

Report

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Role of e-fuels in the European transport system - Literature review

Low
Carbon
Pathways



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Role of e-fuels in the European transport system. Literature review

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ABSTRACT

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

To support the EU low emissions strategy, Concawe is exploring a cross-sectorial Low Carbon Pathways (LPC) programme, identifying opportunities and challenges for different low carbon technologies to achieve a significant reduction of the CO₂ emissions associated with both the manufacturing and use of refined products in Europe in the medium (2030) and longer-term (2050).

As part of the LPC programme, this report is a literature review on e-fuels, which aims to build a better understanding of the e-fuel production technologies and implications in terms of efficiency, greenhouse gases (GHG) reduction, technology readiness level, environmental impact, investment, costs and potential demand.

The main recent state-of-the-art publications have been identified and compared in this literature review, covering detailed assessments, presentations, technology providers and position papers, helping to define a better picture of the potential role of these low-carbon fuels in Europe.

KEYWORDS

E-fuels, efuels, Power-to-X, PtX, Power-to-liquids, PtL, Power-to-gas, PtG, Synthetic fuels, electrofuels.

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SUMMARY

The objective of this literature review is to build a better understanding of the e-fuel production technologies and implications in terms of efficiency, contribution to reductions in greenhouse gases (GHG), technology readiness level, environmental impact, investment, costs and demand that could help to define a better picture of the potential role in decarbonisation of these fuels in Europe.

The interest in e-fuels has increased in recent years: a number of e-fuels-related studies have been published in the recent past, raising some controversy with positive and negative views on e-fuels.

The main recent publications have been identified and compared in this literature review, covering detailed assessments, material from conferences and presentations, technology providers, position papers and the recent European Commission long-term strategy *A Clean Planet for all* [European Commission 2018].

In the scenarios considered by the Commission, e-fuels are one of the potential cost-effective technologies (with a specific scenario focused on them) to achieve the Paris Agreement objective, keeping the global temperature increase to well below 2 °C, and pursue efforts to keep it to 1.5 °C.

E-fuels definition:

E-fuels are synthetic fuels, resulting from the synthesis of green hydrogen produced by the electrolysis of water, using green electricity and carbon dioxide (CO₂) captured either from a concentrated source (flue gases from an industrial site) or from the air (Direct Air Capture).

E-fuels can also be described in the literature as electrofuels, Power-to-X (PtX), Power-to-liquids (PtL), Power-to-gas (PtG) or synthetic fuels.

E-fuels advantages:

- E-fuels achieve a significant CO₂ reduction versus their equivalent fossil-based fuels offering a compelling complementary alternative for low-CO₂ mobility in Europe.
- The main CO₂ abatement potential is ≈ 85-96% (Well-To-Tank -WTT- basis) or 70% (LCA analysis)¹. The CO₂ abatement potential (WTT basis) can be similar if CO₂ comes from direct air capture or from a concentrated fossil source when CO₂ is considered as a waste².
- E-fuels have a higher energy density compared to batteries, and can thus offer a solution in usages for which no electricity-based alternatives can be found (e.g. aviation and shipping)³.
- Liquid e-fuels are easier (and relatively inexpensive) to store and transport compared to electricity:
 - Liquid e-fuels can be kept in large-scale stationary storage over extended periods, and mobile storage in vehicle tanks, allowing to compensate seasonal supply fluctuations and contribute to enhance energy security⁴.

¹ Sources: [Audi 2019], [Sunfire 2019], [JEC 2019] [Lehman, H. 2018].

² Although there are controversial opinions about the total “carbon-neutrality” of the CO₂.

³ There may be small sectors of both where electric options might find a place (some ferries for instance).

⁴ Strategic petroleum reserve within the territory of the EU equal to at least 90 days of average domestic consumption.

- 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 are chemically pure hydrocarbon and could be deployed immediately across the whole transport fleet without any major changes in engine design.
 - In the case of liquid e-fuels, they offer an alternative technology to reduce GHG emissions in both existing and new vehicles without requiring the renewal of the fleet.
- A blending ratio of up to 100% is possible when adding methane to natural gas, and e-liquid fuels to gasoline and diesel, providing they are meeting their corresponding specifications.
- Regarding air quality, e-fuels would possibly have positive environmental impacts, because of the favourable combustion characteristics of the molecules produced.

E-fuels disadvantages/barriers:

- The inherent thermodynamic conversion inefficiency that occur when producing e-fuels, which results in a significant amount of new renewable generation plants required⁵.
 - The overall energy efficiency of electricity use in battery electric vehicles is 4-6 times higher than e-fuels in combustion engines.
- The current low scale of the technology, still in a pilot/demo scale.
 - Some really profound challenges could be discovered as the facilities are scaled up by a factor of 100,000 times (compared to what has been demonstrated so far, in a pilot scale) or 100 times (compared to a new announced project in Norway starting up in 2021) to reach a large-scale commercial plant⁶.
- The very high capital cost, necessary to deploy the technology.
- Renewable electricity is a prerequisite for low carbon e-fuel to contribute to reducing GHG emissions. As such there is a need for a substantial increase in renewable electricity production.
- High e-fuels production costs in comparison with conventional fossil fuels.

Currently, e-fuel costs are relatively high (up to 7 euros/litre). Some authors forecast their decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price, leading to, in 2050 around 1-3 euros/litre (without taxes)⁷. Therefore, cost of e-fuels could range from one to three times higher than fossil fuels by 2050⁸.

⁵ E.g. to supply 1% of the total EU expected demand in transport by 2050 with e-fuels (Fischer-Tropsch route), it is required 6% of the total EU-28 current installed wind power capacity (178 GW) or 100% of, e.g. the Netherlands + Sweden current installed wind power capacity (11.88 GW) [WindEurope 2018].

⁶ Shell's Pearl facility, the largest synthetic liquids (GtL) plant in the world, located out of Europe -Katar-. Only this part of the e-fuels route has been commercialised producing fuels at a scale comparable to conventional refining.

⁷ Sources: [dena 2018], [Cerulogy 2017], [Frontier Economics 2018], [FVV 2018a], [Dechema 2017], [Shell 2018].

⁸ Electricity costs currently ranging from 4 ct/kWh (North Africa - Photovoltaic) to 10-13 ct/kWh (North and Baltic Seas - Offshore wind), and by 2050 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/Agora 2018b].

Main key enablers are:

- Technical development and scale-up
 - Scale-up of the current pilot or demonstration-scale technology to available commercial plants, highlighting the magnitude of the assets and investment needed in a new value chain (electrolysers, carbon capture, syngas and e-fuels conversion facilities).
- High full load hours
 - In order to be operated in an operationally manageable and economically efficient manner, e-fuel facilities need to achieve high full load hours, despite the likely intermittency of renewable power supply.
 - Energy storage will be required at some level of the conversion chain.
- Accessibility to affordable renewable energy price
 - Due to conversion energy consumption, the price of electricity is the major determinant of e-fuel variable costs. Accessibility to a sustainable and affordable renewable power is thus essential for the economically viable operation of e-fuels production facilities. Importing e-fuels could become an important element, allowing the use of highly favourable locations for generating renewable electricity with a positive impact on cost reduction for e-fuel production.
- Policy framework
 - Policymakers at EU and national level, creating the right regulatory framework to encourage and to promote potential investments in Europe, so private companies could have a business case and commit money to this.

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

- Industrial clusters, linking industrial producers of CO₂ (as a concentrated source) to produce e-fuels:
 - In the future, it is likely that there will still be industry sectors that emit large amounts of CO₂ for process-related reasons (energy intensive industries such as refineries, steel or cement)
 - A “notional⁹” refinery in European Union (EU) in 2050, where a high penetration of energy efficiency, electrification and CO₂ capture is assumed, would reduce their direct CO₂ emissions from around 1,600 kt/a to 500 kton/a. To produce 1,000 kton/a of e-fuel, 3,000 kton/a of CO₂ are required. Therefore, to produce 1,000 kton/a of e-fuel in a 2050 notional refinery, 15% of the CO₂ would be produced within the refinery, and 85% would have to be imported from another CO₂ producer.
 - The expected CO₂ generation from large point sources is expected to exceed the amount of CO₂ required for the e-fuels demand
- OEMs-Industry alliances
 - Some OEMs (Original Equipment Manufacturer) such as Audi, are exploring an e-fuels strategy to provide a compliance pathway for their vehicles
- Business models based on regions with large and cheap renewable energy sources
 - The transportation and import of e-fuels from geographically privileged regions is relatively simple.
 - Importing e-fuels from low-electricity price regions in the world could reduce costs up to 20-50%.

⁹ Notional or “average” mid-range refinery (160,000 bbl/d of crude oil intake, assumed throughput - current demand - and process unit capacities consistent with the European average refinery configuration with a current direct CO₂ emission of 1,600 kt/a . This is a hypothetical refinery used for illustration and is not intended to represent a “typical” refinery). See section 2.4.

E-fuels demand:

Regarding all these factors, e-fuels are not expected to play a significant role in meeting the transport sector demand in the short-term (2030), and their use is dependent on a number of factors in the long term (2050).

By 2050, most of the literature sources, including the European Commission *A Clean Planet for all* [European Commission 2018], claim that e-fuel could contribute to the transport sector, ranging from 0 to 50 Mtoe/a (which means from 0 to 30% of the expected transport demand in EU by 2050¹⁰), mainly focused on aviation, maritime and long-haul road transport segments.

¹⁰ EU Reference scenario [European Commission 2016].

1. GENERAL

1.1. BACKGROUND: CONCAWE LOW CARBON PATHWAYS

In December 2015, COP21 in Paris made an important step to address the risks posed by climate change and to keep the global temperature increase to “well below 2°C” and drive efforts to limit it even further to 1.5 degrees. To achieve these goals, the EU is exploring different mid-century scenarios leading to an EU low-carbon economy by 2050.

To support the EU low emissions strategy, Concawe is exploring a cross-sectorial *Low Carbon Pathways* (LCP) programme, identifying opportunities and challenges for different low-carbon technologies and feedstocks to achieve a significant reduction of the CO₂ emissions associated with both the manufacturing and use of refined products in Europe in the medium (2030) and longer-term (2050).

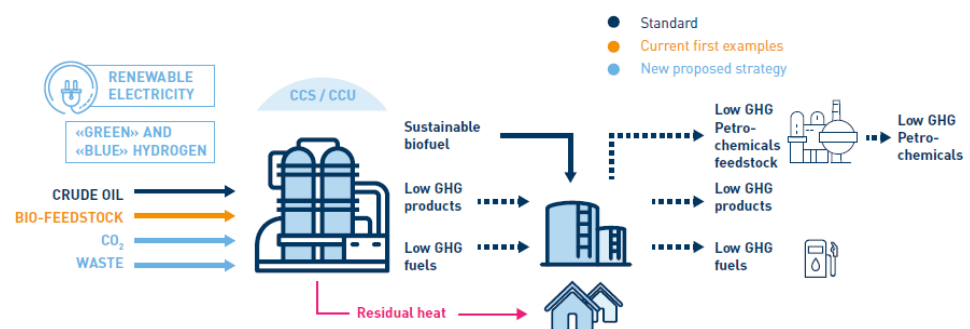
The initial Working plan exploring opportunities from the production phase (Well-To-Tank) to the final use (Tank-To-Wheel) was published in 2018 and since then, a series of reports has already been published and more will follow articulated around two main areas:

- a) Refining technologies: from maximizing CO₂ savings to the Refinery 2050 concept.

These Concawe refining-related series of reports focus on the transition of the European refining industry and products towards a low-CO₂ intensive economy and explores the technical implications of the deployment of the Vision 2050 [Fuels Europe 2018] across the EU refining system contributing effectively to the EU decarbonisation goals.

Some of the technologies identified will be addressed in specific related studies including, among others, energy efficiency, use of low-carbon energy sources (electrification, green hydrogen), CO₂ capture and storage or utilisation (CCS/U) as well as the implications of the progressive replacement of crude oil by “low-carbon” feedstocks (e.g. advanced bio-feedstocks, e-fuels).

Figure 1. Vision 2050 of the refining system as an energy hub within an industrial cluster



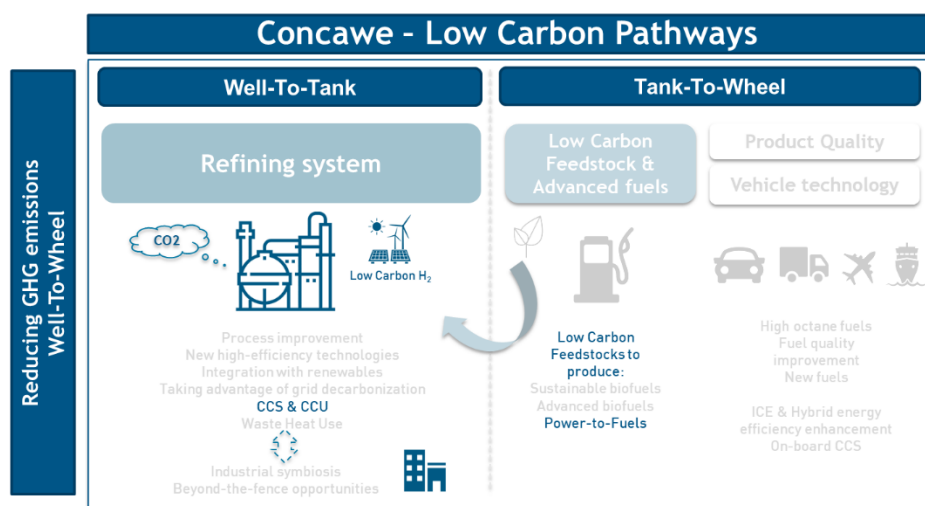
External factors such as the required availability of low-CO₂ electricity, hydrogen or low-carbon feedstocks together with the effective deployment of R&D programs are also investigated as key enablers to boost the effective deployment of the technologies identified.

b) Role of low carbon intensity fuels in the EU transport sector

Through specific deep dives on passenger cars, heavy duty, marine and aviation sectors, other joint research projects are being conducted to provide better scientific understanding on the role of low-carbon fuels across different transport sectors. The potential impact in terms of CO₂ savings (Well-To-Wheels and Life-Cycle Analysis), cost and additional external requirements and infrastructure will be included as part of our joint work which will be conducted through specific programmes with relevant and specialized partners and contractors.

The **Figure 2** summarizes the initial technology areas being explored as part of our Low Carbon Pathways programme and highlights the scope of the present report focused on exploring opportunities and challenges of e-fuels in the EU refining industry to transition towards a low-CO₂ intensive economy in 2050. The following section provides further insights regarding its purpose and scope.

Figure 2. Concawe - Low Carbon Pathways programme. Scope.



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

1.2. MAPPING EXERCISE. SCOPE OF THE REPORT

The objective of this report is to build a better understanding of the state of the art of e-fuel production technologies, implications in terms of efficiency, GHG, environmental impact, capital expenditure (CAPEX), costs and other main factors, that could help define a better picture of the potential role of low-carbon fuels in Europe by 2050.

The European Commission recently published (28th November 2018) its Long-Term Strategy for a climate neutral economy *A Clean Planet for all* [European Commission 2018]. This strategy is in line with the Paris Agreement objective to keep the global temperature increase to well below 2 °C and to pursue efforts to keep it to 1.5 °C. The strategy looks at a range of GHG reduction scenarios, starting at -80% going up to -100% by 2050 compared to 1990. To meet the -100%

goal will require almost complete decarbonisation of electricity generation, buildings, transport and industry.

One of the potential routes to contribute to the transition is the concept of e-fuels (also mentioned in the literature as Electrofuels or Synthetic Fuels or Power to X (PtX) (Power to Gas (PtG)/Power to Liquid (PtL)).

The e-fuels production route combines, in an energy-intensive process, “green” hydrogen produced by the electrolysis of water using green hydrogen with CO₂ captured either from a concentrated source (flue gases from an industrial site, for example) or from the air (Air Capture technologies). As e-hydrogen can be the energy vector in itself, we have included it in this study of e-fuels.

E-fuels can be obtained with a very low Green House Gases (GHG) intensity offering one plausible option to effectively contribute to reduce GHG emissions across different transport sectors, and allowing renewable electricity to be ‘stored’ in liquid and gaseous (e-)fuels.

1.2.1. Key studies

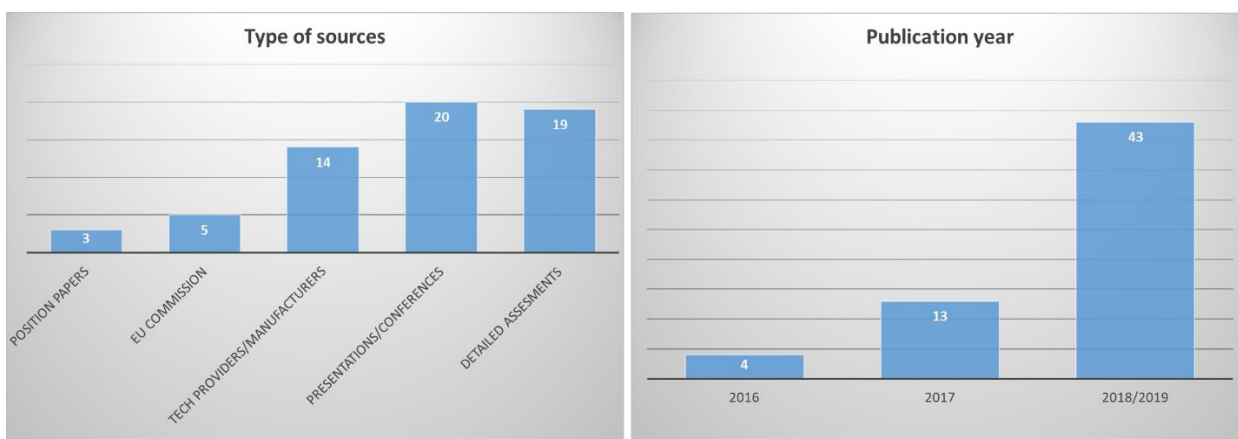
E-fuels have gained in interest over the past years. A number of e-fuels-related studies were published in the recent past - in particular in Germany, but also in other parts of Europe.

The main recent state-of-the-art publications were identified and compared in this literature review, covering detailed assessments, presentations, technology providers and position papers.

In this literature review report, key comments from the sources analysed are extracted. **Figure 3** summarizes these main publications.

In **Appendix A1-1**, a full detailed table assessment matrix covers the main information provided by each publication.

Figure 3. Publications considered in this report (see **Section 5** for further detail)



1.2.2. Potential role of e-fuels across different sectors

Numerous scenarios that model the successful achievement of carbon abatement targets between 2030 and 2050, show the importance of e-fuels. These scenarios all point out that sustainably produced biomass (including wood, biogas and biofuels) is not foreseen to be available in sufficient quantities to replace coal, oil and natural gas completely across all EU sectors.

Besides their potential low GHG intensity, e-fuels offer a number of benefits over direct use of electricity: e-fuels are energy-dense, can be stored and transported, and are also compatible in numerous respects with existing transport infrastructure and technologies. In this way, e-fuels display the same positive features as current fuels in use today. Industrial societies have developed far-reaching technological dependencies and routines in everyday life, therefore the compatibility of e-fuels with existing infrastructure is a clear argument in their favour.

However, the technology to produce e-fuels has large disadvantages that must be overcome:

- e-fuels technology has inherently a low energy efficiency (therefore, large volumes of electricity are needed for their production due to conversion inefficiency)
- the large scale of the construction and investment required lead to high cost of the resulting fuels

Because of these disadvantages, some authors limit e-fuels' use to sectors for which direct electrification is not possible ([Frontier Economics/Agora 2018], [Prognos 2018]).

Frontier Economics allocate e-fuels not only to transport sector but also to heating, industry and power sectors¹, as it is shown in **Table 1**.

¹ Although some other opinions find it hard to see e-fuels in non-mobility applications.

