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.

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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

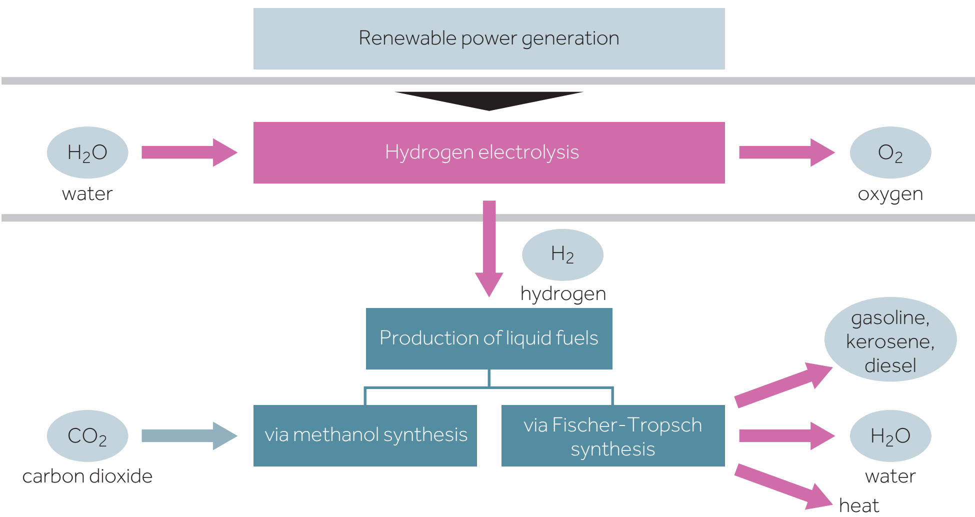
The production of e-fuels requires CO_2 (except e-ammonia), which can be obtained from various sources including biomass combustion, industrial processes (e.g. flue gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air.

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)

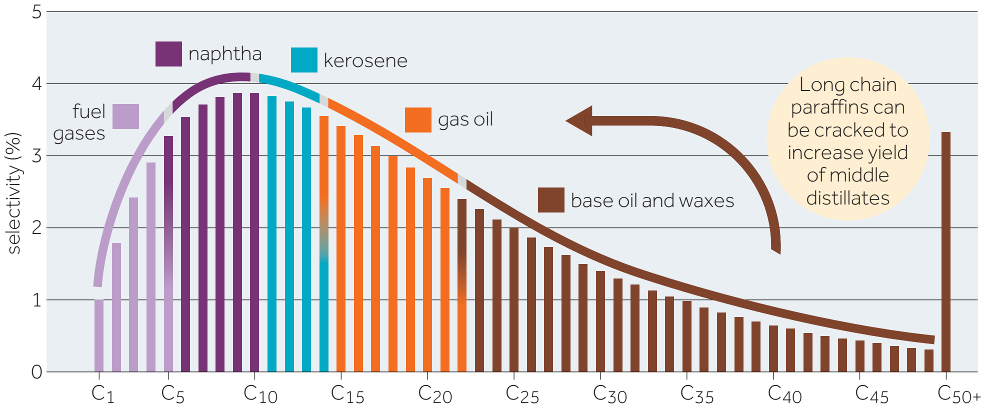


[2] Recent developments are evolving to a new technology (co-electrolysis) where CO_2 and steam are fed into a high-temperature (solid-oxide) electrolyser to produce syngas in a single step, increasing the efficiency of the process [Sunfire, 2019a].

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)

