Norway
EV	Electric Vehicle
EUCAR	European Council for Automotive R&D
FCEV	Fuel Cell Electric Vehicle
FOB	Free On Board
FVV	Forschungsvereinigung Verbrennungskraftmaschinen (Research Association for Combustion Engines)
GHG	Greenhouse Gas
GJ	Gigajoule
GTL	Gas To Liquids
H_2	Hydrogen
H_2O	Dihydrogen Monoxide (water)
H_2tCH_4	Hydrogen to Methane
H_2tL	Hydrogen to Liquids
ICE	Internal Combustion Engine
IEA	International Energy Agency
JEC	JRC-EUCAR-Concawe (a collaboration between the European Commission's Joint Research Centre, EUCAR and Concawe)
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HOP	High-Octane Petrol
ICCT	International Council on Clean Transportation
LCE	Lithium Carbonate Equivalent
LCO	Lithium Cobalt Oxide ($LiCoO_2$)
LCP	Low-Carbon Pathways
LDV	Light-Duty Vehicle
LFP	Lithium Iron Phosphate ($LiFePO_4$)
Li	Lithium
Li-ion	Lithium Ion
LME	London Metal Exchange
LMO	Lithium Manganese Oxide ($LiMn_2O_4$)
LP	Linear Programming
LPG	Liquefied Petroleum Gas
LTO	Lithium Titanate (Li_2TiO_3)
MJ	Megajoule
MON	Motor Octane Number
MTBE	Methyl Tertiary-Butyl Ether
Mtoe	Million Tonnes of Oil Equivalent
NACE	National Association of Corrosion Engineers
NCA	Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)
NH3	Ammonia
NMC	Lithium Nickel Manganese Cobalt ($LiNiMnCoO_2$)
NPI	Nickel Pig Iron
O_2	Oxygen
OEM	Original Equipment Manufacturer
OME	Oxymethylene Ether
PEMC	Proton Exchange Membrane Cell
PHEV	Plug-in Hybrid Electric Vehicle
PtG	Power-to-Gas
PtL	Power-to-Liquids
PtX	Power-to-X

Abbreviations and terms
(continued)

PV	Photovoltaic
RED	Renewable Energy Directive
RES-E	Renewable Energy Sources for Electricity
RON	Research Octane Number
RTR	Roan Tailings Recovery
RVP	Reid Vapour Pressure (the absolute vapour pressure exerted by a liquid at 37.8°C (100°F) as determined by the ASTM-D-323 test method.
RWGS	Reverse Water-Gas Shift
SOEC	Solid-Oxide Electrolysis Cell
SS	Stainless Steel
TTW	Tank To Wheels
USGS	United States Geological Survey
WACC	Weighted Average Cost of Capital
WOL	Whole Ore Leach
WTT	Well To Tank
WTW	Well To Wheels
xEVs	Hybrid and Electric Vehicles

Reports published by Concawe in 2019 to date

9/19	Refinery 2050: Conceptual Assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO_2 intensive economy
9/19A	Appendices, Refinery 2050: Conceptual Assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO_2 intensive economy
6/19	European downstream oil industry safety performance. Statistical summary of reported incidents - 2018
4/19	Air pollutant emission estimation methods for E-PRTR reporting by refineries. 2019 Edition
7/19	Phase 2: Effect of Fuel Octane on the Performance of Four Euro 5 and Euro 6 Gasoline Passenger Cars
8/19	CO_2 reduction technologies. Opportunities within the EU refining system (2030/2050). Qualitative and Quantitative assessment for the production of conventional fossil fuels (Scope 1 & 2)
5 July 2019	Low Carbon Pathways Until 2050. Deep Dive on Heavy-Duty Transportation. Report produced by FEV Consulting for Concawe
5/19	Concawe Substance Identification Group Analytical Program Report (Abridged Version)
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