Table 1. Decarbonisation options (summary)

Decarbonisation options	Competing technologies: Direct use of electricity or H2 vs. Low Carbon Fuels	Supplemental approaches: E-fuels
Transport	Cars, motorcycles, buses, small trucks, trains	Air and sea transport, long-haul trucks and buses without overhead lines
Heating	Low-temperature heat with heat pumps in well-insulated buildings and in the industry	Existing buildings with significant insulation restrictions and hybrid heating systems with back-up boilers
	High-temperature heat with direct electricity use (resistance heating, plasma, etc.)	High-temperature process heat for hard-to-electrify applications (e-hydrogen)
Industry		Carbon source for organic basic chemicals
Power	Short-term storage	Long-term storage and reconversion in gas-fired power plants (e-methane in natural gas grid)

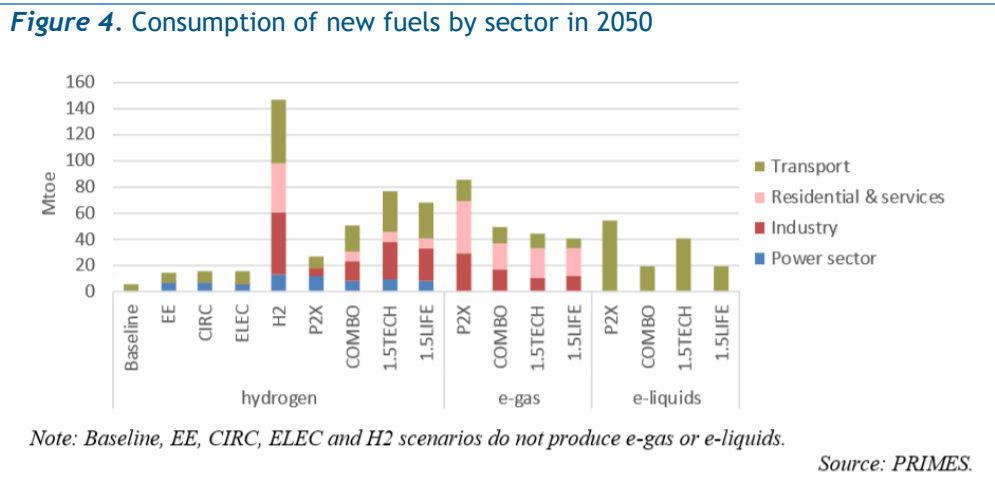
Source: Frontier Economic (2018)

In summary, e-fuels could play an important role in manufacturing chemical precursors, producing high-temperature process heat, as well as powering air, sea and possibly road transport.

In areas that are currently largely supplied with alternative energy sources, including passenger car traffic and the heating sector, competition will arise between low-carbon liquid energy sources and other options (for example, electricity-based systems).

According to Prognos, since liquid energy sources will continue to be needed, the development of the e-fuel technology path is a no-regret measure from a climate protection perspective and is therefore highly recommended as an additional alternative to reduce GHG emissions across the whole EU system [Prognos 2018].

This is aligned with the allocation of e-fuels to different sectors, according to *A Clean Planet for all* [European Commission 2018]. E-liquids are allocated to transport sector, and e-gas / e-hydrogen to transport, residential, industry and power sector.



Note: See detail of the different scenarios in EU long-term strategy *A Clean Planet for all* [European Commission 2018] in **Appendix A1-5**.

1.2.3. A look into e-fuels: types, uses and role in transport

In the sources reviewed, e-fuels are envisaged to play a major role in transport sectors where liquid energy sources are difficult to replace (e.g. air traffic, shipping and long-distance road haulage). Direct electrical power is not an option for mainstream air or maritime transport, according to today’s experts opinion².

In other areas that are currently largely supplied with liquid energy sources, including passenger cars, some references, such as Prognos suggest that competition will arise between low-carbon liquid energy sources and other options (for example, electricity-based systems) [Prognos 2018]. Others such as Cerology support that it is better not to consider vehicle electrification and e-fuels as competing climate solutions, but as complementary ones. Cerology states that e-fuel production for internal combustion engines is best thought of as a technology to reduce the impact of residual (or remaining) liquid fuels combustion during the long transition to electric mobility, rather than an endpoint in itself. Given that this transition will take many decades, there is still potential for e-fuels to make a considerable contribution to reducing greenhouse gas emissions from transport [Cerology 2017].

1.2.3.1. List of e-fuels and potential uses

Table 2 summarizes the list of e-fuels and their potential primary uses across different transport segments. The heading “Other sectors” includes industrial, heating, power generation, and domestic uses.

² Experts such as e.g. [Wartsila 2019], [IASA 2019], [Frontier Economics / Agora 2018].

Table 2. List of e-fuels and potential primary uses

	E-fuels	Passenger Cars	Heavy Duty	Maritime	Aviation	Other sectors (not transport)
Gas	e-Methane (CH ₄)	X	XX	XX		XXX
	e-Hydrogen (H ₂)	XX	XX	X		X
Liquids	e-Ammonia (NH ₃)		X	XXX		
	e-Methanol (CH ₃ OH)	XX	X	X		
	e-DME / e-OME	X	XX	XX		
	e-Gasoline	X				
	e-Diesel	X	XXX	XX		
	e-Jet					XXX

Xs as an initial estimate of the 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.

E-naphtha is not considered in this report. It is not envisaged that e-naphtha could be a possible route to low carbon fuels or even chemicals. Direct syngas to chemicals makes more sense than synthesize e-naphtha, only to then crack it again, unless transportation of feedstock is required.

Table 3. Properties of e-fuels³

	E-fuels	Density (kg/m ³)	RON/CN ⁴	LHV (MJ/kg) / MJ/litre	CO ₂ emission factor ⁵ (g CO ₂ /MJ burnt fuel)
Gas	e-Methane	0,782	-	46.6 / 0.04	56.2
	e-Hydrogen	0,084	-	120 / 0.01	0
Liquid	e-Ammonia	760	130	18.6 / 14.1	0
	e-Methanol	793	109 ⁶	19.9 / 15.8	68.9
	e-DME	670	55	28.4 / 19.0	67.3
	e-OME	1066	84	19.2 / 20.5	83.3
	e-Gasoline	748	95	41.5 / 31.0	73.3
	e-Diesel	780	53	44.0 / 34.3	70.8
	e-Jet	756	-	44.1 / 33.3	70.2

Table 4. Quick overview on e-fuels

	E-fuels	LHV	Storability	Additional infrastructure	Powertrain development
Gas	e-Methane	High	Difficult ⁷	No	No
	e-Hydrogen	High	Difficult	Yes	No ⁸
Liquid	e-Ammonia	Low	Easy	Yes	Yes
	e-Methanol	Low	Easy	No	Yes ⁹
	e-DME	Low	Easy	Yes	Yes
	e-OME	Low	Easy	Yes	Yes
	e-Gasoline	High	Easy	No	No
	e-Diesel	High	Easy	No	No
	e-Jet	High	Easy	No	No

Green = positive characteristics; yellow = negative characteristics.

³ These properties refer to conventional fossil fuels, due to lack of public available properties for e-fuels (properties are expected to be similar although more research is needed).

⁴ RON: Research Octane Number, CN: Cetane Number.

⁵ CO₂ emission factor is referred to fuel combustion.

⁶ Expressed as pure alcohol.

⁷ Storability issues depending on the increase of volume required.

⁸ Fuel Cell Electric Vehicles (FCEV) are commercially available, but are limited in number and it is difficult to assess if they will become a mainstream option.

⁹ E-methanol could be included in blend in gasoline, and possibly diesel, with no or very minor development of powertrain.

In **Appendix A1-2**, a more detailed comparison between advantages and disadvantages of each type of fuel is included.

A brief description of each one is detailed in this section:

a) **E-methane**

- **Properties:** Methane is the simplest hydrocarbon (CH₄), and is the main constituent of natural gas.
- **Use:** It can be used in industry, buildings and power. As a fuel for transport, it could be used as conventional compressed natural gas (CNG) and liquefied natural gas (LNG) in different transport modes, such as heavy duty and marine, and is compatible with existing powertrains.
- **Storage:** E-methane could use all or most natural gas related logistics, including transportation, storage and distribution systems. The use and injection in the natural gas grid is direct.

b) **E-hydrogen**

- **Properties:** Hydrogen has a very high specific energy (or gravimetric energy density), but a very low (volumetric) energy density. Even heavily compressed or liquefied, it still occupies four to seven times the volume of gasoline.

E-hydrogen could be directly injected into the natural gas grid up to a maximum level of 15% to lower the CO₂ intensity of the natural gas. Its high inflammability (range between the LEL and UEL¹⁰) creates difficulties for direct combustion if not in mixes, in heating appliances or furnaces.

- **Use:** It can be used in industry, buildings, power and transport sector. At present, about 70-80 Mton/a H₂ are produced annually for industrial uses, mostly for refining oil products (removing sulphur on increasing conversion into lighter products) and ammonia production, or as feedstock for nitrogen-based fertilizers, explosives, cleansers or refrigerant. Its current use as fuel is marginal, mostly in rockets and some fuel-cell vehicles. The Fuel cell hydrogen vehicles have been developed for passenger cars and available in the market, but market, but it is difficult to predict whether these will become a significant part of the future vehicle fleet, and the refuelling infrastructure is not in place yet across Europe.
- **Storage:** Storing hydrogen is not a simple matter. It can be stored as:
 - Compressed gas: Small amounts are usually stored at 35 to 70 MPa. Embrittlement of metals by H₂ dictates specific choices of materials. For example, on-board vehicles and stationary storages for building blocks or refuelling stations (up to about one ton) would use metallic or composite-reinforced polymer tanks. Other stationary options include metal hydrides, which store H₂ in a solid under moderate temperature and pressure that gives them a safety advantage, but they are heavy and can only store 1.8% hydrogen by weight.

¹⁰ Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL).

- Liquid hydrogen: It can also be stored as a liquid, although liquefaction at minus 253°C is a complex and energy-intensive process. Maintaining the fuel at low temperature requires continuous energy use.
- Surface absorption: hydrogen can be stored as a sorbate by attachment (adsorption) on materials with high specific surface areas. Such sorption materials include, among others, microporous organometallic framework compounds (metal-organic frameworks (MOFs)), microporous crystalline aluminosilicates (zeolites) or microscopically small carbon nanotubes. Adsorption materials in powder form can achieve high volumetric storage densities [Hydrogen Europe 2018].
- Inside salt caverns: Large amounts of hydrogen gas can be stored in underground salt caverns, at various pressure levels. Air Liquide operates the world's largest (300,000 m³) such storage in Texas. In Europe, a number of smaller salt caverns currently storing natural gas could be adapted for hydrogen storage.
- **Transportation:** Transporting hydrogen is also difficult. Its low volumetric density makes transport mode relatively energy-intensive in pipelines. Transport over long distances in large amounts would presumably take one of the three roads identified by the Japanese cross-ministerial program "SIP Energy carriers": cryogenic, liquid hydrogen; bound with carbon atoms in organic hydrides as methylcyclohexane, or bound with nitrogen in ammonia [Research Gate 2008].

The distribution cost of gaseous hydrogen (compressed) by trailers can be assessed at USD 1 to 4/kg - roughly doubling the price from large hydrogen producing plants. This may justify decentralized production from electrolysis, even if small-scale is costlier than large-scale.

- **Advantages versus the rest of e-fuels:**
 - No additional conversion of H₂ is needed
 - Less energy losses in conversion
 - No CO₂ as input required
 - Applications are relatively efficient (e.g. fuel cells)
- **Disadvantages versus the rest of e-fuels:**
 - Substantial investments in new infrastructure/conversion of infrastructure required
 - Investments in new applications or conversion of end-user applications at consumer side
 - International transport with additional significant energy losses due to compression or liquefaction
 - Applications such as fuel cells are (still) relatively expensive

c) **E-ammonia**

- **Properties:** Ammonia is the simplest hydride of nitrogen (NH₃), and is a colourless gas with a characteristic pungent smell. Ammonia has a boiling point of 33.5°C and quickly turns to a gas when exposed to air. Its specific energy is significantly lower than that of most conventional hydrocarbon fuels. It is toxic for lungs and eyes¹¹. Although accidents are infrequent, the risks associated with handling ammonia would likely

¹¹ Human volunteers exposed to ammonia showed slight irritation at 30 ppm (10 min); highly intense irritation at 110 ppm (30 min to 2 h), and excessive lacrimation and irritation at 500 ppm. Acute lethality studies in animals showed that the lethal concentration in 50% (LC50) of the rats ranged from 40,300 ppm for a 10-min exposure to 7,338 and 16,600 ppm for 60-min exposures. Source: [NCBI 2019].

restrict its uses to various professional environments, with training and specific equipment.

- **Use:** Ammonia has been used as a refrigerant for 170 years, and as a feedstock for nitrogen fertilizers for a century.

NH₃ can be also combusted in gas turbines, industrial furnaces or internal combustion engines, most likely after partial or complete thermal cracking into nitrogen and hydrogen to balance out its high ignition temperature - a safety feature.

Ammonia can be used as a mere hydrogen carrier, both for large-scale long haul transportation (e.g. in oceangoing tankers) and for distribution e.g. to refuelling stations for vehicles. However, full dehydrogenation, i.e. chemical and physical separation of species to produce hydrogen of extreme purity (“fuel cell grade”) is currently associated with significant losses. Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO) has road-tested its ammonia to hydrogen technology for hydrogen fuel-cells in two purpose-built hydrogen-cell cars [New Atlas 2018].

Figure 5. Toyota fuel cell vehicle, fuelled with ammonia to hydrogen



Source: [New Atlas 2018]

The CSIRO approach is to use a membrane reactor technology incorporated into a modular unit that can be installed at the fuel-cell car refuelling station. The membrane is designed to allow the smaller hydrogen molecules through while blocking the larger nitrogen molecules. This way, by passing a pressurized stream of a hydrogen/ammonia mix past the membrane, the output is purified hydrogen.

Direct use of ammonia in alkaline fuel cells is also possible, and commercialized by at least one company [GenCell 2019] but targeting the off-grid generation sector [IEA 2018], not focused on vehicles.

- **Storage:** ammonia is easily and indefinitely stored as a liquid at about 1 MPa, a very low pressure which does not require special high pressure tanks. But the infrastructure required for their extensive use as a fuel is not in place yet and it is claimed by experts such as Wartsila (specialized in designing engine-related solutions for different sectors) to be of the factors which could constrain their potential future use as fuel in some transport segments (e.g shipping).

d) E-methanol

- **Properties:** Methanol is the simplest alcohol (CH_3OH). It is liquid at normal temperature and pressure, and it is toxic¹².

Methanol has just half of the (volumetric) energy density of gasoline (based on the lower heating value (LHV)); i.e. 2 litres of methanol contain the same energy as one litre of gasoline. Its density corresponds to the density of most other liquid fuels, its boiling point is at 64.7°C . As a fuel methanol has a high-octane rating. Theoretically this would allow spark-ignition engines to run at higher compression ratios, which would be more efficient. The low cetane number for methanol makes it less suitable for diesel engines.

- **Use:** Global demand for methanol is about 80 Mton/a. The primary use is as a feedstock in the chemical industry. Under the Fuel Quality Directive, European fuels standard EN228 limits on the oxygen content of gasoline which then restrict the amount of methanol to a maximum of 3% vol for EU transport fuels [Celurology, 2017]. Up to 3 vol% methanol has been proven to have no adverse effects on the engine or material wear. For higher concentrations, a new fuel specification would be required [Dechema 2017]. China is the biggest methanol producer and consumer worldwide and has formulated national fuel standards for M15 and M85, which are motor fuels with methanol shares of up to 15% and 85% respectively.

As with e-ammonia, e-methanol is also considered as an option for decarbonisation of chemicals. As it has similar heating value and air/fuel ratio in combustion, the use of a mix of ammonia and methanol is also considered.

- **Storage:** it is very easy to store and ship, being liquid at normal temperature and pressure.

e) E-DME, e-OME

- **Properties:** DME (Dimethyl ether), also known as methoxymethane, is the simplest ether (CH_3OCH_3). As a diesel substitute DME has a cetane number of 55 which is higher than the European diesel specification EN 590. Despite moderate octane ratings, DME could in principle be used as admixture to Liquefied Petroleum Gas (LPG) for spark ignition engines. The lower heating value (LHV) of DME is lower than that for diesel. The boiling point is -24.8°C , i.e. DME is gaseous at room temperature. Therefore, for transport and use as fuel DME must be compressed.

DME can be used as a clean high-efficiency compression ignition fuel with reduced NO_x and particulate matter, it can be efficiently reformed to hydrogen at low temperatures, and is not considered toxic.

Oxymethylene ethers (OME) are more complex compounds of carbon, oxygen, and hydrogen ($\text{CH}_3\text{O}(\text{CH}_2\text{O})_n\text{CH}_3$). Due to their high oxygen concentration, they suppress pollutant formation in combustion.

OMEs' chemical properties depend on their chain length. Common features of OME fuels are: no carbon-carbon linkage and a high oxygen content between 42 - 48 wt%. Their volumetric energy density is low, but still exceeds that of methanol. OME fuels are not compatible with the existing fuel infrastructure and would deviate from current European

¹² 10 mL of pure methanol can cause permanent blindness by destruction of the optic nerve. The median lethal dose is 100 mL (i.e. 1-2 mL/kg body weight of pure methanol).

diesel specifications (EN 590, EN15940). Hence OMEs could only be used in small quantities as drop in fuels, which limits their potential for emissions reduction. Also, the materials compatibility of OMEs is unknown and approval would be needed for their use in existing vehicles. For high concentrations of OMEs, engine and fuel system would have to be fully adapted.

- **Use:** DME is used as propellant in aerosol sprays, but is also a potential substitute fuel for (modified) diesel engines, same as OME. For DME service in vehicles, only moderate modifications of engine and injection systems are required. So far mainly small commercial vehicle fleets (buses and heavy duty vehicles) have used DME as a transport fuel, especially to address air quality issues [Shell, 2018].
- **Storage:** DME and OME are gaseous at normal temperature and pressure, can be liquefied under modest pressure or cooling. This easy liquefaction makes them easy to transport and store.

Despite the potential role of these fuels, especially in the heavy duty segment, most of the publications do not consider e-DME and e-OME as part of their assessment. Ford is currently leading a 3.5 million euros research project, co-funded with the German government, to test cars running on OME and DME [Green Car Congress 2019].

f) E-Gasoline, e-Diesel and e-Jet

- **Properties:** Gasoline, diesel and jet have high energy density, which makes them excellent combustion fuels for road, maritime and aviation transport. The properties of e-gasoline, e-diesel and e-jet are sufficiently close to the conventional fuels produced in refineries and are zero sulphur. As such they are often categorized as “drop-in” fuels (fuels that could substitute crude oil derived products with no change in the customer applications).
- **Use: Fuels for combustion in engines.** No powertrain modifications are required when substituting current fossil fuels with their analogous e-fuels.
- **Storage:** they are easy to store and transport. Only minor changes may be required to the existing logistics for current fossil fuels, including transportation, storage, distribution systems, and powertrains.

1.2.3.2. Role of e-fuels in transport

Due to low conversion efficiency of e-fuels compared to direct electrification (see further details on efficiency in [section 2.1.2.7](#)), e-fuels are widely accepted to play a role for transportation sectors where there are limited electrification alternatives, such as marine and aviation. There is a wide consensus amongst experts that direct electrification is not an option for mainstream maritime or aviation transport. Nevertheless, there are differences of opinion and some controversy with respect to the future fuels for passenger cars and heavy duty transport.

a) Maritime Transport

To ensure that shipping is cleaner and greener, in April 2018, the International Maritime Organization [IMO 2019], adopted an initial strategy on the reduction of greenhouse gas emissions from ships, setting out a vision to reduce GHG emissions from international shipping and phase them out, as soon as possible in this century.

More specifically, under the identified “levels of ambition”, the initial strategy envisages a reduction in total GHG emissions from international shipping which, it says, should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008.

Under this strategy, apart from increasing energy efficiency in ships, the substitution of fossil fuels by low-carbon fuels will play a major role:

- Biofuels likely represent the least costly option for ship owners, as they require virtually no change in the ship machinery and storage. However, globally, there are uncertainties on the availability of sufficient volumes of sustainable biofuels.
- E-fuels such as e-diesel, e-LNG, e-ammonia and e-methanol today are all possible candidates for replacing marine fuels in long haul ocean-going ships.

The lack of an existing infrastructure and its toxicity are the main drawback for massive use of e-ammonia as transport fuel. For this reason, experts such as Wartsila (specialized in designing engine-related solutions for different sectors, including marine), do not forecast ammonia as a fuel for the maritime sector in the coming years, although they confirm that existing internal combustion engines could use ammonia as a fuel with relatively minor modifications [Wartsila 2019].

- E-hydrogen and direct electricity, may be suitable for shorter distance shipping, such as inland or cross channel voyages.

According to IEA, biofuels and e-ammonia are better options to long haul maritime transportation than e-hydrogen and electricity [IEA 2018].

b) Aviation

The Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA, aims to stabilize CO₂ emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020 [European Commission 2019].

During the period 2021-2035, and based on expected participation, the scheme plans to offset around 80% of the emissions above 2020 levels. This is because participation in the first phases is voluntary for states, and there are exemptions for those with low aviation activity. All EU countries will join the scheme from the start.