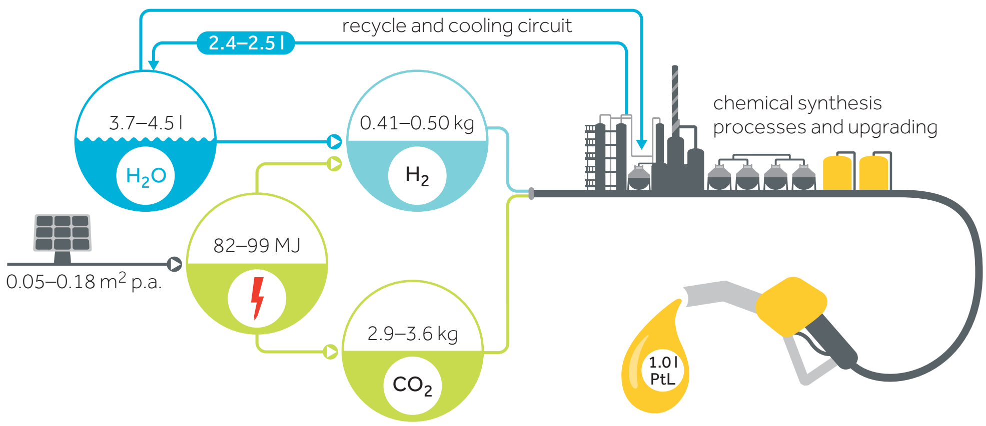


The resulting 'e-crude' from the Fischer-Tropsch reaction, which can be a single stream or several separate streams, could be fed to a hydrocracking unit. The intermediate wax molecules are hydro-processed within a hydrocracker into shorter 'middle distillate' molecules, which are then purified by distillation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

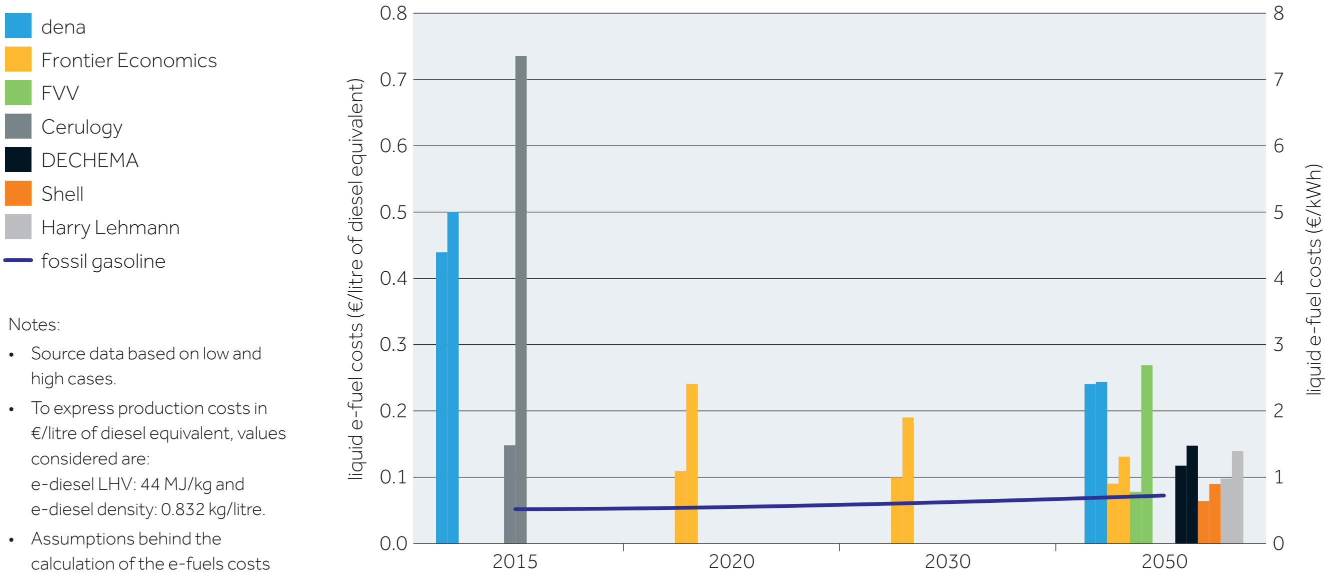
Source: Shell (2018a)



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) (€/kWh and €/l)



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.