In this context, apart from increasing energy efficiency in airplanes, replacing conventional fossil jet fuel by an alternative low-carbon fuel would be part of the solution:

- Bio-jet from e.g. used cooking oil, algae, plastic wastes, etc. is an option, but there are very small quantities available compared to aviation market demand. Lufthansa was the first airline in the world to test bio-kerosene in regular flight operations in 2011 [Innofrator 2019].
- E-jet. Aviation is the transport mode in which the specific energy of the fuel, i.e. its ratio energy over weight, matters the most, and thus, where e-jet might prove the most useful solution.

Other solutions are not foreseen as technically feasible in the long term, as:

- Compressed hydrogen. Due to its low volumetric energy density, hydrogen would require four to seven times the space of jet fuel, and would require heavy storage cylinders.
- Full electrification. In aviation, this would be limited by battery mass¹³. There are some claims that battery powered flights are feasible, but for short journeys with light loads (e.g. air taxis).
- Liquid cryogenic gasses (liquefied hydrogen -LH₂ - and liquefied natural gas -LNG-). These technologies are conceptually feasible, but requires at least 4 times the tank volume compared to kerosene, and are also incompatible with existing aircraft and infrastructure. In 2050 LH₂ powered aircraft likely to only occupy a niche (at best case) [Lehman, H. 2018].

c) Long-distance heavy duty road transport

With respect to heavy trucks operating over extended distances, possible options are:

- Heavy duty trucks operating over long distances operated with overhead power lines (this will require very high infrastructural investments and limits vehicle flexibility)
- Hydrogen fuel cells (commercially available but subject to further infrastructure development)
- LNG
- Biodiesel
- E-diesel combustion engines, using existing infrastructure and powertrains. In this context, e-diesel could play a major role in the heavy duty segment.

Other solutions are not foreseen as technically feasible in a medium term, as full electrification. With respect to long-distance heavy duty, the vehicle batteries have not enough specific energy density as a single source of power. It means that either a huge (and therefore heavy) battery will be required or either the range driven would be limited, requiring to recharge the vehicle every few kilometres or installing a catenary / induction system in motorways.

d) Passenger cars and vans

In passenger cars, there are a number of emerging technologies that are likely to play a role in the future. Vehicles using full electric battery power, plug-in hybrids, hydrogen, compressed natural gas (CNG) or liquefied natural gas (LNG) have all entered the market as alternatives to gasoline and diesel fuels.

E-gasoline and e-diesel offer major advantages in road transport as they require only a minimal infrastructural change, and benefit from existing storage, distribution and refueling assets. Furthermore, these low carbon gasolines and diesel can reduce overall emissions from the existing vehicle fleet as well as new vehicles. As such these e-fuels represent one of the potential quickest pathways for decarbonisation.

¹³ The jet fuel capacity of a Boeing 787 Dreamliner is about 223,000 pounds. The estimated weight of a battery pack with equivalent energy would be 4.5 million pounds. Source: [Los Angeles Times 2016].

A diversity of opinions are expressed among the different sources:

- According to several references, e.g. Cerulogy, it is therefore best not to consider vehicle electrification and e-fuels as competing climate solutions, but as complementary one. Cerulogy considers that *e-fuel production for internal combustion engines is best as a technology to reduce the impact of residual (or remaining) liquid fuels combustion during the long transition to electric mobility, rather than an endpoint in itself. Given that this transition will take many decades, there is still potential for e-fuels to make a considerable contribution to reducing greenhouse gas emissions from transport* [Cerulogy 2017].
- Other references, as Prognos, suggests that competition will arise between low-carbon liquid energy sources and other systems (for example, electricity-based systems) [Prognos 2018].
- On the opposite side, references as Bellona, conclude that e-fuels would not play any role, and that efforts should be focused on developing sufficient infrastructure for electric vehicles and supporting interoperable policy development such as public procurement to facilitate the transition towards electric transport, instead of wasting resources on creating e-fuels with limited decarbonisation potentials [Bellona 2017]. This opinion is shared by Transport and Environment and Frontier Economics who state that e-fuels have no role to play in passenger cars, where better alternatives for direct electrification exist ([Transport and Environment 2017], [Frontier Economics/Agora 2018]). A charging infrastructure for light-short distances vehicles, such as light utility vehicles, municipal buses, and trucks operating over short distances, is also easier to envisage than the same for longer distance road vehicles.

2. TECHNOLOGY ASSESSMENT

2.1. TECHNOLOGY

2.1.1. Feedstock-related technologies

2.1.1.1. CO₂ capture

The production of e-fuels requires carbon dioxide which can be obtained from various sources, including biomass combustion, industrial processes (flue gases from fossil oil combustion), biogenic CO₂ and CO₂ captured directly from the air.

The CO₂ emitted during e-fuel combustion is equal to the CO₂ absorbed during e-fuel production.

The following section covers the technologies currently in development and consider their advantages and disadvantages [Frontier Economics/Agora 2018], [dena 2018], [FVV 2016]:

- **Capture from biomass combustion:** Higher concentrations of CO₂ ranging from 10 to 13% can be found in flue gas from solid biomass fired heaters [dena 2018].

The current state-of-the-art technology is to extract CO₂ from flue gas via scrubbing with amines such as monoethanolamine (MEA) or advanced proprietary amine-based solvent formulations. Recent examples in the industry are the Boundary Dam capture project in Canada, that has adopted the *Cansolv capture process*, and the Petranova project in USA, which is using the Mitsubishi Heavy Industries's capture process (both based on aqueous amine proprietary solvents).

The scrubbing agent washes the CO₂ from the gas stream, and is regenerated through heating. Another process is to wash out the CO₂ from the gas stream via scrubbing with K₂CO₃ solution. The CO₂ concentration in the scrubbing agent is then increased via electrodialysis and the CO₂ stripped out by a vacuum pump.

Another process uses a combination of PSA (Pressure Swing Adsorption) and TSA (Temperature Swing Adsorption), technologies used to separate some gas species from a mixture of gases under pressure and temperature, respectively, according to the species' molecular characteristics and affinity for an adsorbent material.

Table 5 shows the energy demand for various methods of extracting CO₂ from flue gases.

Table 5. Energy demand for various methods of extracting CO₂ from flue gases

	Unit	MEA	Next-generation solvent	Absorption/ electrodialysis	PSA/TSA
CO ₂ content	-	12,8%	11%	10%	10-13%
Heat	MJ/kg CO ₂	3.84-4.30	n.d.a.	-	n.d.a.
Electricity	MJ/kg CO ₂	0,033	n.d.a.	0.756	n.d.a.
Total	MJ/kg CO ₂	3,873-4,333	2.5	0.756	2.016
Temperature	°C	97	120	-	n.d.a.

Source: [dena 2018]. n.d.a.: no data available

Note: In Technology Centre Mongstad (Norway) many new advanced solvents have been tested. Flue gas from a Combined Heat and Power unit (CHP) with a CO₂ content below 4% was used as a CO₂ source. Employing a proprietary amine solvent, the specific reboiler duty was reduced to 3.4 MJ/kgCO₂ from the 3.8 MJ/kgCO₂ obtained with a standard MEA aqueous solution.

Costs are considerably lower for capture from biomass combustion than for CO₂ extracted via direct air capture since the CO₂ is more concentrated in the stream. Different sources claim that CO₂ can be captured from biomass at a current cost of from **90 €/t** [Frontier Economics/Agora 2018].

- **Capture from industrial processes (such as refineries) or power generation plants:** The CO₂ content of concentrated sources such as flue gas, blast furnace gas and coke-oven gas ranges from 2% (coke-oven gas) to 18% (blast furnace gas) [dena 2018].

Technologies to extract CO₂ from them are similar to the previous case.

- Advantage: Again, this option to capture CO₂ is cheaper than direct air capture as the CO₂ is at a higher concentration. CO₂ can be captured from the emissions of industrial processes at a cost from **30-50 €/t CO₂** [Frontier Economics/Agora, 2018] to **100 €/t** [ICCT 2018], in the case of the most concentrated/easy-to-capture sources. Power generation plants based on natural gas (or even coal) or Steam Methane Reformers (SMR) units are a potential concentrated source to capture CO₂ (typical CO₂ concentration in the flue gas (i.e.: 3.5 - 4% vol.)).
- Disadvantage: there are controversial opinions/concerns about the total carbon-neutrality of the CO₂, especially if the fuel input from the industry is based on fossil energy sources such as oil products or natural gas. Even in those cases, significant CO₂ savings could be achieved compared with the use of a purely fossil-based fuel (see **Figure 21**, in **chapter 2.1.3.**)¹⁴.

Technically, WTT CO₂ abatement potential is similar if CO₂ comes from direct air capture or from a concentrated source [JEC 2019].

Sintef analyses the cost of retrofitting CO₂ capture from refineries [Sintef 2017]. Sintef's assessments focus on retrofit costs, including modifications in the refineries, interconnections, and additional combined heat and power (CHP) and utility facilities. The results of the cost evaluation of the CO₂ capture cases shows that the cost of retrofitting CO₂ capture lies between 160 and 210 \$/ton CO₂ avoided, depending on the CO₂ concentration in flue gases.

¹⁴ Although there are controversial opinions/concerns about the total "carbon-neutrality" of the CO₂, especially if the fuel input from the industry is based on fossil energy sources such as oil products or natural gas.

Table 6. CO₂ avoidance cost of retrofitting CO₂ capture from refineries

CO ₂ avoidance cost (\$/t _{CO₂,avoided})	Characteristics
210	Very low CO ₂ concentration in flue gas (4-5%) coupled with a small amount of CO ₂ captured (around 750 kt _{CO₂/y})
200-180	Low to medium CO ₂ concentration in flue gas (6-9%), very low amount of CO ₂ captured (300-600 kt _{CO₂/y}), significant fraction of the flue gases require FGD (50-100%) or a combination of these factors
180-170	Low to medium CO ₂ concentration in flue gas (6-9%), low amount of CO ₂ captured (600-750 kt _{CO₂/y}), small fraction of the flue gases require FGD (20-50%) or a combination of these factors
170-160	medium to high CO ₂ concentration in flue gas (10-18%), large amount of CO ₂ captured (2000-3000 kt _{CO₂/y}), small fraction of the flue gases require FGD (<10%) or a combination of these factors

Source [Sintef 2017]

- **Biogenic CO₂** sources include biogas-upgrading plants, CO₂ from ethanol plants, and CO₂ from the combustion of biogas.

The CO₂ content of biogas ranges from 25 to 55% (dena, 2017). The CO₂ can be separated from the biogas stream via scrubbing with amines or via pressure swing adsorption (PSA). Both technologies provide high CO₂ purity (99%). Alternatively, if methane is the desired product, the biogas stream including the CO₂ is fed directly into a methanisation reactor (direct methanisation) in which the CO₂ fraction is converted to methane. The methane gas is swept through the methanisation reactor like an inert gas. In this case, no CO₂-separation step is required.

- Advantage: In this type of technology, CO₂ is more concentrated in the stream.
- Disadvantage: Sustainable biogenic CO₂ is available only in limited quantities and is particularly scarce in dry regions best suited for wind and PV power generation.
- **Direct Air Capture (DAC):** various technologies are being currently investigated to extract CO₂ from the air where the CO₂ content is ≈ 0.04% (dena 2017):
 - a) Absorption + Electrodialysis
 - b) Absorption + Calcination
 - c) Adsorption/desorption (Temperature Swing Adsorption process (TSA))

a) Absorption + Electrodialysis

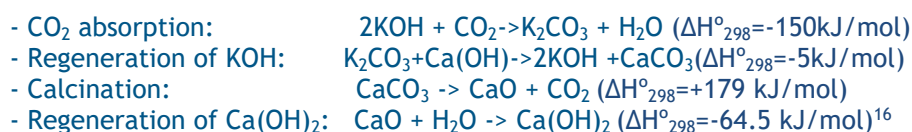
According to FVV (2016), extracting CO₂ from the air is done via absorption or “scrubbing” using either sodium hydroxide (NaOH) or potassium hydroxide (KOH), which are converted to the carbonated forms (Na₂CO₃ or K₂CO₃), respectively. The carbonates are subsequently decomposed via electrodialysis (ZSW process).

- CO₂ absorption: CO₂ + 2 NaOH → Na₂CO₃ + H₂O (ΔH₂₉₈^o=-109 kJ/mol)
- Stripping: Na₂CO₃ + H₂SO₄ → Na₂SO₄ + CO₂ + H₂O (ΔH₂₉₈^o=-56 kJ/mol)
- Electrodialysis: Na₂SO₄ + 2 H₂O → 2 NaOH + H₂SO₄ (ΔH₂₉₈^o=112 kJ/mol)

At a current density of 100 mA per cm² of electro dialysis cell area¹⁵ the electricity consumption for the whole process including fan blower amounts to 430 kJ per mole of CO₂ [FVV 2016].

b) Absorption + Calcination

The process which has been developed by the Canadian company [Carbon Engineering 2019], consists of CO₂ absorption with KOH, formation of CaCO₃ from K₂CO₃ and regeneration of the CaCO₃ via calcination and subsequently conversion to Ca(OH)₂. The following reactions occur:



Carbon Engineering indicates a natural gas consumption of about 10 MJ per kg of CO₂. The theoretical minimum heat requirement for the calcination reaction amounts to about 4.1 MJ per kg of CO₂ [FVV 2016].

The calcination process requires very high temperatures (900°C) to convert the CaCO₃ back to CaO to recover the CO₂ [Keith D. 2018].

In 2015, [Carbon Engineering 2019] started operations in its full end-to-end pilot plant, located in Squamish (Canada). This facility captures roughly 1 ton of atmospheric CO₂ per day. In 2017, Carbon Engineering incorporated fuel synthesis capability into the DAC pilot plant and converted the captured CO₂ into fuel for the first time in December, 2017.

Technology has been proven at Carbon Engineering's pilot plant and are now being scaled up into commercial markets. Carbon Engineering claims that individual DAC facilities could be built to capture 1,000,000 tons of CO₂ per year. At that scale, one Carbon Engineering air capture plant could negate the emissions from ~250,000 cars - either by sequestering the CO₂ or by using the recycled carbon dioxide as a feedstock to produce e-fuels.

c) Adsorption / desorption (Temperature Swing Adsorption process (TSA))

The Swiss company Climeworks, Direct Air Capture technology provider, uses an adsorption/desorption cycle to extract CO₂ from the air. The CO₂ is chemically bound on a sorbent (in contrast to most adsorption processes, the Climeworks process uses chemisorption instead of physisorption) [Climeworks 2019].

The regeneration of the sorbent is carried out by low temperature heat (95°C). The process can also be referred to as a temperature swing adsorption (TSA) process.

TSA involves capturing the CO₂ in a filter and then releasing it from the filter using heat (using mainly low-grade heat as an energy source) to around 100°C (212°F). The CO₂ is then released from the filter and collected as concentrated CO₂ gas to supply to customers or for negative emissions technologies. CO₂-free air is released back into the atmosphere. This continuous cycle is then ready to start again. The filter is reused

¹⁵ The specific electricity consumption depends on the current density of the electro dialysis plant. The higher the current density the higher is the specific electricity consumption.

¹⁶ Sources: [Frank Zeman 2017] <https://pubs.acs.org/doi/pdf/10.1021/es070874m>, https://www.scirp.org/pdf/IJCCE20120100002_68811201.pdf.

many times and lasts for several thousand cycles. The electricity consumption of the plant is, on average, 0.9 MJ/kg (CO₂).

Table 7. Examples of Climeworks DCA plants

	DAC-1	DAC-3	DAC-18	DAC-36
Number of CO ₂ collectors	1	3	18	36
CO ₂ Capacity nominal (kg/day) ¹⁷	135	410	2,460	4,920
Footprint excl. options (m ²)	20	20	90	180

Source: [Climeworks 2019]

In **Table 8**, a comparison of energy requirement is made among the technologies:

Table 8. Comparison of various technologies for the extraction of CO₂ from air

	Unit	ZSW	PARC	Carbon Engineering	Climeworks
Technology		Absorption/ Electrodialysis	Absorption/ Electrodialysis	Absorption/ Calcination	Absorption/ Desorption
Natural gas	MJ/kg CO ₂	-	-	10 ¹⁸	-
Heat	MJ/kg CO ₂	-	-	-	5.4-7.2
Electricity	MJ/kg CO ₂	8.2 - 12.3	6.8	-	0.72-1.08
T (heat)	°C	n.a.	n.a.	> 850	
CO ₂ purity		> 99%	> 99%		> 99.5%

Source: [FVV 2016], [dena 2017]

Note: Carbon Engineering needs a high temperature heat source for the calcination step, which is very unlikely to be found in the industry. That is the reason why Carbon Engineering has included a natural gas burner with pure oxygen (oxy-combusting) from an Air Separation Unit in their calcination process step. Carbon Engineering is currently working on electric furnace version of the design but this will require additional power [Carbon Engineering 2019].

Advantage: renewability for e-fuels produced with CO₂ from DAC is guaranteed.

Disadvantage: CO₂ concentration in air is low (ppm order of magnitude: 387 ppm, or 0.0387%), which makes this by far the most expensive carbon capture technology to supply CO₂ - reported costs range from 100 €/t [Frontier Economics/Agora 2018] to 300 €/t [dena 2018], [FVV 2016] by 2050. In **Table 9** a summary of CO₂ sources used by different references to do their assessments is given.

¹⁷ It will vary with factors such as temperature, humidity and air composition.

¹⁸ Natural gas used for heat and electricity supply.

Table 9. CO₂ source approach followed by different references

Main references	CO ₂ source for their assessments
[Frontier Economics/Agora 2018]	DAC
[FVV 2016]	DAC + Concentrated source
[ICCT 2017]	Concentrated source
[ICCT 2018]	DAC + Concentrated source
[Prognos 2018]	DAC
[Cerulogy 2017]	Concentrated source
[LBST and dena 2017]	DAC
[Dechema 2017]	Concentrated source

In **Appendix A1-4**, tables are included showing the different CO₂ capture costs according to different origins and sources.

- **CO₂ purification**

Pure CO₂ with a very low oxygen content is needed to avoid damaging the catalysts used for methanisation and Fischer-Tropsch synthesis. Also low water concentrations are needed in order to avoid corrosion problems of the material of the CO₂ pipelines (typically carbon steel), due to the production of carbonic acid [IOP Science 2018].

The CO₂ is purified via liquefaction. The temperature of liquefied CO₂ is about -25 °C at an elevated pressure, and the purity amounts to 99.999% (vol.). The oxygen content after liquefaction is less than 5 ppm, which is sufficient for the catalysts used in methanisation and synthesis [dena 2018].

As an example, dena shows the technical and economic data for the CO₂ liquefaction plant in Lüdinghausen (Germany) (**Table 10**).

Table 10. CO₂ liquefaction plant, including storage, in Lüdinghausen, Germany

Parameter	Value
Capacity	2,300 kg CO ₂ /h
Production	17,000 ton CO ₂ /year
Electricity consumption	3.5 GWh/year
Storage capacity	300 ton (3 tanks, each 100 ton)
Investment	3.5 million euros

Source: [FVV 2016]

2.1.1.2. Hydrogen electrolysis

E-hydrogen (also called green hydrogen) is also a feedstock for producing the rest of e-fuels (or it can be a final product as itself). It is produced by electrolysis from water.

There are different hydrogen electrolysis technologies. Hydrogen electrolysis can be carried out using low-temperature processes (at 50 to 80°C) or high-temperature processes (700 to 1000°C).

Commercially available, low-temperature processes include alkaline electrolysis (AEC) and proton exchange membrane electrolysis (PEM). In comparison, currently high-temperature electrolysis (SOEC) is less well developed.

The **Table 11** summarizes some key parameters of these technologies:

Table 11. Efficiency and system sizes

		AEC	PEM	SOEC
Today	Efficiency, kWelec/kg H ₂	50-73	47-73	37
	H ₂ production capacity per cell, Nm ³ H ₂ /h	0.25-760	0.01-240	40
	kWelec	1.8-5,300	0.2-1,150	100
2030 +	Efficiency, kWelec/kg H ₂	48-63	44-53	37
	System sizes, MW	500 MW installations	MW (stacks) ¹⁹	MW (stacks) ¹⁹

Source: [Dechema 2017]

a. Alkaline Electrolysis (AEC)

This is the state-of-the art industrial process for electrolytic hydrogen production. Rather than pure water, a 20-40% solution of KOH is used and the electrodes coated with Ni as catalyst. Both half-cells are separated via a diaphragm to prevent mixing of the gaseous products. Alkaline electrolysis can be applied at normal pressure or under pressure of up to 30 bars.

About 4% of global hydrogen production is based on this process.

In terms of further technical advancements, by 2050 a few percentage points in the area of efficiency can be expected.

Even if alkaline electrolysis is considered as a ‘mature’ technology, production volumes are still low. It is expected that cost reductions can be leveraged through increased production volumes.

b. PEM-electrolysis

Over the last 20 years, PEM (Polymer Electrolyte Membrane) electrolysis has been developed. In contrast to the alkaline version, it uses water and no treatment or recycling of the KOH solution is necessary. PEM stacks are very compact and can be designed for pressures up to 100 bars. PEM electrolysis also demonstrates a very good dynamic behaviour, which allows them to

¹⁹ Scale-up is to be realized by numbering-up of stacks.

follow, for example, the power-profile of a wind turbine without significant delay.

The main drawbacks of this technology are the investment costs which are dominated by the high costs for materials like Pt and Ir. Whilst the first units have been operating successfully for some years, a full life-cycle under operational conditions has not yet occurred. This technology is at the core of Audi's e-gas project, where wind turbines provide electricity for a PEM electrolyser. Hydrogen then reacts with CO₂ separated from biogas to produce methane which is fed into the natural gas grid.

For PEM electrolysis, investment costs are expected to drop significantly as production experience increases and alternative, cheaper catalysts are developed. Current PEM electrolyser installations reach up to 6 - 112 MW power [Siemens 2018]. Further technological development is expected to boost the performance of this technology significantly and therefore enhance the installed capacities by at least one order of magnitude. The system cost of PEM electrolysers is currently about twice that of alkaline systems.

c. High-temperature solid-oxide electrolysis (SOEC)

Higher temperature electrolysis at around 700-1000°C can reduce the electricity requirements as the energy needs can be covered in part by heat input.

The temperature range requires different materials whilst the cell membrane is a ceramic material capable of conducting oxygen ions. This technology could be most appropriate for industrial sites with significant waste heat sources.

High-temperature electrolysis (SOEC - ion conducting solid oxide electrolysis) are already offered by companies such as Sunfire who offer modular designs [Sunfire 2018].

A fundamental drawback of high-temperature electrolysis is its lack of flexibility compared to low-temperature electrolysis. This impairs the use of the SOEC electrolysis in combination with fluctuating renewable energy.

In the case of methanisation, methanol synthesis and Fischer-Tropsch synthesis, heat is generated as a by-product, which could be used as an input for SOEC electrolysis (capturing the CO₂ input for the conversion from the air, however, also requires heat input, leading to competition for heat resources).

2.1.2. E-fuels technologies

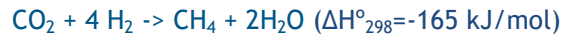
2.1.2.1. E-fuels conversion technologies

Most e-fuels conversion routes (except from e-hydrogen or e-ammonia) consist of e-hydrogen reacting with captured CO₂ to produce clean syngas consisting of hydrogen and carbon monoxide.

Syngas can further be processed to produce different type of fuels: e-methane, e-ammonia, e-methanol, e-DME/e-OME, e-gasoline, e-diesel and e-jet.

2.1.2.2. E-methane

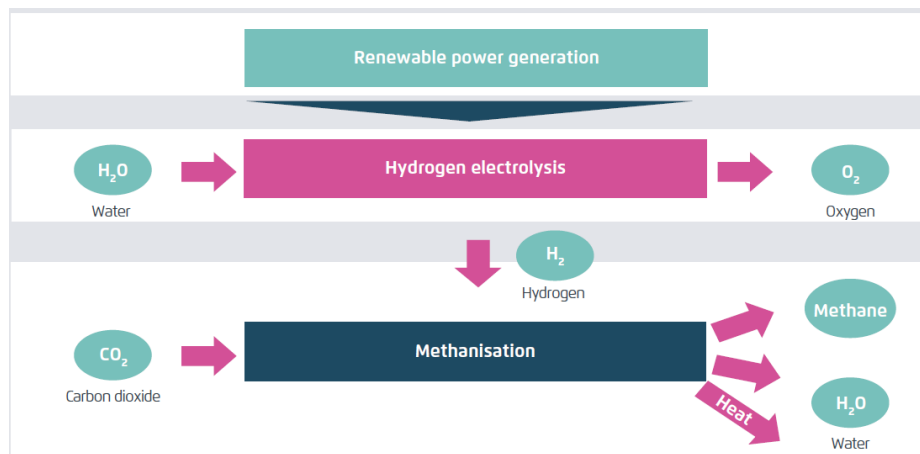
In the process of methanisation, methane (CH₄) and the by-products water (H₂O) and heat are generated from carbon dioxide (CO₂) and e-hydrogen (H₂). It is called the Sabatier reaction of methanisation:



This reaction is the exact inverse of the steam methane reforming process.

The waste heat from methanisation can be used as the input for capturing CO₂ from the air or flue gases (concentrated sources). As an example, Frontier Economics (2018) assumes in their calculation that this waste heat would be sufficient to cover all of the heat requirements for Direct Air Capture (DAC) plants.

Figure 6. Conversion of electricity to e-methane



Source: [Frontier Economics/Agora 2018]

Today, methanisation is largely based on a catalytic (thermochemical) process, although biological methanisation is also currently under development.

- **Catalytic methanisation**
Catalytic methanisation is carried out at 300 to 550°C, usually using a nickel-based catalyst. Good heat recovery is possible for catalytic methanisation. Even in stand-by mode, the temperature of the methanisation plant must always exceed about 200°C.
- **Biological methanisation**
Biological methanisation is carried out at 30 to 70°C via micro-organisms suspended in an aqueous solution. These micro-organisms absorb CO₂ and hydrogen through their cell walls and convert them to water and methane. Biological methanisation (as most biological processes) has a lower overall efficiency and a lower rate of reaction than catalytic methanisation.

Due to lower rates of methane formation, larger reactors are also required, thus making biological methanisation primarily suitable for small-sized production plants.²⁰

²⁰ Small size is assumed to be a threshold (typical size of a biofuels plant) of 10,000 bbl/d (300 kton/a). That, in terms of e-fuels, would require around 900 kton/a CO₂.

Due to the fact that biological methanisation is still under development, has a lower degree of efficiency, and is also more suited to small-scale production (at least for the time being), references such as Frontier Economics (2018), do not consider this option further in their cost calculations.

The assumed degree of efficiency for converting hydrogen to methane is 80%. The production of one kilowatt hour of methane requires 0.198 kilogram of CO₂.

2.1.2.3. E-Ammonia

The principal commercial method of producing ammonia is by the Haber-Bosch process:



Today, most methanol is produced from natural gas reforming and coal gasification. There is currently a combined production capacity of 110 million ton methanol/a (90 plants).

Ammonia synthesis is an exothermic reaction that requires the use of a catalyst, high pressure (100-1000 atm), and elevated temperature (400-550 °C).

The estimated energy consumption rate of a Haber-Bosch plus electrolyser plant is estimated in 12 kWh / kg NH₃ [Bicer, Y. and Dincer, I. 2017]. The energy consumption of Haber-Bosch ammonia synthesis is considered as 2 kWh per kg NH₃. Some additional key parameters related to the technologies are also described below:

- Haber Bosch efficiency is around 86% [Brown T. 2017].
- Nitrogen is supplied through air separation process where there is additional electrical work required.
- Cryogenic air separation is the preferred technique for large scale nitrogen manufacture. Cryogenic air separation process becomes more cost effective compared to non-cryogenic methods at the level of 200-300 tons/day nitrogen production.
- Commercial cryogenic air separation plants require electricity in the range of 0.6-1 kWh per kg of liquid nitrogen product [Bicer, Y. and Dincer, I. 2017].

According to Dechema, the individual technologies are available and the system integration should be relatively straightforward, nevertheless combination of electrolysis with ammonia synthesis is not at the commercial stage and a certain level of heat integration will be lost in such a setup [Dechema 2017].

The **Table 12** shows a comparison between fossil and low carbon e-ammonia production.

Table 12. Energy demand of fossil and low carbon ammonia production

per ton of NH ₃	Fossil (SMR + NH ₃ synthesis)	Low carbon (power to NH ₃)
Energy feedstock (GJ)	21	-
Fuel demand (GJ)	10.9	-
Electricity (GJ)	0.74	38.9
Compressors	5	5
Other utilities	1.7	1.19
Steam balance (GJ)	-4.3	0
Total energy demand (GJ)	35.04	45.1

Source: [Dechema 2017]

2.1.2.4. E-Methanol

The alternative low-carbon pathway to methanol is again based on hydrogen, produced by water electrolysis with low-carbon electricity followed by hydrogenation of CO₂ as carbon source.

- Electrolysis: $6 \text{ H}_2\text{O} + \text{renewable electricity} \rightarrow 6 \text{ H}_2 \text{ (cathode)} + 3 \text{ O}_2 \text{ (anode)}$
- Hydrogenation: $2 \text{ CO}_2 + 6 \text{ H}_2 \rightarrow 2 \text{ CH}_3\text{OH} + 2 \text{ H}_2\text{O}$ ($\Delta H_{298}^\circ = -40.9 \text{ kJ/mol}$)

Methanol synthesis is a commercially proven process. The first methanol synthesis plant, using syngas made from coal, was commissioned in 1923 in Leuna, Germany [Shell 2018].

Methanol synthesis processes can be differentiated according to the pressure, the type of reactor and the catalysts used. The most common process today is the relatively low-pressure synthesis which operates at pressures between 50 and 100 bar and temperatures of 220 to 280°C. The catalysts usually consist of copper/ zinc oxide and are typically very active and selective. The selectivity to methanol of this process is close to 100%. However, the single-pass conversion is low, and recycling of the syngas is needed to achieve high yields. The chemical reaction of hydrogen and carbon dioxide is exothermic, and the reaction heat can be recovered and used for the downstream methanol distillation and / or other processes such as regeneration of the sorbent used to capture CO₂.

E-methanol can be produced from CO₂ in one or two steps. In the latter case, CO₂ is converted to CO with the reverse water gas shift (RWGS) reaction, followed by hydrogenation of CO into methanol. In one step, these two reactions take place simultaneously with direct methanol synthesis. The resulting product mixes methanol and water that needs then to be distilled.

For the hydrogenation of pure CO₂ to e-methanol, catalysts are commercially available, and a number of pilot plants are in operation, e.g. by Mitsui Chemicals (Japan) and Carbon Recycling International (Iceland) to investigate the feasibility of industrial-scale production.

- ✓ Carbon Recycling International in Iceland produces renewable methanol using almost entirely decarbonized electricity from the Icelandic grid and CO₂ captured in geothermal power plant, which would otherwise be vented. The potential for expansion is however limited [Carbon Recycling International 2018].
- ✓ Sunfire is producing methanol in Dresden in co-electrolysing carbon dioxide and water in solid oxide electrolyzers to deliver syngas, thus bypassing the reverse water gas shift reaction otherwise necessary - recycling CO₂ from industrial fluxes [Sunfire 2018].

Alternative concepts to produce conventional CO/H₂-syngas are in an early development phase and include direct electrochemical reduction of CO₂ and electrocatalytic co-reduction of CO₂ to CO and water to hydrogen. These concepts are investigated in a number of research institutes on lab-scale, their TRLs are therefore relatively low (TRL 1-3).

The **Table 13** shows a comparison between fossil and low carbon methanol production.

Table 13. Energy demand of fossil and e-methanol production

per ton of NH ₃	Fossil (SMR + NH ₃ synthesis)	E-methanol
Energy feedstock (GJ)	25	-
Fuel demand (GJ)	13.9	-
Electricity (GJ)	0.6	34.3
Utilities (GJ)		5.4
Steam balance (GJ)	-2	0
Total energy (GJ)	37.5	39.7
Feedstock related CO ₂ emissions (ton)	0.97	-0.79
Process emissions (ton)	0.52	0.123
Total emissions (ton)	1.49	-0.67

Source: [Dechema 2017]

2.1.2.5. e-DME/e-OME

The methanol can either be used directly or converted further to monoconstituent fuels such as OME (oxymethylene ether) and DME (dimethyl ether, CH₃OCH₃).

a. e-DME

DME can be readily synthesized through dehydration of methanol over ordinary solid acid catalysts such as phosphoric acid modified alumina g-Al₂O₃.



As potential alternative options that are yet to be commercially proven, DME can also be produced directly from syngas in a single reactor - with methanol still as an intermediate molecule in the reaction - or from CO₂ hydrogenation over a bifunctional catalyst with both methanol synthesis and methanol dehydration activity.

²¹ Source: <https://www.longdom.org/open-access/catalytic-dehydration-of-methanol-to-dimethyl-ether-dme-using-the-alcufe-quasicrystalline-alloy-2157-7048.1000164.pdf>.

In the e-fuel case where CO₂ is the original carbon source, the direct hydrogenation of CO₂ to DME avoids the CO formation. Furthermore, the single-pass conversion of CO₂ will be significantly higher than the case of CO₂ reduction to methanol, as the thermodynamic equilibrium is shifted favourably. There are some bio-DME prototype vehicles [Volvo 2010].

Figure 7. Example of DME fueled-vehicles



Project BioDME, 2012, Sweden BioDME

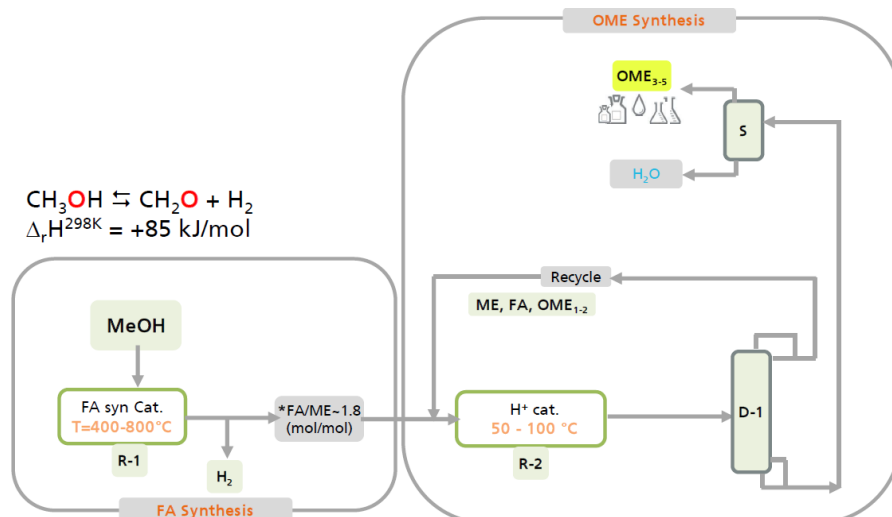
Source: [Volvo Group 2019], [Volvo 2010]

b. e-OME

Alternatively, methanol can be converted into poly (oxymethylene) dimethyl ethers, also called Oxymethylene ethers (OMEn). While there are various processes currently under investigation, only OME1, also known as methylal or dimethoxymethane, is produced in commercial quantities in Europe via a catalytic 2-step-process. The first step is the oxidation of methanol to formaldehyde, which is followed by the subsequent condensation of formaldehyde with an excess of methanol to yield OME1 (CH₃-O-CH₂O-CH₃).

Current industrial synthesis routes (e.g. in China) to higher molecular OMEs (n = 2-5) are based on OME1 and trioxane in the presence of a heterogeneous catalyst. Trioxane itself is produced commercially by the trimerization of formaldehyde. Another pathway under investigation is the synthesis from methanol and formaldehyde directly in the presence of an acidic catalyst in an aqueous solution.

Figure 8. Anhydrous formaldehyde as key step for OME Synthesis



Source: [Franhoffer ISE 2018]

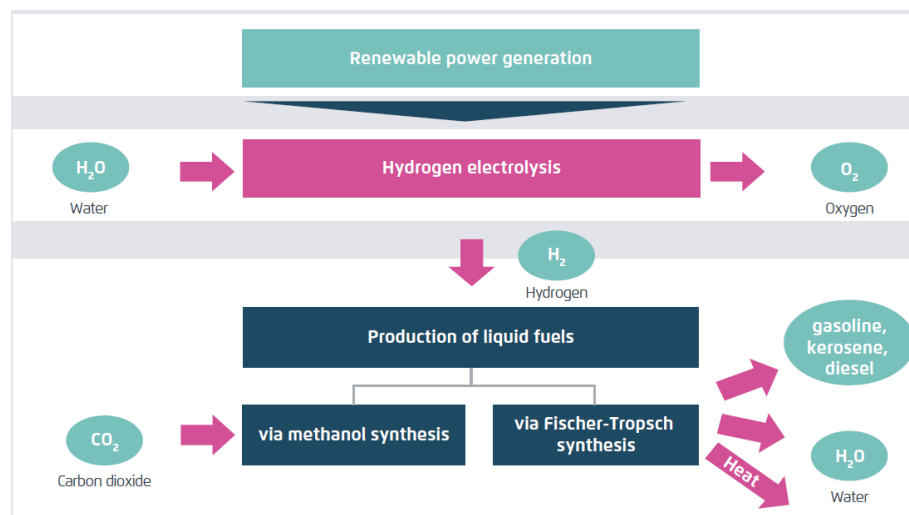
The direct synthesis of dimethylether (DME) from CO₂ process should allow for a CO₂ reduction potential of 0.125 t CO₂ /t DME compared to the current state-of-the-art process with an intermediate methanol stage, corresponding to a 30% reduction. This process is under investigation at lab scale, with substantially lower Technology Readiness Level (TRL).

2.1.2.6. Liquid e-fuels (e-gasoline, e-diesel, e-jet)

Synthetic gas (syngas) produced from electricity-based hydrogen and CO₂ can be used in Fischer-Tropsch / methanol synthesis for the production of e-liquid fuels as e-gasoline, e-diesel and e-jet.

There are two possible processes to synthesize these liquid hydrocarbon e-fuels.

Figure 9. Main processes to synthesize e-liquid fuels



Source: [Frontier Economics/Agora 2018]

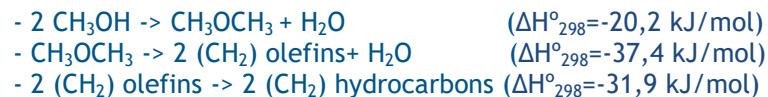
1) Via methanol synthesis

As methanol cannot be directly used as a fuel in existing vehicles fleets, it can be processed further into gasoline via the Methanol-to-Gasoline process (MTG). This process was developed in the 1970s by Mobil, and several variants using fixed or fluidized reactors were developed by other technology providers [Shell 2018].

The Mobil technology was applied in the New Zealand MTG plant to produce 570,000 tons of gasoline per year from 1985 to 1997. The concept has also been tested in parts of what is now Shell's Rhineland Refinery, the biggest refinery in Germany.

In China, the one-step MTG process (direct conversion from MeOH to gasoline in one reactor) has been tested at a plant with a capacity of 200,000 tons of gasoline per year, and a commercial plant using the Exxon Mobil technology (500,000 tons of gasoline per year) is now under construction [Shell 2018].

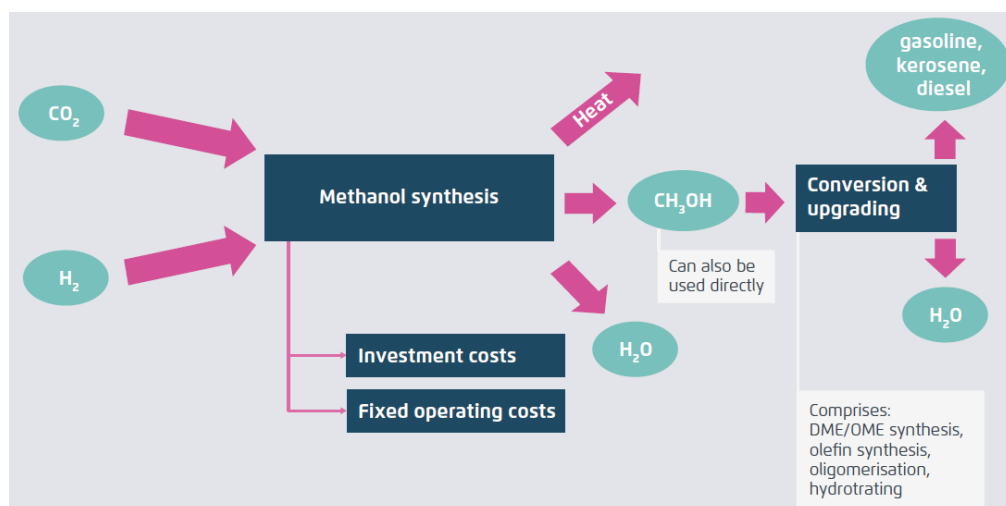
First, methanol (CH_3OH) is catalytically dehydrated to obtain a mixture of dimethyl ether (DME), methanol, and water ($\Delta H^\circ_{298} = -20,2 \text{ kJ/mol}$). This mixture is then fed into an MTG reactor, in which methanol and DME are completely dehydrated by a catalyst (ZSM-5), to form light olefins (and water) ($\Delta H^\circ_{298} = -37,4 \text{ kJ/mol}$). Light olefins oligomerize into higher olefins, to ultimately form paraffins, naphthenes, and methylated aromatics ($\Delta H^\circ_{298} = -31,9 \text{ kJ/mol}$) (Total $\Delta H^\circ_{298} = -89,5 \text{ kJ/mol}$)²².