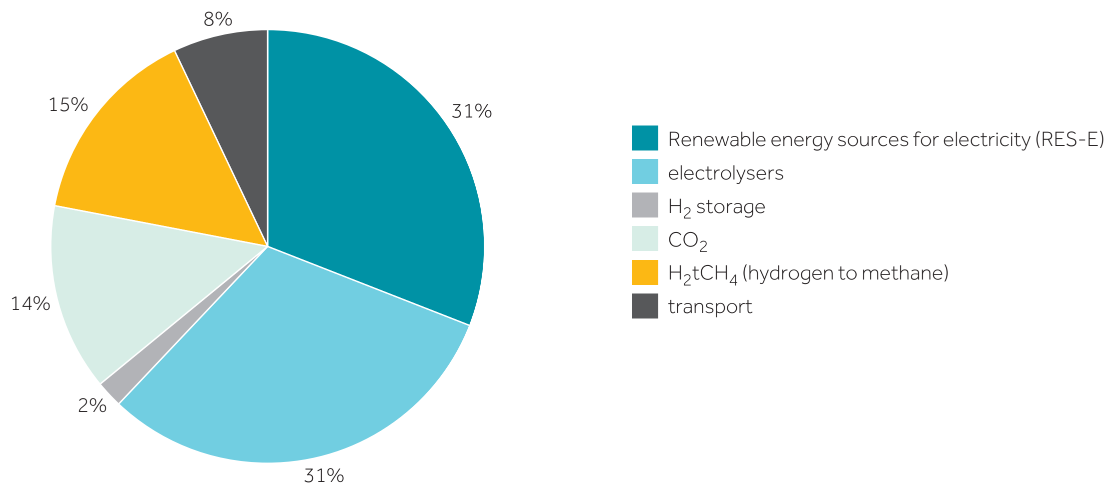
[3] Dena and Cerulogy (up to 7 euros/litre currently). Dena, Frontier Economics, FVV, DECHEMA, Shell (1–3 euros/litre in 2050).

[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/

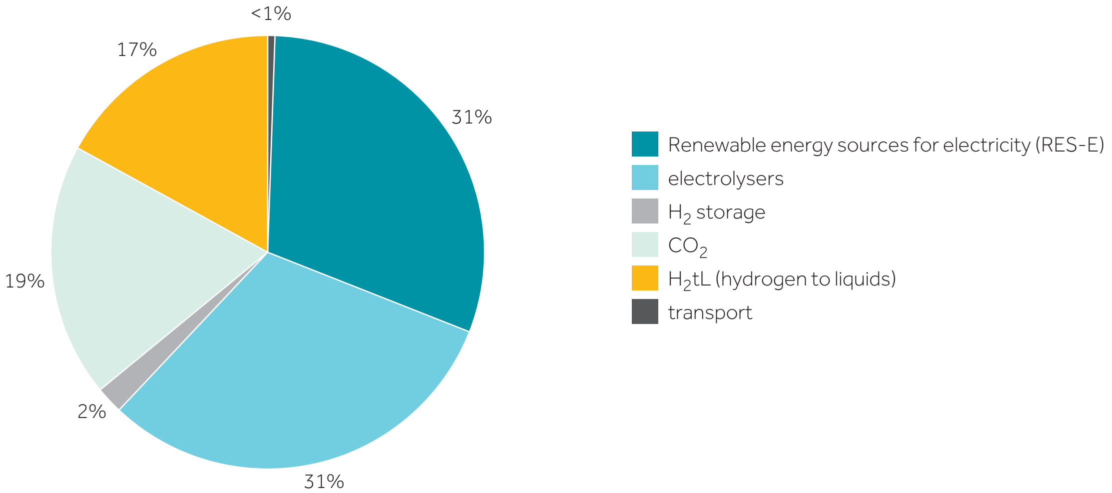
Figure 5: Cost breakdown for e-fuels

Source: Frontier Economics (2018)

a) E-methane



b) E-liquids



Note:

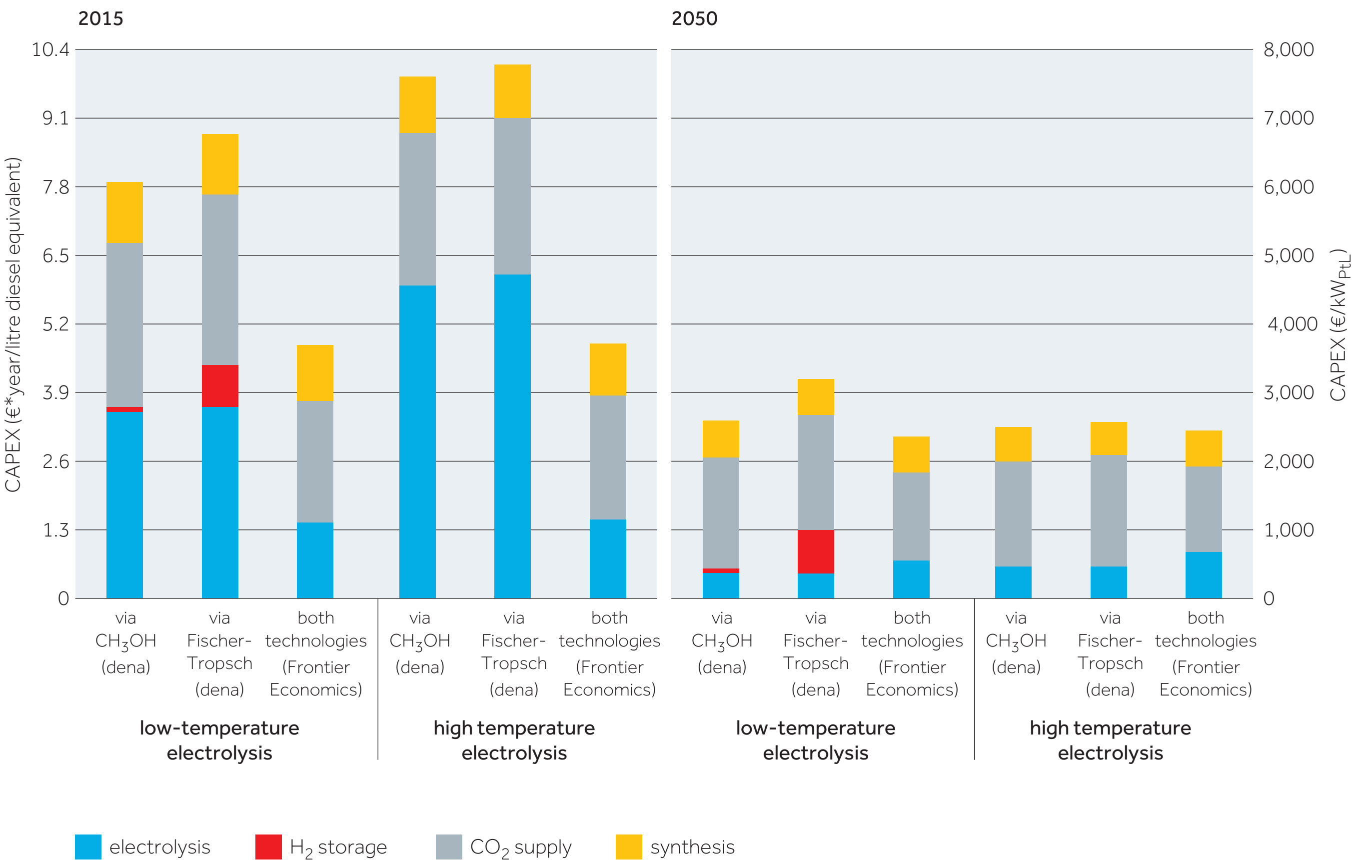
- All cost shares (%) and absolute figures (ct/kWh) are rounded and associated with the following scenario: North Africa, reference scenario 2030, PV-wind-combination, CO_2 from DAC, 6% WACC.

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).



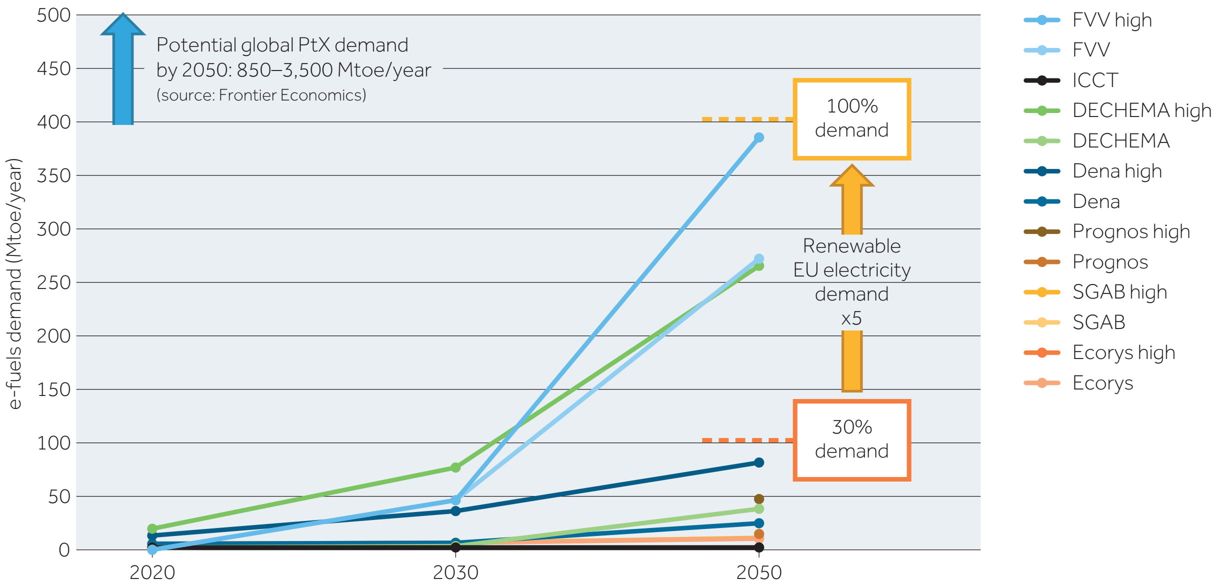
Notes:

- 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)



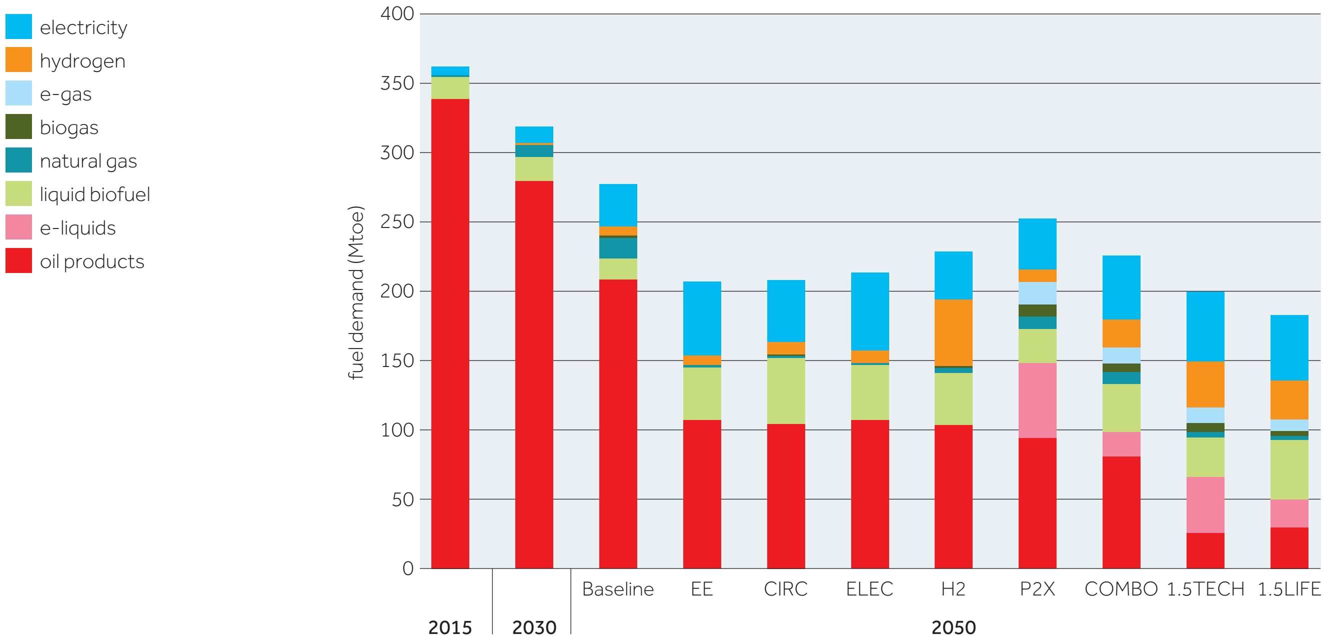
Notes:
- Energy contents: 1 toe = 41,868 GJ; 1 t = 1,051 toe
- Efficiency from electricity to e-fuel: 44% (Reference: Frontier Economics, 2018)
- Note: % of demand refers to the predicted transport demand in EU by 2050 (all transport segments). Source: EU Reference scenario.

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).