The MTG catalyst limits the hydrocarbon synthesis reactions to approx. C11 hydrocarbons. Although the process is relatively selective (86% weight selectivity to gasoline, EM 2017), the raw product is split into several streams. The heavier components such as durene in the heavy gasoline fraction have to be (partially) separated, or alternatively be converted through mild hydrotreating to give the product the required specifications [FVV 2016].

The final MTG product is an ultra-low-sulfur, low-benzene octane gasoline. MTG gasoline properties are close to the properties of gasoline produced at refineries, and can be relatively easily upgraded to EN 228 standards by adding oxygenates. MTG gasoline matches ASTM D4814, the US specification for gasoline.

Figure 10. Liquid fuel production via methanol synthesis



Source: [Frontier Economics/Agora 2018]

2) Via Fischer-Tropsch synthesis

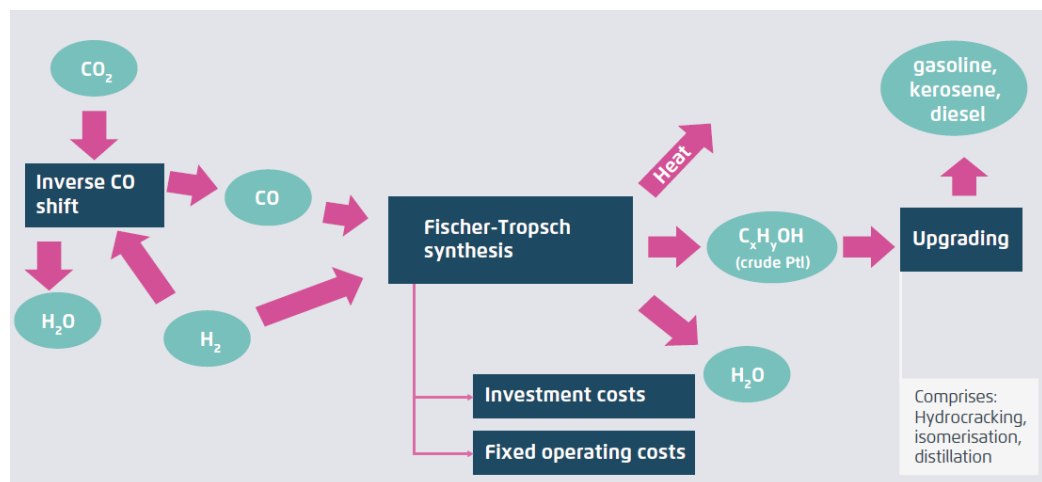
Fischer-Tropsch synthesis was developed in the 1920s. It converts a mixture of hydrogen (H_2) and carbon monoxide (CO), also called syngas, to hydrocarbons. Fischer-Tropsch technology has been further developed since then. It has been deployed in a number of different forms including both High and Low Temperature Fischer-Tropsch (HTFT

²² Source: [Eindhoven University of Technology, 1981, <https://pure.tue.nl/ws/files/2268508/30334.pdf>].

and LTFT) processes, predominantly using variations of iron and cobalt as Fischer-Tropsch catalysts.

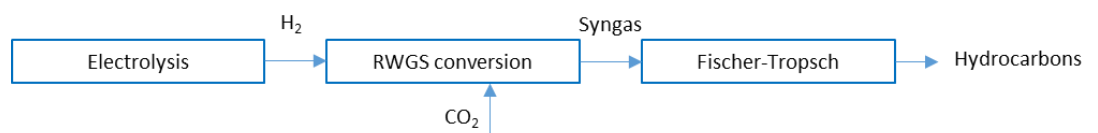
Today, large-scale commercial Fischer-Tropsch processes can be found in Malaysia, Qatar, China, South Africa and Nigeria using both natural gas as a feedstock for Gas-to-Liquids (GTL) plants or coal as a feedstock for Coal-to-Liquids (CTL) plants [Shell 2018].

Figure 11. Liquid fuel production via Fischer-Tropsch synthesis



Source: [Frontier Economics/Agora 2018]

The simplified reaction sequence is as follows (3 stages):



- Electrolysis: $3 \text{H}_2\text{O} + e^- \rightarrow 3 \text{H}_2 + 1.5 \text{O}_2$ ($\Delta H_{298}^\circ = 237 \text{ kJ/mol}$)
- Reverse Water Gas Shift (RWGS): $\text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CO} + 2\text{H}_2 + \text{H}_2\text{O}$ ($\Delta H_{298}^\circ = -40.6 \text{ kJ/mol}$)
- Fischer-Tropsch: $\text{CO} + 2 \text{H}_2 \rightarrow -\text{CH}_2- + \text{H}_2\text{O}$ ($\Delta H_{298}^\circ = -165 \text{ kJ/mol}$)

Source: [Dechema 2017]

Water is also produced during the reduction of CO to a CH₂-group by the addition of hydrogen during Fischer-Tropsch synthesis. After biological treatment, this water is available for re-use within the facility either as a process stream or an utility stream.

The Reverse Water Gas Shift (RWGS) is a well-known reaction, taking place as an additional reaction in HVO commercial plants, during the desoxygenation of the vegetable oils in the production of biodiesel [Haldor Topsoe 2016], [Bhabani Prasanna Pattanaik 2017]. Besides, RWGS reaction is similar to the reaction occurring in the steam methane reformers. However, the reaction is known but the process to

convert CO₂ in CO is not yet to an industrial level and needs further R&D efforts to be made commercially available²³.

Recent developments are evolving from 3 to 2 stage process. Sunfire has announced a new technology (co-electrolysis) where CO₂ and steam are fed into a high-temperature (solid-oxide) electrolyser to produce syngas in a single step [Sunfire 2019].

Upgrading of raw Fischer-Tropsch product (“wax”) to meet the demand for different lighter products resembles refinery hydrocracking, providing options from low-level co-processing to complete Hydrocracker transformation. Second option using FCC for upgrading may be more suited to integrated fuels/chemicals production [Concawe 2019. Refinery 2050 report]

The resulting e-gasoline and e-diesel are close to drop-in fuels which have almost the same chemical composition as fossil fuels and could replace them completely.

This route also produces naphtha, but with poor properties for use as a gasoline due to its low octane rating²⁴.

According to FVV [FVV 2018b], the compatibility of these e-fuels with the existing engines is 100% (Figure 12).

²³ To avoid the RWGS reaction, some announced projects rely on the synthesis of methane from CO₂ and e-hydrogen in a “methanization” reactor before feeding it to a GTL (gas-to-liquid)-technology. GTL process then consists of 3 steps:

- 1) Syngas production from natural gas (partial oxidation of methane): $\text{CH}_4 + \text{O}_2 \rightarrow 2 \text{H}_2 + \text{CO}$ ($\Delta H^\circ_{298} = -319$ kJ/mol)
- 2) Fischer-Tropsch reaction: Syngas (CO & H₂) → Hydrocarbons
- 3) Cracking + isomerization of hydrocarbons

Syngas can be produced from natural gas via catalytic processes based on steam reforming of methane (SRM) or partial oxidation of methane (POM). Some of the pros/cons of POM versus SMR are:

Pros	Cons
POM is an exothermic reaction, and has reduced capital and operation costs versus SMR, which is an endothermic reaction, and requires high investments	POM is a less efficient than SMR for syngas production. POM produces less hydrogen per unit of the input fuel than is obtained by SMR of the same fuel.
POM is much faster than steam reforming and requires a smaller reactor vessel.	POM needs oxygen, and the cost of its production is about 50% of the investment of the whole process.
POM has proved advantageous for small scale operation where efficiency is not such an issue. Here the low overall cost, compactness and low operating temperatures are a real advantage.	There is a high risk of explosion at an elevated temperature.

Sources: [K. Tamião de Campos Roseno 2018], [Yousri M.A.Welaya 2012], [S.A. Amelie Glas 2013]

²⁴ Further research could be done to find other commercial possibilities for this product.

Figure 12. Compatibility with existing stock

Compatibility with existing stock (max. admixture in %)				
	Gasoline	Diesel	LPG	CNG
Battery electric*	-	-	-	-
Hydrogen	-	-	-	2
E-fuels				
DME	-	-	-	-
OME	-	-	-	-
Methane – compressed (LD/HD)	-	-	-	100
Methane – liquid (HD)	-	-	-	-
Methanol (M100)	3	-	-	-
FT gasoline**	100	-	-	-
FT diesel**	-	100	-	-
FT propane**	-	-	100	-

Source: [FVV 2018b]

In **Figure 13**, provided by Shell, qualities of liquid e-fuels can be compared with standard fuels. The main product for use as a transport fuel is a diesel substitute, compliant with the EN 15940 European standard for paraffinic fuels and in fact, is very close to the EU standard diesel specification EN 590. Although paraffinic fuels have a lower density than EN 590-diesel, they may have significantly higher cetane numbers of 70 or more and are nearly free from aromatics [Shell 2018].

To be compatible with the existing vehicles (such as Methanol-to-Gasoline) e-fuels would have to meet existing fuel standards (i.e. EN 228 or EN 590). In the following sections we call these fuels “drop-in fuels”.

Figure 13. Liquid e-fuel qualities (compared to standard fuels)

12 COMPARISON OF PTL FUELS WITH RELEVANT EN 228 FUEL PROPERTIES ...

	Gasoline fuel EN 228:2012	Methanol-to- Gasoline	Methanol	Ethanol
Research Octane number	≥ 95	92	114	130
Density @15 °C (kg/m ³)	720 - 775	728 - 733	792	789
Reid vapour pressure (kPa)	45 - 60 (summer class A)	62	13	6
Oxygen content (%m/m)	≤ 3.7	n.a. *	50	34.7
Oxidation stability (Min)	≥ 360	260 - 370	n.a.	n.a.
Aromatic content (%v/v)	≤ 35.0	26.5	0	0
Distillation (°C)	≤ 210	29 - 209	65	78
Typical lower heating value (MJ/kg)	42.7 - 44.2	n.a. *	22.7	29.7
Typical flash point (°C)	-20	n.a. *	9	12

* Likely similar to EN 228 Gasoline based on the other properties; n.a. = data not available

EN 228; Maus et al. 2014; EM 2017

... AND WITH SELECTED EN 590 FUEL PROPERTIES

	EN 590: 2013	EN 15940: 2016	DME	OME ₁	OME ₃	OME ₄	OME ₅	OME ₆
Cetane number	≥ 51	≥ 70	55 - 60	28	72	84	93	n.a.
Density @15 °C (kg/m ³)	820 - 845	765 - 800	660	863	1035	1079	1111	1140
Polycyclic aromatic hydrocarbons (%m/m)	≤ 8	<1.1*	0	0	0	0	0	0
Flash point (°C)	> 55	> 55	-41	-32	54	88	115	n.a.
Lubricity, HFRR (60 °C) (µm)	460	460	n.a.	759	534	465	437	n.a.
Kinematic viscosity (40 °C) (mm ² /s)	2 - 4.5	2 - 4.5	0.12 - 0.15**	0.36**	0.87	1.33	1.96	n.a.
Distillation (°C)	Ca. 180 - 360	Ca. 180 - 360	-24.8	42	155.9	201.8	242.3	273
Typical lower heating value (MJ/ kg)	42.9	44.1	28.4	23.3	19.6	19.0	18.5	17.7
Typical Oxygen content (%m/m)	< 1	< 0.5	34.8	42.1	48 ± 1		49.5	

* Likely to be 0 due to EN 15940 specified Total Aromatic Content ≤ 1.1 %m/m

** Measured @ 25 °; n.a. = data not available

Shell 2015; Lautenschütz et al. 2016; Wachtmeister et al. 2017

Source: [Shell 2018]

As Shell explains, whilst methanol is a potential gasoline substitute, its Lower Heating Value (LHV) is significantly lower than the one of gasoline and even ethanol. The EU Fuels Quality Directive (FQD) limits methanol to a maximum of 3% v/v in gasoline. The use of pure methanol or higher blend rates requires adapted vehicles; hence methanol does not have drop-in capabilities. Even more, the World-Wide Fuel Charter (WWFC 2013) does not permit methanol in all their five categories of gasoline, because methanol is an aggressive material that can cause corrosion of metallic components of fuel systems and can degrade plastics and elastomers.

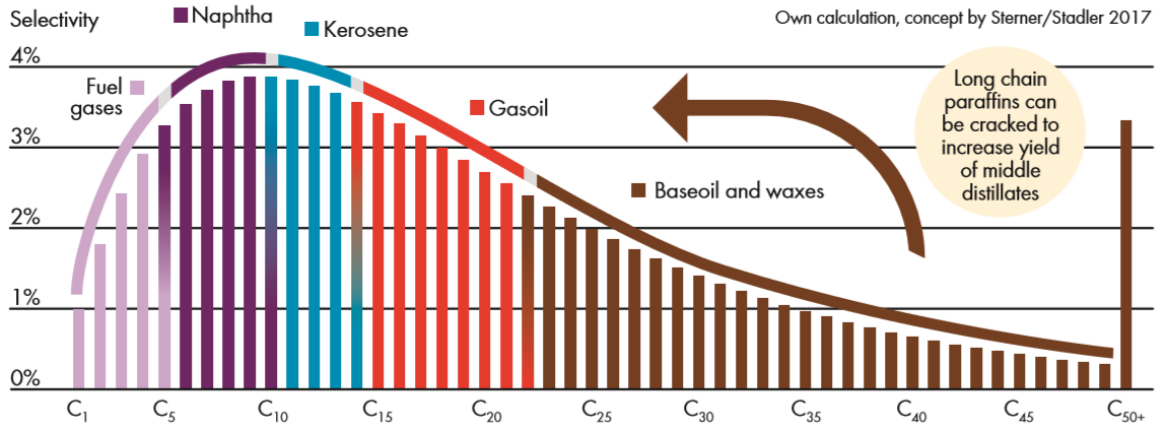
Methanol's emission characteristics vary with engine design and show lower NO_x emissions, no particulate matter, lower VOC but potentially higher direct formaldehyde emissions (EPA 2002). Another vehicle emissions study showed increased aldehyde-emissions and directionally higher regulated emissions (CO, NO_x, HC) with M15 compared to standard gasoline.

As already described in Section 2.1.2.6. above, the product of the Methanol-to-Gasoline (MTG) process is a much better substitute for gasoline in spark-ignition engines and represents a gasoline blending component that can be easily upgraded to full EN 228 compliance.

Fischer-Tropsch e-fuels for compression ignition (diesel cycle) engines are paraffinic fuels with drop-in capabilities, fitting largely in the diesel standard EN 590. Paraffinic fuels have substantially higher cetane numbers (≥ 70) and are (nearly) free from aromatics. Only their density is slightly lower than EN 590 determines. Paraffinic fuels are standardized by the EU fuel specification EN 15940.

Besides the product specifications, yields are also an important factor. Production of liquid e-fuels using the Fischer-Tropsch process results in a mix of fuel gases, naphtha/gasoline, kerosene, diesel/gasoil, base oil and waxes. **Figure 14** 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. The more valuable fraction of material has more than five carbon atoms (C₅+) [Shell 2018].

Figure 14. Fischer-Tropsch liquid e-fuel products



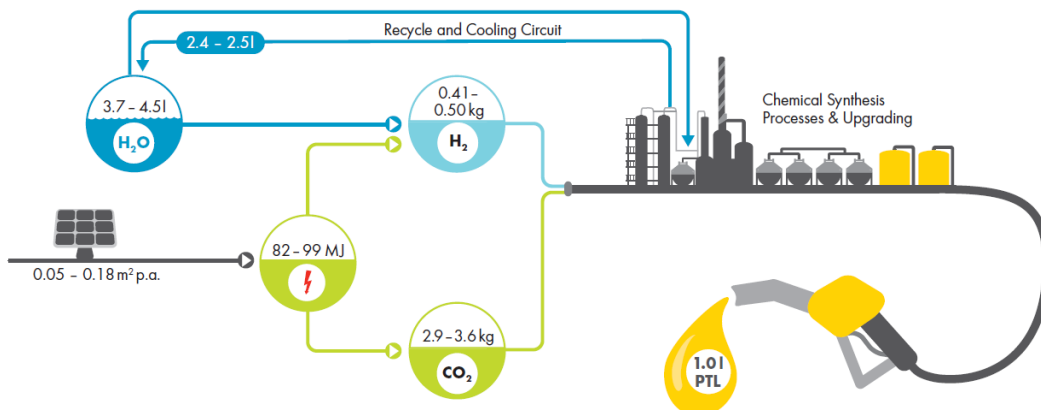
Source: [Shell 2018]

The resulting “e-crude” from the Fischer-Tropsch, which can be a single stream or several separate streams, is 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, jet and gasoil fractions.

Like Shell, Ceruly indicates that maximising diesel or jet fuel yield requires tuning catalyst and process to preferentially produce the correct length of hydrocarbon for a given application. In general, it is not possible to produce 100% molecules of any given class from a fuel synthesis process, so industrial liquid e-fuel processes will yield a range of molecules that may be more suitable for gasoline, diesel or aviation kerosene use. However, the product mix could be shifted towards one preferred product [Ceruly 2017].

Shell also shows a mass balance to produce 1 litre of liquid e-fuel, requiring 3.7-4.5 l of water, 82-99 MJ of renewable electricity and 2.9-3.6 kg of CO₂.

Figure 15. Resources required for liquid e-fuel production



Source: [Shell 2018]

3) Fischer-Tropsch versus methanol synthesis

Having looked at the technical features of liquid e-fuel production, what are the key differences and similarities between the Fischer-Tropsch (FT) and methanol (MeOH) route?

The two principal conversion pathways start with the same feedstock (water, CO₂, and renewable power) to produce syngas (H₂ and CO₂). However, both pathways obtain different liquid e-fuels: 1) FT in combination with hydrocracking mainly produces naphtha, diesel or kerosene and 2) methanol synthesis followed by MTG produces gasoline.

In contrast with FT route, methanol synthesis can tolerate higher amounts of CO₂ in the feed, or even use 100% CO₂ as a carbon feedstock. This is relevant as it may affect the design of the CO₂ Capture or RWGS unit.

FT processes produce an intermediary product (“syncrude”) with a distribution of long-chain hydrocarbons which is tailored by a hydrocracking step to produce final products. The MeOH synthesis, in contrast, is highly selective and mainly gives methanol as a product. Methanol is subsequently selectively converted into products via a series of processing steps to produce gasoline. However, both processes need final upgrading steps after the main conversion to produce fuels that comply with current fuel specifications.

Finally, both routes display similar overall process efficiencies (power-to-fuel), which vary between 30% to 45% (MJ fuel/MJ primary energy), depending on the integrated design and the technology selection. The precise efficiency is ultimately affected by many factors, among which the size of the plant, the selected conversion technology, operating conditions, etc.

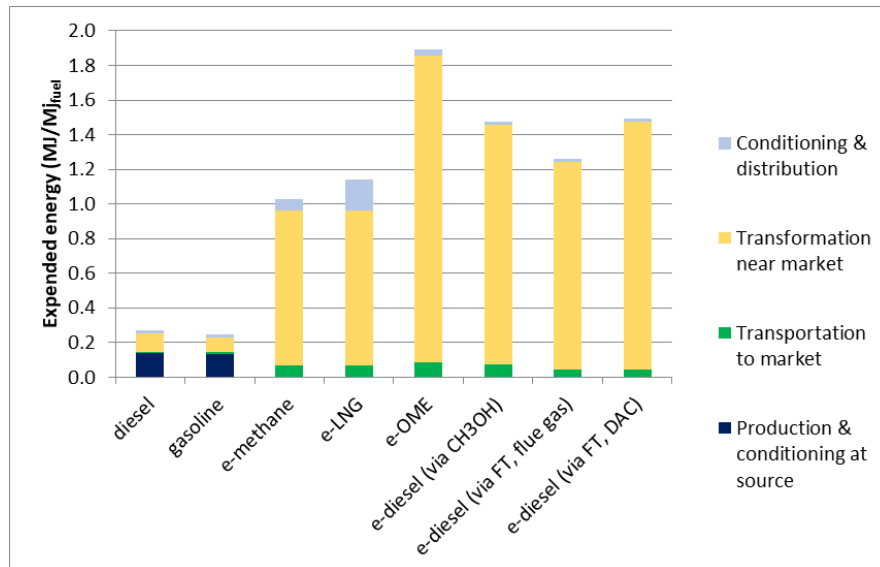
Whereas FT processes have been developed mainly to produce waxes, fuels and lubricants, the naphtha and LPG from FT process can be used for chemical feeds too. MeOH synthesis is also run to obtain feedstock for chemicals.

2.1.2.7. Efficiency

In the JEC consortium, the expended energy (MJ per MJ of fuel) is quantified for different e-fuels compared to fossil diesel and gasoline [JEC 2019].

In the following graph, it is shown how the WTT energy requirement of 0.2 MJ/MJ of fossil diesel is increased up to 1.2 - 1.5 MJ/MJ for e-diesel (6-8 times more). The main differences are in the transformation near market stage, meaning crude refining for fossil fuels and hydrogen electrolysis + e-fuel synthesis for the e-fuels.

Figure 16. Expended energy, MJ per MJ fuel. Additional energy expended to produce 1 MJ of fuel



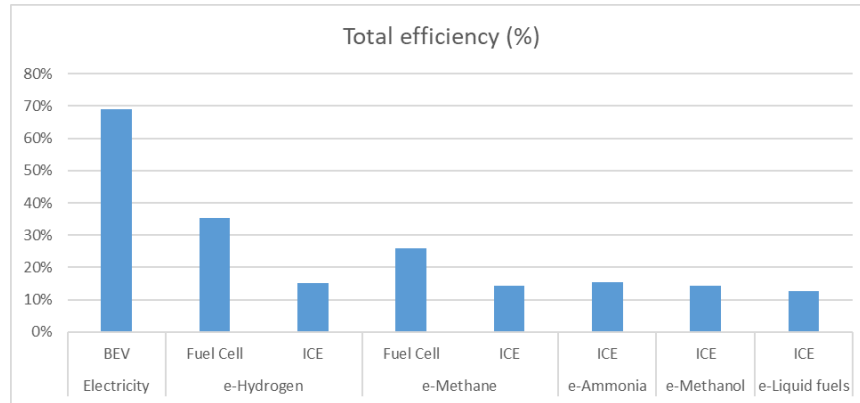
Source: [JEC 2019]

Note: CO₂ equivalent also includes CH₄ emissions in the case of fossil diesel and gasoline. Expended energy for fossil LNG is 0.26 MJ/MJ, as a reference.

Table 14. Description of each pathway

Fuel	Description [JEC 2019]
Diesel	Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.
Gasoline	Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.
e-methane	e-methane (as CNG) from renewable electricity and CO ₂ from flue gases
e-LNG	e-methane (as LNG) from renewable electricity, CO ₂ from flue gases
e-OME	Renewable electricity to oxymethylene ether (OME) via methanol synthesis, and OME synthesis (CO ₂ from biogas upgrading)
e-diesel (via CH ₃ OH)	Renewable electricity to Syndiesel via methanol (CO ₂ from flue gases)
e-diesel (via FT, flue gas)	Renewable electricity to Syndiesel high temperature (HT) electrolysis based on SOEC and FT route (CO ₂ from flue gases)
e-diesel (via FT, DAC)	Renewable electricity to Syndiesel high temperature (HT) electrolysis based on SOEC and FT route (CO ₂ from direct air capture)

Figure 17 compares a range of e-fuels using a Well-to-Wheel (WTW) approach. The figure shows the e-fuels final efficiency in engines (WTW approach) while Table 15 shows the efficiency in each intermediate conversion step.

Figure 17. E-fuels final efficiency in engines (WTW approach)

Table 15. E-fuels WTW energy efficiency

	Electricity	e-Hydrogen		e-Methane		e-Ammonia	e-Methanol	e-Liquid fuels
	BEV	Fuel Cell	ICE	Fuel Cell	ICE	ICE	ICE	ICE
WTT								
Renewable power	100%	100%		100%		100%	100%	100%
Transmission eff.	95%	95%		95%		95%	95%	95%
Electrolysis eff.	-	70%		70%		70%	70%	70%
e-Hydrogen	-	67%		67%		67%	67%	67%
Methanisation eff.	-	-		80%		-	-	-
Ammonia syn, HB eff.	-	-		-		86%	-	-
Methanol synthesis eff.	-	-		-		-	80%	-
Fischer-Tropsch eff.	-	-		-		-	-	70%
Transport eff. ²⁵		80%		80%		95%	95%	95%
e-Methane	-	-		43%		-	-	-
e-Ammonia	-	-		-		54%	-	-
e-Methanol	-	-		-		-	51%	-
e-Liquid fuels	-	-		-		-	-	44%
TTW								
Battery eff.	90%	-	-	-	-	-	-	-
Fuel cell eff.	-	82% ²⁶	-	75%	-	-	-	-
Electric motor eff	85%	85%	-	85%	-	-	-	-
ICE, eff	-	-	30%	-	30%	30%	30%	30%
Mechanical eff.	95%	95%	95%	95%	95%	95%	95%	95%
WTW								
Total efficiency	69%	35%	15%	26%	14%	15%	14%	13%

Source: Concawe assessment based on [Frontier Economics/Agora 2018] efficiencies
 Electrolysis efficiency can vary from 63% [Bicer, Y. 2017] to 70% [Dechema 2017].
 BEV: Battery Electric Vehicle, ICE: Internal Combustion Engine

²⁵ Transport including compression in the case of hydrogen and methane.

²⁶ Fuel cell efficiency can vary from 60% [Frontier Economics/Agora 2018] to 82% [Hasely Y 2018].

In comparison terms, a battery-electric vehicle has a total overall efficiency (from the power generation point to the final user) of 69% and a fuel cell vehicle of 26-35%, meanwhile a liquid e-fuel engine car efficiency is around 13-15% (Frontier Economics, 2018). The whole efficiency of the production of an e-diesel including their use in an internal combustion engine is only 15% meaning that for 1 MJ of renewable power, only 0.15 MJ are finally effectively used to power the vehicle (including losses in electricity transmission, conversion process, internal combustion engine and mechanical losses in the powertrain).

Battery-driven vehicles are thus four-five times more efficient than combustion engines that run on renewable e-fuels. This means that a combustion-engine vehicle would need five times as much renewable electricity as a battery-driven vehicle to travel the same distance.

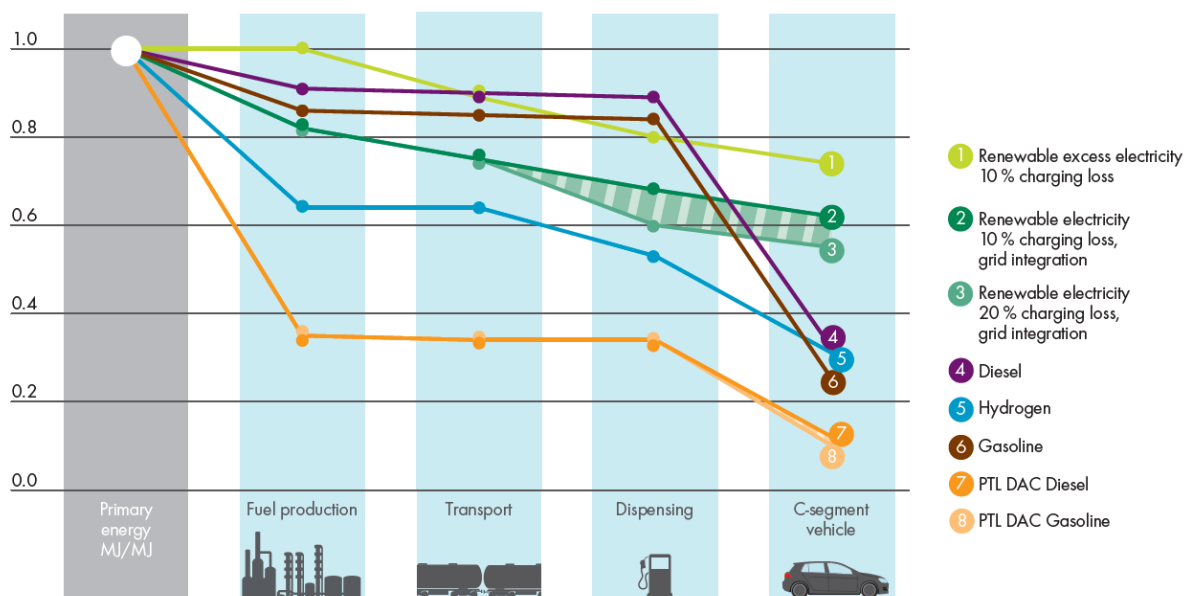
As mentioned in different parts of the report, WTW energy efficiency is the basis for some of the negative claims in relation to e-fuels (e.g. [Bellona 2017] or [Transport & Environment 2017]).

However, other sources as Cerulogy claim that even if production of e-fuels is not as energy efficient as direct supply of electricity for electric drive vehicles, it still offers an important opportunity to produce very low-CO₂ fuels with a significant opportunity to reduce GHG emissions in transport [Cerulogy 2017].

As mentioned at the beginning of this report, 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 in the engine, using much of the current distribution infrastructure).

The following figures show the WTW total efficiency of light duty and heavy duty vehicles with different fuels - powertrains. Liquid e-fuels have efficiencies around 15%, lower than the others fuels - powertrains [Shell 2018].

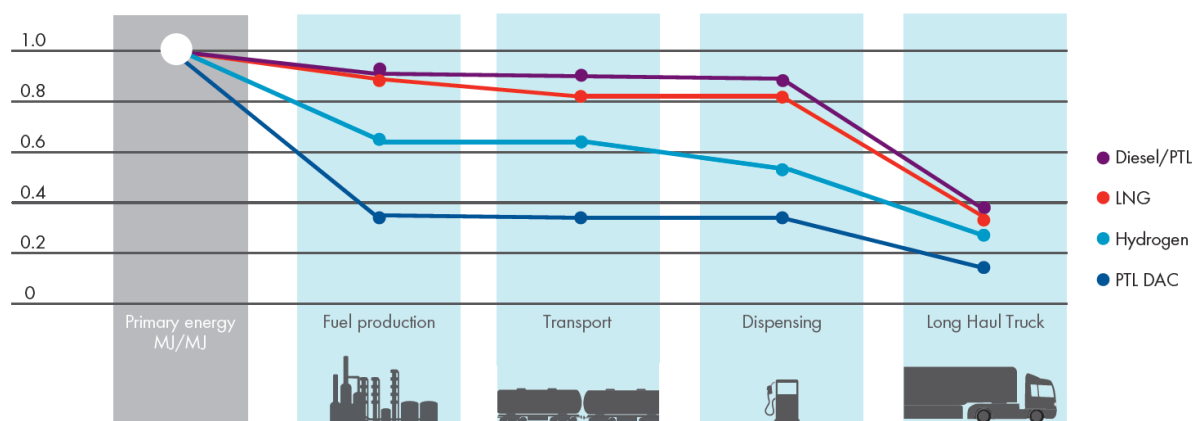
Figure 18. Cumulated fuel-powertrain efficiency for light duty vehicles



Source: [Shell 2018]

Note: The Power-to-Liquid pathways assume renewable power generation in a favourable region, with low temperature electrolysis (LTE) hydrogen production, CO₂ capture from air (DAC) and fuel synthesis. The liquid e-fuel production (incl. hydrogen production, CO₂ capture and chemical synthesis) achieves an overall efficiency of 35%. Transport and distribution drops the chain efficiency to this point only marginally to 34%. Losses for filling the tank are assumed negligible. A diesel internal combustion engine is assumed to have a 36% efficiency leading to a WTW efficiency of 12% for this liquid e-fuel pathway. For a gasoline engine with an efficiency assumed of 30% the overall pathway's efficiency would be just 10%.

Figure 19. Cumulated fuel-powertrain efficiency for heavy duty vehicles



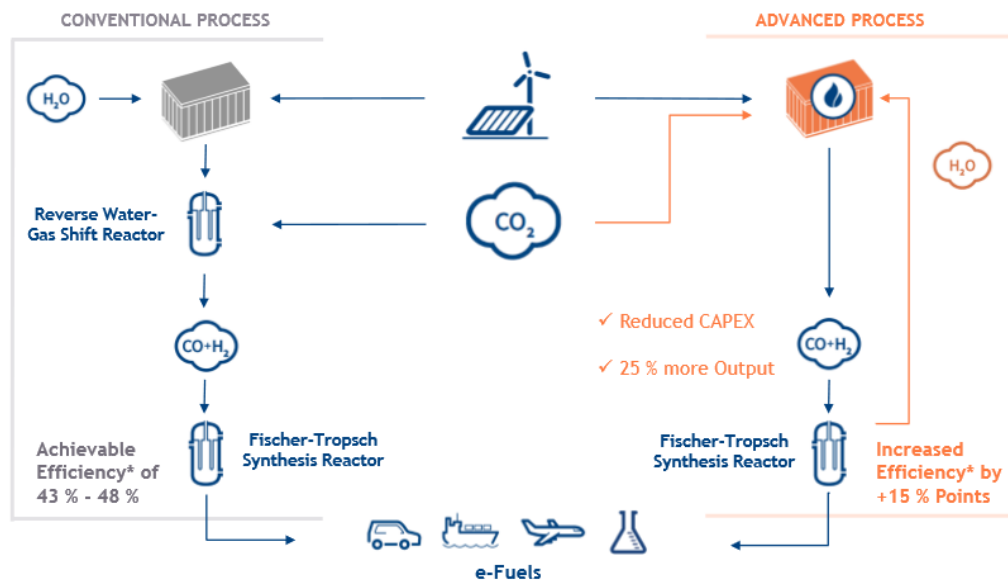
Efficiency assumptions based on expert input: Diesel/PTL CI 41%; LNG HPDI 40% ; Hydrogen FCEV 50%.

Source: [Shell 2018]

Recent developments in e-fuel production using a two-stage process (co-electrolysis) instead of a 3-stage process (electrolysis + RWGS reaction), claim that e-fuel efficiency can increase by 15% points in the Fischer-Tropsch pathway and by 10% points in the methanol pathway [Sunfire 2019].

Figure 20. Co-electrolysis vs. conventional e-fuel process (Fischer-Tropsch pathway)

Technology Comparison: Fischer-Tropsch Pathway



Source: [Sunfire 2019]

The technology, called Sunfire-SynLink, is a prototype and increases the efficiency of e-fuels production (according to Sunfire, in future approx. 80% efficiency would be potentially achieved on an industrial scale) [Sunfire 2019].

2.1.3. CO₂ abatement potential

Despite the lower e-fuels efficiency, the CO₂ abatement potential is very significant, compared with the use of a purely fossil-based fuel (even if the CO₂ comes from a fossil source).

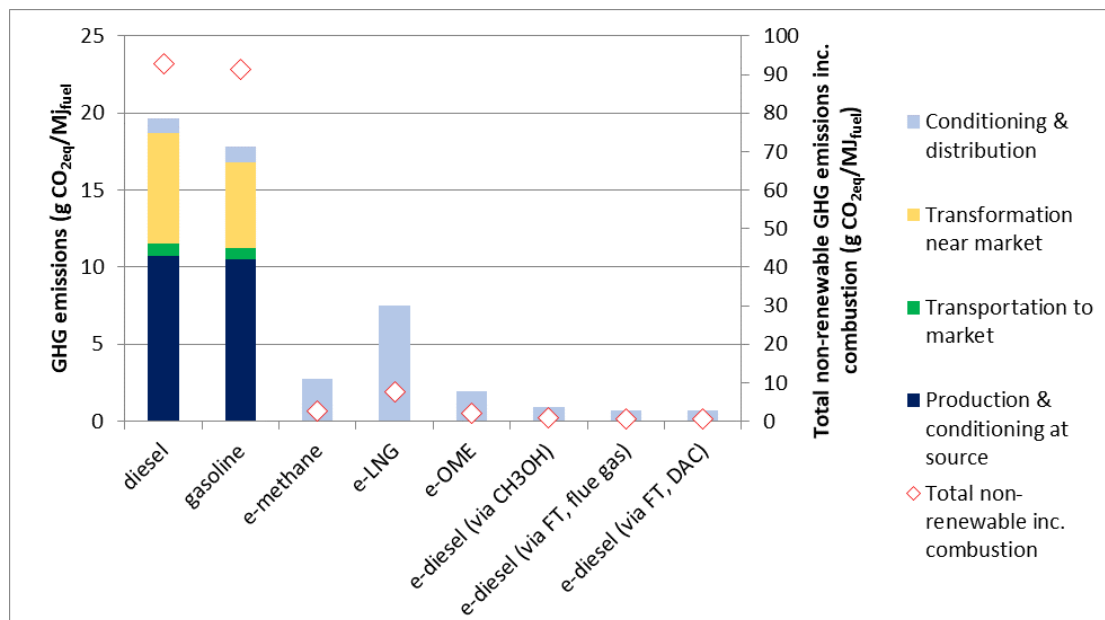
In the JEC consortium, GHG emissions have also been estimated for different pathways [JEC 2019]. In **Figure 21**, some e-fuels versus conventional diesel and gasoline are compared in terms of g CO₂ equivalent/ MJ fuel.

- **WTT analysis**

E-fuels could deliver a potential significant CO₂ savings for transport on a Well-to-Tank or WTT (assessing the emissions from the production of the fuel to the point of fuel supply / refilling station) basis. For a diesel-like fuel, the comparison shows that while the GHG WTT emissions associated with an oil-based diesel are 20 g CO₂ equivalent/ MJ fuel, they decrease to 0,7 g CO₂ equivalent/ MJ fuel when an e-diesel is considered. These figures result in a CO₂ abatement potential of 96% WTT (on an energy basis).

These results are even bigger when a Well-to-Wheel (WTW) approach is applied, (shown in the right axis) due to the fact that the emissions associated to the use of the e-fuels in the engine can be considered as zero (CO₂ considered as a waste).

Figure 21. GHG in the production phase (Well-to-Tank). The theoretical combustion-related emissions are included without engine efficiency losses (g CO₂ eq/MJ fuel)



Source: [JEC 2019]

Notes from the chart:

- CO₂ equivalent also includes CH₄ emissions in the case of fossil diesel and gasoline.
- Same cases as described in the **Table 14**.
- Red squares correspond to right axis (total non-renewable GHG emissions. Bars correspond to left axis (GHG emissions))
- Technically, based on the JEC data, WTT CO₂ abatement potential in e-diesel is similar if CO₂ comes from DAC or a concentrated source. CO₂ abatement potential is 96% WTT and not 100% because in modelling exercise, some fossil diesel is used in road trucks to distribute it.
- Fossil fuels have a higher total GHG emissions value due to combustion, but e-fuels do not, as the combustion GHG emissions are not added for being considered from renewable electricity and CO₂ as a waste).
- E-LNG higher GHG emissions is due to liquefaction stage, where 2030 electricity-EU mix is considered. No e-LNG leakage and its impact on GHG emissions has been taken into account.
- E-fuels produced with the current EU electricity mix (300 g CO₂/kWh), GHG intensity would be three times higher than the fossil fuel comparator ([Transport & Environment 2017], [Cerulogy 2017]).

References including Audi and Sunfire claim that a total CO₂ mitigation potential of 85% WTW could be achieved versus conventional fossil-based fuels ([Audi 2019], [Sunfire 2019]). Dechema is more conservative, estimating that Well-to Wheel emission reductions varying from 35% up to 85%²⁷ depending on the selected pathway (Combination of e-fuel production route and engine efficiency) providing the electricity source is 100% renewable [Dechema 2017].

A different approach is followed by Dechema, who report a mass balance, comparing electricity consumption and CO₂ per ton of product of different e-fuels and assume a medium term reduction potential of 60% WTW compared to the fossil fuel [Dechema 2017].

²⁷ The causes of this big variability are not defined in the original source.

Table 16. Electricity and avoided CO₂ compared to fossil fuel, per t of product

per ton of product	Electricity (MWh)	CO ₂ as feed (ton)	Avoided CO ₂ (ton)
e-Ammonia	12.50	-	1.71
e-Methanol	11.02	1.37	1.53
e-Diesel	18.40	3.15	2.30
e-Jet	18.40	2.85	1.85
e-Methane	26.90	2.70	1.31

Source: [Dechema 2017]

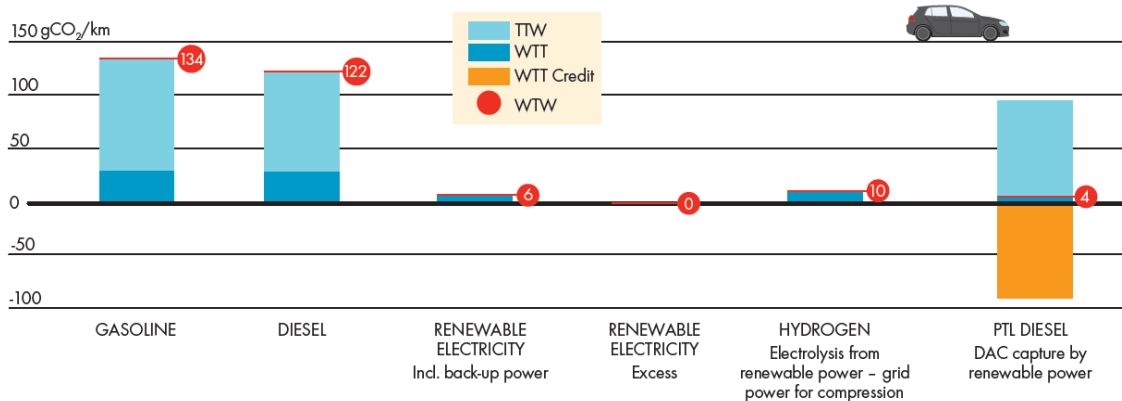
WTW emissions of conventional diesel account for 88.6 g CO_{2eq}/MJ or 3.82 ton CO_{2eq}/ton diesel. For jet, CO₂ emissions are at 71.5 g CO_{2eq}/MJ or 3.08 ton CO_{2eq}/ton.