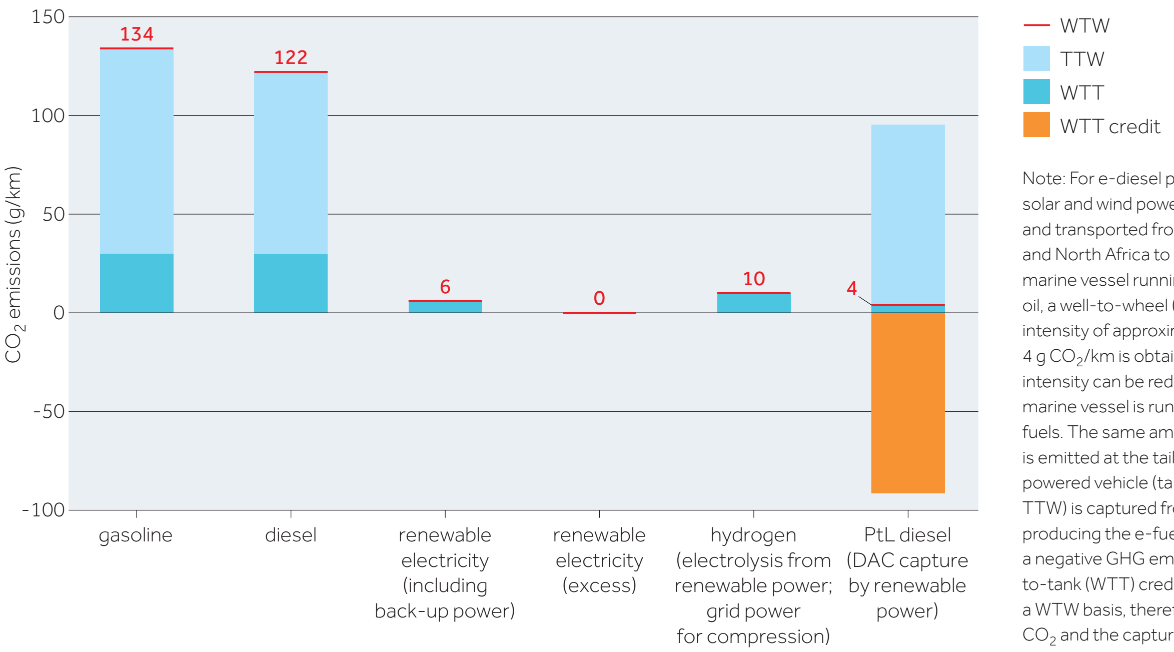
[7] There are, however, controversial opinions about the total 'carbon-neutrality' of the CO_2.

[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

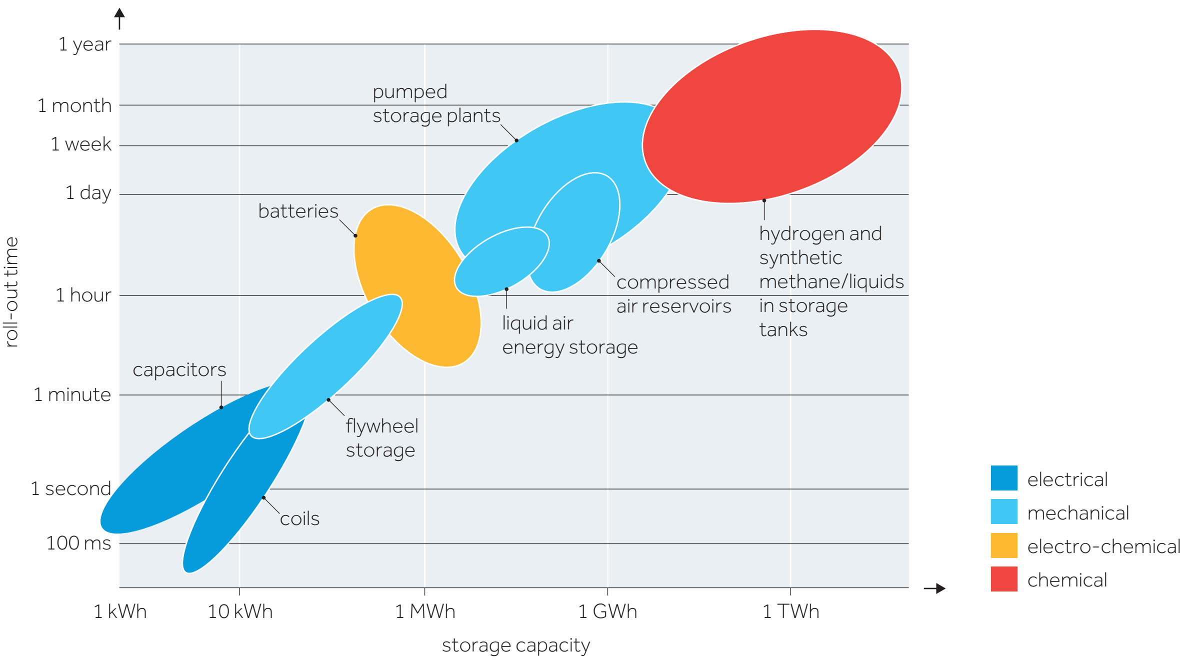
Source: Shell (2018a)