The CO₂ reduction (avoided CO₂) is calculated using a medium reduction potential of 60% compared to the fossil fuel: 2.3 ton CO_{2eq} per ton of e-diesel and 1.85 ton CO_{2eq} per ton of e-jet.

In a different analysis, Shell uses a WTW analysis of different fuel-powertrain combinations, expressed as g CO₂ per kilometre. Shell examines the energy and emission balances for IC-engine vehicles fuelled by liquid e-fuels, from their primary energy source, then the fuel and finally its use in the vehicle. E-fuels-fuelled vehicles are compared with vehicles operated with different powertrain/fuel combinations.

The analysis focuses on C-segment passenger cars (Light Duty Vehicles, LDVs), for which best data is available, and long-haul Heavy Duty Vehicles (HDV).

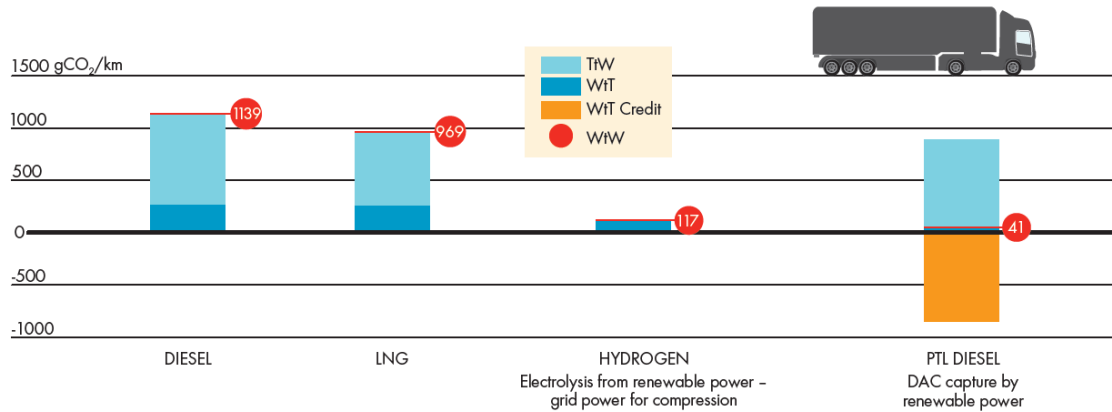
Figure 22. WTW GHG intensity (g CO₂/km) of different light vehicle fuel-powertrain combinations



Source: [Shell 2018]

Note: For e-diesel, produced from solar and wind power sources only and transported from the Middle East and North Africa region to Europe on a marine vessel running on heavy fuel oil, a WtW GHG intensity of approximately 4 g CO₂/km is obtained. This GHG intensity can be reduced further if the marine vessel would run on low carbon fuels. The same amount of CO₂ that is emitted at the tailpipe of the e-fuel fuelled vehicle (TTW) is captured from air while producing the e-fuel. This is shown as a negative GHG emissions or a WTT credit in Figure 22. On a WTW basis, therefore, the tailpipe CO₂ and the captured CO₂ cancel each other out [Shell 2018].

Figure 23. WtW GHG intensity (g CO₂/km) of different heavy duty fuel-powertrain combinations



Source: [Shell 2018]

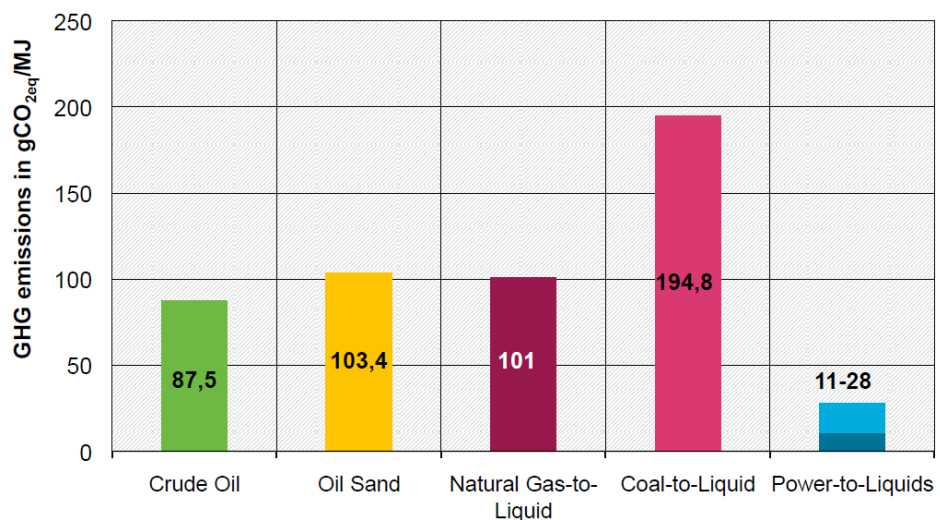
Note: For heavy duty commercial vehicles with higher fuel consumptions, LNG HDVs can reduce WtW GHG intensities by 25% when fossil-based methane is used, further reductions can be achieved through blending of renewables based methane. Fuel cell HDVs fuelled with hydrogen produced renewably (via electrolysis) can reduce the WtW GHG emissions by more than 80%. Similar to LDV pathways, HDV/e-diesel combinations could reduce the greenhouse gas intensity by even more than 95% when produced with CO₂ sourced from DAC using renewable power.

Bosch estimates that savings of CO₂ emissions between 2025 and 2050 would total approximately 2.8 Gton, representing 3 times the overall emissions of Germany in 2014 [Bosch 2018].

- **LCA (Life Cycle Analysis)**

Some references such as Lehmann, H, use an LCA analysis and estimate a decrease in GHG emissions from 87 (crude oil) to 11-28 (e-fuel) g CO₂, or a 70% decrease [Lehmann, H. 2018].

Figure 24. LCA GHG emissions



Source: adapted from LBST/BHL, 2016

Source: [Lehmann, H. 2018]

However, on an LCA basis, given the very large plants needed to perform the energy conversion, including CO₂ emissions from building such plants, tempers the total CO₂ mitigation potential.

2.2. FEEDSTOCKS: AVAILABILITY AND REQUIREMENT

2.2.1. CO₂

Will the CO₂ provided by the industry be able to cover the CO₂ needed for e-fuels production? This question aims to provide an answer to whether the availability of concentrated CO₂ could potentially constrain fuel production.

The **Table 17** summarizes the potential availability some references claim may still be available in the future.

Table 17. CO₂ potential availability from concentrated sources and potential e-fuel production from the available CO₂, according to different references

References	CO ₂ potential availability from concentrated sources (Mton/a)		Theoretical max e-fuel production (Mtoe/a)	
	2030	2040	2030	2040
ICCT [2017]	896	680	130	100
LBST and dena [2017]	165		50	
Dechema [2017]	952	516	140	80

According to ICCT data on CO₂ generation was collected from large point sources (including power, iron and steel, refineries, and others) in 16 EU Member States by the International Energy Agency (IEA). The data was adjusted by applying expected rates of CO₂ emission reduction from 2004 to 2030 and 2040 for the power generation sector (42% in 2030 and 54% in 2040) and the industrial sector (40% in 2030 and 56% in 2040) from the EU Reference Scenario [ICCT 2017].

Table 18. Projected availability of CO₂ from large point sources in EU and theoretical max production of e-fuels from these sources in 2030 and 2040

EU Member State	2030	2030	2040	2040
	Total annual CO ₂ production (million ton)	Theoretical max fuel production (billion litres)	Total annual CO ₂ production (million ton)	Theoretical max fuel production (billion litres)
Austria	12.9	2.8	9.7	2.1
Belgium	31	6.9	23.2	5.1
Denmark	19.4	4.3	15	3.3
Finland	14.3	3.1	11	2.4
France	89.4	19.8	65.2	14.4
Germany	295.2	65.2	225.8	49.9
Greece	36.4	8	27.9	6.2
Ireland	8.1	1.8	6.3	1.4
Italy	87.5	19.3	66.5	14.7
Luxembourg	1.3	0.3	1	0.2
Malta	0	0	0	0
Netherlands	50.9	11.2	38.6	8.5
Portugal	17	3.8	13	2.9
Spain	64.7	14.3	49.4	10.9
Sweden	11.3	2.5	8.6	1.9
UK	157	34.7	120.1	26.5

Source: [ICCT 2017]

Total EU CO₂ production by 2030: 896 Mton/a, and by 2040: 680 Mton/a. Total EU theoretical max fuel production by 2030: 188 billion litres (aprox 130 Mtoe/a), and by 2040: 150 billion litres (aprox 100 Mtoe/a).

According to ICCT [ICCT 2017], expected CO₂ generation from large point sources in 2030 and 2040 greatly exceeds the amount of CO₂ that would be consumed by the volumes of CO₂-based e-fuel that have been projected. On the contrary [LBST and dena 2017] provides a less optimistic estimate of the availability of concentrated CO₂ from biogenic and industrial sources in the EU28, estimating there to be a total of 165 Mton/a of CO₂.

Table 19. Availability of CO₂ and associated potential for the production of transportation fuel in EU

EU 28		Biogenic sources	Industrial processes	Total
CO ₂ potential	Million ton/a	85.9	78.9	164.8
	Billion Nm ³ /a	43.7	40.2	83.9
Liquid e-fuels potential	TWh/a	311	286	597
	PJ/a	1,121	1,029	2,150
E-methane potential	TWh/a	434	399	832
	PJ/a	1,562	1,435	2,997

Source: [LBST and dena 2017]. Note: E-fuels production of 2,150 PJ/y corresponds to 50 Mtoe/a.

Dechema also estimates the projected availability of CO₂ from large point sources (Industry + power) [Dechema 2017].

Table 20. CO₂ direct emissions from the EU power sector and industrial sources

CO ₂ direct emissions	2015	2020	2030	2050
Industry	647	671	521	313
Power	1,315	962	430	69
Total	1,962	1,633	952	381

Source: [Dechema 2017]

The Dechema study explored the use of CO₂ to produce both transport e-fuels but also in chemical products [Dechema 2017].

Dechema concludes that the total amount of CO₂ would be sufficient to supply the demand of chemicals production, even if 100% of the targeted petrochemicals would be produced by the described low-carbon technologies. However, they also concluded that there would not be sufficient CO from industrial sources to meet the demand from transport e-fuels as well as chemical production after 2040 (Dechema's high demand scenario).

Dechema also emphasize, though, that the required amounts of low-carbon electricity exceed the available power capacities but that, given the high economic hurdles, this scenario is unrealistic. When comparing to Dechema scenario with the IEA scenario, it should also be pointed out that the IEA scenario does not cover emissions from smaller industrial plants or from many small other sources such as biogas plants or breweries, which nevertheless can be suitable local sources for CO₂ supply. It is therefore concluded, that carbon dioxide availability as feedstock is unlikely to become a bottleneck in the considered timeframe of the next 35 years.

As a summary,

Will the industrial sources of CO₂ be able to cover the CO₂ needed for e-fuels production?

In all references, the availability of CO₂ generated from large point sources is more than sufficient to meet the demand for e-fuels production in 2030 of 50 Mtoe/a.

Most sources predict a potential e-fuels demand of approximately 100 Mtoe/a by 2040, and again this is likely to be covered by the availability of CO₂ from large point sources in the EU. However, studies with the most optimistic predictions up to 400 Mtoe/a of e-fuels, may hit a CO₂ availability constraint (high FVV, dena and Dechema scenarios). The outlook is even less certain beyond 2050 and CO₂ from industrial sources is likely to become a bottleneck. This would then require the implementation of direct air capture technologies.

From a geographical point of view, local conditions might look different, but ideally, e-fuels production sites would be located close to sources of low-carbon power and industrial CO₂ as well as other necessary infrastructure and utilities.

What is the best CO₂ source to deploy the e-fuels technology?

Due to the high cost advantages, capturing CO₂ from industrial processes and biomass could help to establish a global e-fuels industry by 2050. In principle, CO₂ from cement, chemicals and refining industries would be suitable sources in many countries in the world.

While CO₂ emissions from the power industry are expected to reduce significantly in the long-term, industry sectors that emit large amounts of CO₂ for process-related reasons (for example, production of steel, cement or biogas) are likely to remain. If these industries move to a low carbon energy source, then the CO₂ they produce will be effectively lower carbon. Furthermore, the increase in the use of biomass as feedstock can also increase the amount of bio-CO₂. In the longer term, if the amounts of enriched CO₂ from industrial processes look to be insufficient to meet demand it could also stimulate CO₂ enrichment from Direct Air Capture (DAC).

According to FVV, CO₂ separation from the air is expensive in plant component. For simple synthesis processes such as for CH₄, separation of CO₂ from the ambient air comprises up to 40% of the total investment costs for the fuel synthesis plant. As stated earlier in the report, there is a significant need for research in this area to reduce plant costs. FVV concludes that emitters of CO₂ should be used as CO₂ sources, particularly during the transition from a fossil fuel-based to a completely sustainable energy sector. Capturing CO₂ requires significant energy expenditure for capture, purification and compression [FVV 2018a].

Using energy to enrich the CO₂ from the atmosphere, whilst there are sources of CO₂ at higher concentration does not make sense from either economical or climate perspective. According to Cerulogy, the atmosphere doesn't care whether carbon dioxide is delivered to an e-fuel plant straight from the chimney of an industrial plant that would otherwise emit it, or by extracting ambient carbon dioxide from the atmosphere [Cerulogy 2017].

In the long term, if industrial sources of CO₂ are insufficient, there may be a need to encourage atmospheric capture, but this is highly unlikely to be necessary before 2040²⁸.

2.2.2. Electricity

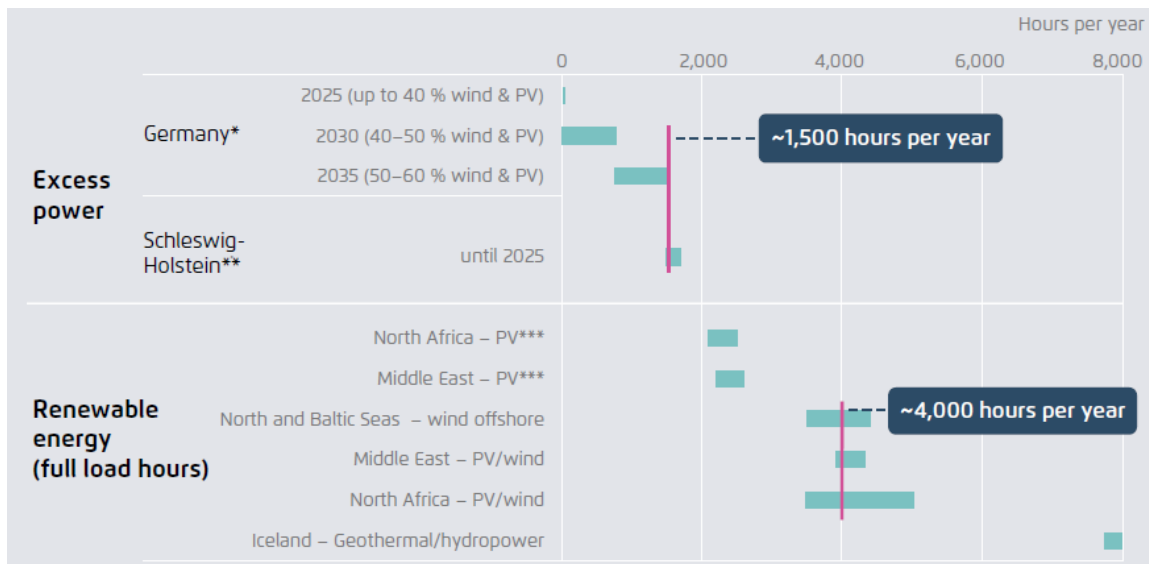
The average carbon intensity for electricity production by the EU 28 member states in 2013 was 407 g/kWh, with a range of carbon intensities over the different member states from the lowest (Sweden) with 25 g/kWh to the highest (Estonia) at 1,152 g/kWh. For e-fuels production using the average EU electricity carbon intensity would result in a greenhouse gas intensity approximately three times higher than that for liquid fossil fuels ([Transport & Environment 2017], [Cerulogy 2017]). Whilst it is important to build the future infrastructure, care must be taken not to make the problem we are trying to solve (GHG emissions) worse in the process.

A major challenge posed by electricity from renewables is its strong intermittent and unpredictable character (minutes, hours, diurnal, seasonal). To be economically efficient, e-fuels facilities require cost-competitive renewable electricity and high full-load hours that overcomes the intermittency and unpredictability of renewable sources such as solar and wind. E-fuel facilities need to achieve high full load hours, dealing with the intermittency of renewable power supply to achieve efficient and economic operations. Frontier Economics [Frontier Economics/Agora 2018] estimate that e-fuel facilities need to achieve 3,000 to 4,000 full load hours annually (although this assertion is debatable regarding the 8,000 - 8,600 full load-hours operation in industrial sites as refineries, and the intermittency patterns of renewable power supply).

Taking Germany as an example (the largest producer of renewable energy in the EU-28), current renewable energy curtailment is around 1,500 hours annually. Energy excess supply depends heavily on the geographical location of the renewables: there are only a few areas in Europe where the supply of renewable power exceeds the demand. Even when it does, it does not happen on a regular basis. Bellona reports that the excess renewable energy production is around 10% per year at EU level, although is planned to increase over the next decades [Bellona 2017].

²⁸ Could hybrid systems with CO₂ from lower-carbon fossil fuels be considered? Another option would be to consider the carbon from lower-carbon fossil fuels like natural gas, possibly in a hybrid type scheme in which seasonality and intermittency are compensated by the use of fossil feeds. It could be a way to build scale faster than when relying upon excess renewable electricity to become available.

Figure 25. Excess renewables production in Germany vs the full-load hours of renewable electricity generation



Source: [Frontier Economics/Agora 2018]

Consequently, it will not be possible to operate e-fuel facilities with the “excess” renewable power and dedicated plants / or guarantee of origin certificates would be required.

Therefore, sufficient renewable power plants capacity must be built before the production of e-fuels to contribute to the overall GHG emissions reductions targets. Such plants can be located in Europe (i.e. as offshore wind) and/or in areas where renewable energy is cheap and potentially higher than local demand (such as in North Africa and the Middle East, as onshore wind turbines and/or photovoltaic) [Frontier Economics/Agora 2018]. An electricity prices comparison in this areas versus Europe is included in section 3.1.3.1. (Figure 64)).

Table 21. Renewable electricity requirements

	Current total EU electricity generation	Electricity required for 100% e-fuel in cars in Europe	Electricity required for 100% e-fuels in transport in Europe
TWh	3,030	3,940	12,000

Sources: [Bellona 2017], [FVV 2016]

Note: Values much higher in comparison with electricity required for 100% electrified car fleet in Europe (800 TWh, according to Bellona, 2017)

A moderate target of delivering 50% of EU aviation fuel from e-fuels by 2050 would require a level of EU renewable electricity generation in 2050 equivalent to a quarter of total current EU electricity generation [Cerology 2017].

Delivering 50% of truck fuel in 2050 would require additional renewable electricity generation equivalent to over a third of the current EU electricity supply.

Clearly, any of these scenarios would have significant implications for EU renewable electricity investment and electricity grid management, even if the facilities in question were operating at less-than-100% capacity to support grid balancing.

The investments required to deliver fuel production on this scale would also be large. Delivering 50% of EU aviation fuel would require in the order of 300 billion euros in cumulative investment for the e-fuel production facilities alone, plus the cost of additional renewable power capacity (450 billion euros in investment, estimated by [Cerulogy 2017]).

The prerequisite for renewable electricity, the resource intensity and cost of expanding e-fuel production are reasons why some experts consider e-fuels as a long-term climate solution only for relatively small niches of demand that are not readily addressed with other approaches such as direct electrification.

2.3. CURRENT TECHNOLOGY READINESS LEVEL

2.3.1. Technologies TRL

Technology readiness levels (TRL) are a method of estimating technology maturity. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRL enables consistent, uniform discussions of technical maturity across different types of technology²⁹.