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

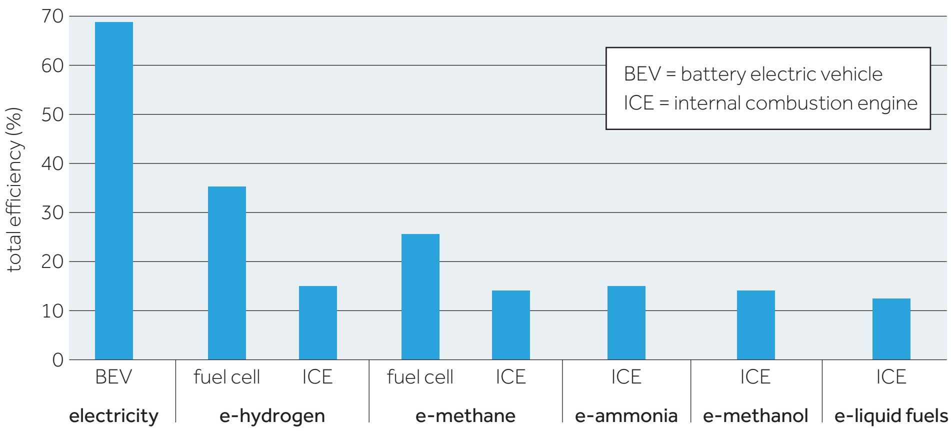
The main disadvantages or barriers of these low-carbon fuels are detailed below:

- 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

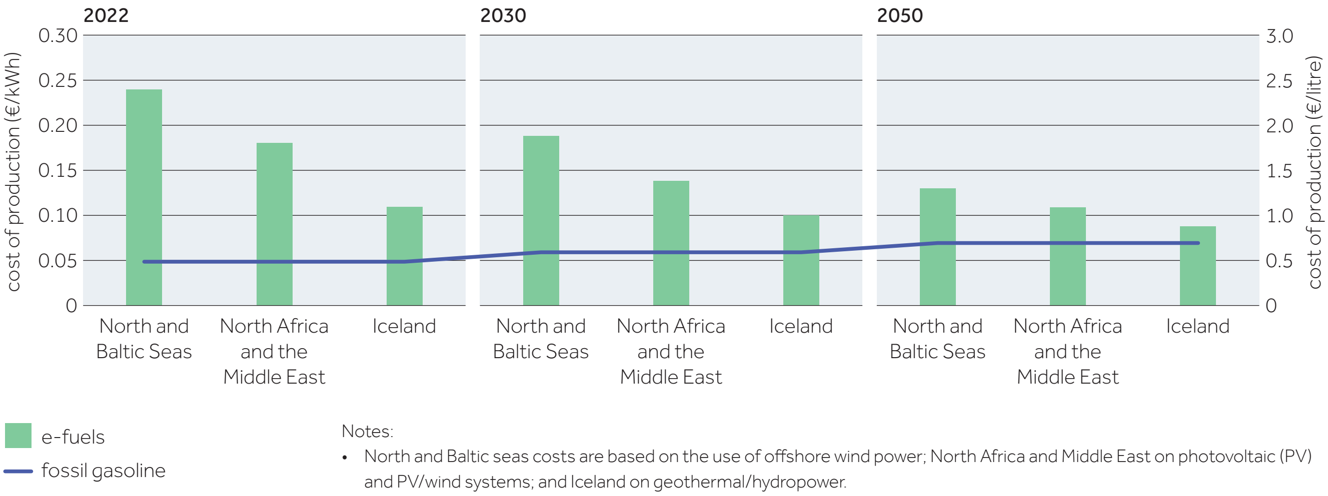
The main key enablers for the deployment of e-fuels on a commercial scale are listed below:

- 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

[16] FuelsEurope (2018). *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

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