See a further TRL description in **Appendix A1-3**.³⁰

In the **Table 22**, the TRL of the different parts of the e-fuels production process is shown [Cerulogy 2017]. They are almost all between a TRL 6 to 9, which means they are all feasible technologies, some of them ready to scale-up (TRL 9).

²⁹ TRL has been in widespread use at NASA since the 1980s where it was originally invented. The European Commission advised EU-funded research and innovation projects to adopt the scale in 2010, which they did from 2014 in its Horizon 2020 program.

³⁰ TRL 6 means: Technology demonstrated in industrially relevant environment.

TRL 9 means: Actual system proven in operational competitive manufacturing environment.

Table 22. TRL of e-fuels process technologies

Technology	TRL (today)
Water electrolysis	
Alkaline electrolyser	9
Polymer-electrolyte membrane electrolyser (PEM)	8
High-temperature electrolyser cell (SOEC)	5
CO₂ supply	
CO₂ extraction	
CO ₂ from biogas upgrading, ethanol production, beer brewing, ...	9
CO ₂ exhaust gas	
Scrubber with MEA	9
Scrubber with 'next generation solvent'	8
Absorption/electro-dialysis	6
Pressure-swing absorption (PSA)/Temperature-swing absorption (TSA)	6
CO ₂ from air	
Absorption/electro-dialysis	6
Absorption/desorption (TSA)	6
CO ₂ conditioning (liquefaction and storage)	9
Synthesis	
H ₂ storage (stationary)	9
Fischer-Tropsch pathway	
Fischer-Tropsch synthesis	9
Reverse water gas shift (RWGS)	6
Hydrocracking, isomerization	9
Methanol pathway	
Methanol synthesis	9
DME synthesis	9
Olefin synthesis	9
Oligomerization	9
Hydrotreating	9

Source: [Cerulogy 2017]

Note: in some cases the TRLs will have increased until now, but the **Table 22** clearly shows that most of the technologies are in an advanced stage of development.

2.3.2. Examples of demo/pilot plants

In this section, some examples of current demo plants and future announcements in Europe are shown. An example of a large Fischer-Tropsch plant currently in operation outside of Europe is also described.

2.3.2.1. Current demo/pilot plants


- CO₂ capture from air (TRL 6-7)

Figure 26 CO₂ capture demonstration plant



Global Leader in CO₂ capture from air (TRL 6-7)
Climeworks, Switzerland / Germany

✍️
GREENHOUSE FLAGSHIP PROJECT



Plant type:	DAC-18
CO₂ capacity:	2'460 kg/day
Customer:	Greenhouse
Heat source:	Waste heat
Location:	Hinwil, CH
Commissioning:	31 st May 2017

Worldwide first commercial DAC plant

CONFIDENTIAL

Source: [Climeworks 2019]

The first Direct Air Capture demonstration Plant, installed in Switzerland, has a 2,460 kg/day capacity (commissioned in May 2017).

- E-Hydrogen (TRL 7-8)

Figure 27. E-hydrogen demo plant



Global Leader in green hydrogen generation (TRL 7-8)
Hydrogenics, Belgium / McPhy, France / ITM, UK

E-hydrogen generation plants in Belgium, France and UK [Hydrogenics 2019]



Sunfire's containerized Sunfire-HyLink HL40

Containerised 40 Nm³/h e-hydrogen demo plants (input: 150 kW electricity). Efficiency: 82% LHV

Sunfire has started up a prototype (SynLink) of a high-temperature co-electrolysis system at Dresden (November 2018) with a >500 hours test run (10 kilowatts DC, up to 4 Nm³/h synthesis gas) [Sunfire 2019a].

- E-fuels conversion
 - E-Methanol (TRL 8-9) - Carbon Recycling International.

Figure 28. E-methanol demo plant



Source: [Dechema 2017] [Chemicals Technology 2019]

Carbon Recycling International pilot plant in Iceland generates more than 5000 m³/year of methanol, which meets about 2.5% of the total gasoline market in Iceland.

In 2011, Carbon Recycling International started operation of the “George Olah Renewable Methanol Plant” and hereby demonstrated the potential of tapping into Iceland’s geothermal energy. The 7.1 million euros plant (for a capacity of 1,300 metric tons) was designed to currently produce 4,000 tons of renewable methanol per year (5 million litres). This plant serves as a pilot study for the planned extension to a 40,000 tons plant. The feed consists of CO₂ from geothermal power plant and hydrogen produced by 5 MW water electrolysis fed by a geothermal power plant. All units are operated continuously. The methanol product is mixed into gasoline and substitutes up to 2.5% of Iceland’s fuel consumption. Further uses are as feed in biodiesel production or in other methanol-based processes. In comparison to fossil-fuel based methanol, renewable methanol reduces GHG emissions by 90%.

- Fischer-Tropsch technology (TRL 6-7)

Figure 29. Fischer-Tropsch demo plant



Sunfire's pilot plant in Germany has a capacity of 1 barrel per day (0.057 Million litres/year) and claims to save up to 3.14 tons of CO₂ for each ton of fuel produced.

Sunfire is running the first e-fuel pilot plant worldwide in Dresden, Germany. With the combined operation of a steam-electrolysis reaching an electrical efficiency level of well over 90% (for 10 kW_e) under pressure, a CO₂-Reverse Water Gas Shift conversion and Fischer-Tropsch-synthesis, the plant can produce hydrocarbons from CO₂, water and renewable energy with an overall efficiency level up to 65% (LHV H₂/kW_e). The hydrocarbons can serve the road traffic, shipping, aviation and chemical sector with fuels as gasoline, diesel, kerosene, methanol and methane. Sunfire highlights especially the production of an e-diesel ("blue crude") that already meets required characteristics and can be used without further adaptations for vehicles.

The plant combines a Solid Oxide Fuel Cell (SOFC) and a Solid Oxide Electrolysis (SOE) Cell. The so-called reversible Solid Oxide Cell (rSOC) operation is a SOFC and SOE cell in a single device. This combination makes it possible to supply electricity in time of renewable energy penury. Thus, the process can contribute to balancing power for the stabilization of the grid and can enable added value for the supply of electricity in decentralized regions. The first rSOC sold operates with a 100 kW SOEC power input and 50 kW SOFC power output.

Table 23. Characteristics of e-diesel from Sunfire's pilot plant

Characteristics	Diesel (EN 590)	Sunfire blue crude
Gravimetric Density, kg/m ³	820-840	780
LHV, MJ/kg	42,5	44.7
Energy density (MJ/l)	34.9-35.7	34.9
Cetane number	>51	65-76
Further		Sulphur-free, aromatics content 1%

Source: [Dechema 2017]

2.3.2.2. Large-scale projects announcements

a) E-hydrogen

- A 2x1 MW hydrogen electrolysis is planned to start-up in 2019 [Sunfire 2019].

Figure 30. E-hydrogen large-scale project announcements (HyLink HL 200)



Refinery and steel production

- 2x 1 Megawatt hydrogen electrolysis
- Feed-in of renewable hydrogen into refinery and annealing processes
- Start of operation in 2019

Source: [Sunfire 2019]

- Shell, together with ITM Power, plans a project to install by 2020 a large scale electrolyser to produce hydrogen at the Wesseling refinery site within the Rheinland Refinery Complex. With a capacity of 10 MW, this would be the largest unit of its kind in Germany and the world's largest PEM (Polymer Electrolyte Membrane) electrolyser.

b) E-fuels

- Sunfire Norsk project³¹ and Nordic Blue Crude projects are aiming to scale-up the e-fuel technology, starting to operate in 2021 in Heroya (Norway). In the Norsk project, the Sunfire SynLink multipliable co-electrolysis module is to be used. They will be the first commercial plants, and will produce 10 million litres or 8,000 tons of the synthetic crude oil each, substitute e-crude annually on the basis of 20 megawatts of input power. According to Sunfire, if the Heroya Industrial Park plant goes into operation, about 21,000 tons of CO₂ 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 and the target-price per litre lies below 2 Euros [Sunfire 2019b].

Figure 31. E-fuel large-scale project announcement (Sunfire - SynLink). Start operation in 2021



e-Fuel production

Industrial park of Heroya

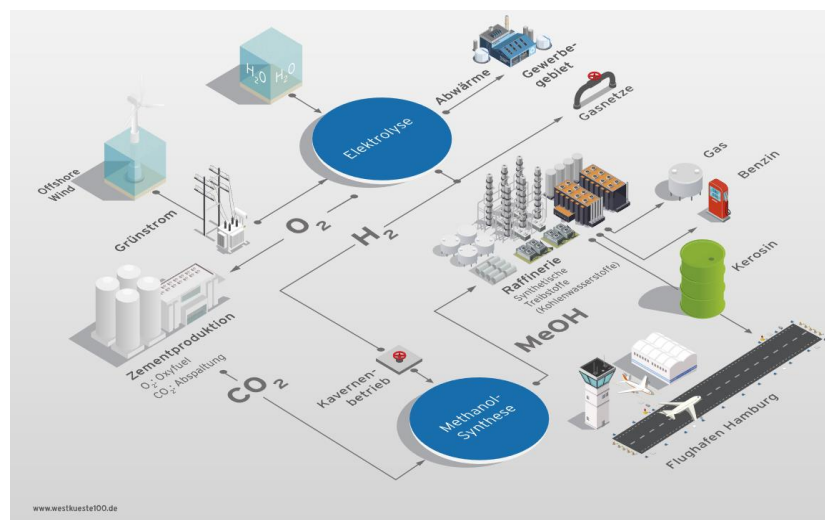
- First global commercial e-Fuel plant
- Production of 10 Mio. l of e-Fuel
- e-Fuels will be sold as drop-in fuel to industrial customers

Source: [Sunfire 2019]

³¹ <http://www.co2value.eu/wp-content/uploads/2019/09/8.-SUNFIRE.pdf>

- Shell and the German state ministry has also announced a new feasibility study in a Rheinland Refinery (Germany) on the production of e-fuels, expecting final findings by the end of 2019 [Shell 2018a].
- Lufthansa has announced a project to source 5% of the kerosene it uses at Hamburg airport with e-jet within five years [Transport & Environment 2019], [ReWest 100 project]³². The supplies will come from the nearby Heide refinery (Germany, Klesch Group) which already provides 350,000 tons per year of conventional fossil jet fuel. The contract between Lufthansa and the Heide refinery is said to draw on excess wind energy produced on the North Sea coast at times when the electricity generated cannot be used by electricity grids. The source of CO₂ for e-fuel will be direct air capture from Carbon Engineering. Together with researchers at the University of Bremen, the refinery hopes this project will be the start of a synthetic kerosene production line³³.

Figure 32. ReWest 100 project (Heide refinery)



Source: <https://www.westkueste100.de/>

- Sunfire and Total announced³⁴ they will team up on a pilot project to produce e-methanol at the Leuna refinery in Germany. Production is expected to start in 2021, generating 500 tonnes of e-methanol in the first three years (0.2 kt/a e-methanol). Sunfire will provide and operate a 1MW electrolyser that could later be integrated in the production of industrial-scale amounts of e-methanol and green hydrogen from CO₂ generated in the refinery processes.
- There are also already announcements of future plants out of Europe, as for example, the ProQR, a cooperational project in Brazil³⁵. Amazon region in Brazil have enormous logistical challenges due to the long and complicated fuel transportation (done by boat or by plane), generating

³² <https://www.westkueste100.de/>

³³ Transport & Environment states that converting all aviation fuel demand to non-fossil kerosene would cost 58% per ticket more than current prices.

³⁴ <https://www.reuters.com/article/total-sunfire-hydrogen/germanys-sunfire-partners-with-total-to-produce-hydrogen-fuels-at-refineries-idUSL5N26N4BY>

³⁵ <https://www.giz.de/en/worldwide/63299.html>

high costs and harm to the environment. It is a region in the world well placed to build decentralised e-fuels plants (1000 litres/day - 0.3 kt/a e-fuels) for these niche markets. Their future plans are to scale it to not only to remote airports in the north of Brazil but also to the regional airports in the south of Brazil.

2.3.2.3. Current large-scale projects out of Europe

- Fischer-Tropsch technology, Shell

Figure 33. FT reactors at Shell's Gas-to-Liquids plant Pearl GtL in Qatar (production $\approx 7 \times 10^9$ litres/year).



Source: [Nordic Blue Crude 2018]

As an example of a big plant located out of Europe, Pearl GtL in Qatar, ramped up in 2012, is the world's largest source of Gas-to-Liquids (GtL) products, capable of producing 140,000 barrels of GtL products per day. The Shell GtL process uses a trickle bed reactor for Fischer-Tropsch synthesis. Additional reactor concepts such as slurry bubble columns have also been commercialized [Shell 2018].

Fischer-Tropsch is a well-established technology. So far, this route is the only part of the whole e-fuels technologies chain that has been commercialised producing fuels at a scale comparable to conventional refining (not the whole e-fuel chain).

In any case, apart from what TRL defines, some profound challenges could be found as the facilities should be scaled up by a factor of at least 100,000 times (compared to what has been demonstrated so far - Sunfire 1 bbl/day e-fuel current pilot plant in Germany-) or 100 times (compared to the new announcement - Sunfire 10,000 m³/year e-fuel starting operation in Norway by 2021) to reach a large-scale commercial project (as Shell 140,000 barrels/day or 7×10^9 litres/y in Qatar).

2.3.2.4. A look into OEMs vision

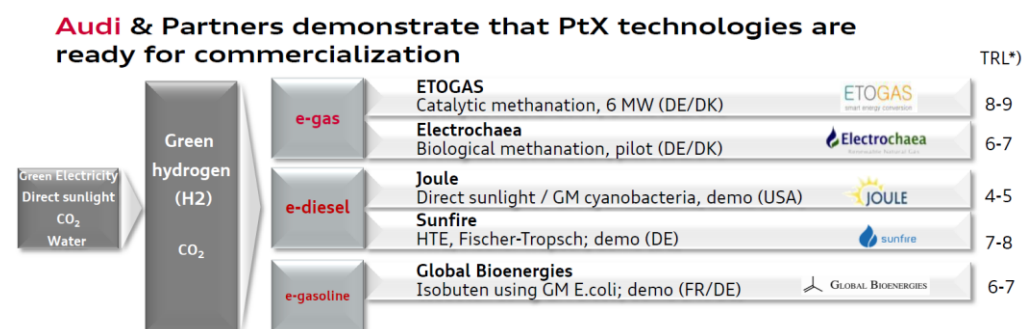
Despite the announcements from many OEMs that they are focusing on electric vehicles, many OEMs are very interested or are actively developing advanced low carbon fuels.

Electric vehicles (EV) are needed to support compliance and avoid penalties under the current emissions regulation for passenger cars which is restricted to a Tank-to-Wheel approach. Currently most electric vehicles are heavily subsidised both by governments and the OEMs. As a result, some OEMs as Audi are exploring more affordable, alternatives which could offer significant reductions at comparable CO₂ reduction costs on a Well-to-Wheel (WTW) basis ([Audi 2018a], [VDA 2017]).

The complete turnover of the EU passenger vehicle fleet with new models is a 10-12-year process, and EVs only represent 10% of the new vehicle sales. Low carbon e-fuels have the advantage that they can contribute to GHG reductions for the existing fleet as well as the future fleet. Offering such fuels for more efficient drivetrains engines can be an important complimentary solution to EVs.

The current TTW-based vehicle CO₂ standards regulation does not allow to take into account the benefits from renewable alternative fuels, as they still emit CO₂ at the tail-pipe. Adaptions are needed to recognise the renewable sustainability of e-fuels in the vehicle CO₂ standards regulation to enhance their development.

Figure 34. Audi e-fuels development strategy



Source: [Audi 2018a]

- Audi e-gas is already on the market. Audi has its own power-to-gas demonstration facility in Werlte, north Germany, which makes Audi e-methane - for the g-tron models A3, A4 and A5. Customers fill up their Audi g-tron model at any CNG filling station and pay the regular price for it.
- Since 2014, Audi has collaborated with Sunfire for a new e-diesel pilot plant in Dresden.
- Audi is also partnering Ineratec GmbH and Energiedienst Holding AG for a new 400,000 litres/year e-diesel pilot facility in Laufenburg, in Canton Aargau (Switzerland). This will use hydropower as the energy source. Construction work started in early 2018.
- Audi together with Global Bioenergies S.A. to develop a new e-gasoline in Leuna (Germany). Audi “e-benzin” (e-gasoline) is a liquid isooctane, produced from biomass in a two-step process. In the first step, Global Bioenergies produces gaseous isobutene (C₄H₈). In the second step, the Fraunhofer Center for Chemical Biotechnological Processes (CBP) in Leuna uses additional hydrogen to transform it into isooctane (C₈H₁₈). The fuel is sulphur and benzene free.

The European Council for Automotive R&D (members include Volvo, Toyota, Hyundai, Ford, BMW, Renault, Volkswagen, etc.) [EUCAR 2019] considers that the high energy density of e-fuels make these an attractive option for road transport in 2030/2050.

2.4. INTEGRATION WITHIN REFINERY ASSETS

The design of an e-fuel plant is different from a traditional refinery/petrochemical facility. The intermittent character of renewable power introduces challenges when it is integrated with electrolyzers, CO₂ capture plants, and

conventional downstream conversion technology. Due to the fluctuating nature of renewables, the dimensioning and operating strategy of the plant is not straightforward.

The challenge associated with intermittency comes from two aspects: both the limited technical flexibility and the lower capacity factor of the e-fuel production units. A typical synthesis plant does not allow fast ramp up and ramp down rates (minutes to hours), but requires steady and continuous operation.

Moreover, turning down the throughput to less than 50% might be challenging and may require a more specific and hence expensive design. The CO₂ capture unit will very likely resemble traditional separation units, which also operate on continuous basis. Low temperature electrolysers, in particular PEM electrolysers can be switched on and off in matters of seconds. However, the capacity factor deteriorates with fluctuating feedstock, which will result in higher investment cost because the capacity is not fully utilized.

Technical solutions to cope with intermittency within the refinery include:

- a) the combination of different renewable energies such as solar PV, wind energy, and (pumped) hydro to reduce intermittency,
- b) to build storage facilities for electricity, hydrogen and/or carbon dioxide,
- c) to introduce novel flexible downstream designs that allow both a low turndown level and agile operation. All these solutions come with additional complexity and cost, and the optimal solution can be a blend of these solutions. For example, including a hybrid fossil-renewable feed strategy for the elements of the plant which must be run at high utilisation and which cannot be rapidly switch.

For an actual design targeting minimal production cost, the optimal sizing of the individual units (solar PV or wind, CO₂ capture unit, electrolyser, storage facilities and downstream synthesis) will depend on the location (abundance of renewable sources and its temporal distribution over the year), the relative cost of the units (e.g. cost of battery versus gas storage), and the availability of flexible designs (e.g. a high turndown ratio of the synthesis process).

Assuming the e-fuels synthesis and CO₂ capture units can only run continuously at high load, with mild throughput variations, energy storage will be required to cover day-night fluctuations or to manage a series of cloudy days with limited fresh feed production. The exact sizing of the storage facilities will also depend on the total installed electrolyser capacity. When a large electrolyser capacity is installed to operate intermittently to follow the output profile of solar PV, the electricity storage requirement will be minimal, but hydrogen storage is still necessary to provide constant feedstock to the downstream units.

Modelling different cases of penetration of e-fuel in a “notional³⁶” or “average” refinery in Europe, as a simplified exercise to foresee the effect on a refinery, has been done as part of the Concawe *Refinery 2050* report [Concawe 2019]. The primary strategy was to best match the demand for all major products, by substituting the crude input by alternative low-carbon feedstocks, as e-fuels exploring different scenarios:

³⁶ *Notional mid-range* refinery (160,000 bbl/d of current crude oil intake, assumed throughput - current demand - and process unit capacities consistent with the European average refinery configuration. This is a hypothetical refinery used for illustration and is not intended to represent a “typical” refinery).

Refinery 2050 - Exploring the integration of e-fuels in existing assets in the European Refining System [Concawe 2019]

The example pathway for refinery integration involves the use of the raw FT “e-crude” as co-feed to the refinery hydrocracker. The e-fuel facility would then not need its own hydrocracking and product recovery equipment, nor would it need storage or equipment to handle co-products such as LPG. Eliminating the hydrocracker element of the e-fuels project might reduce the capital cost of the e-fuel plant. A second integration option involves the use of the refinery’s own CO₂ emissions as feed for the e-fuels plant; if the refinery does not have a pre-existing CO₂ capture system, this element should still be included in the e-fuel investment.

Table 24 shows some illustrative integration options. The first case shows an e-fuels plant which provides 5% of the feed for the existing refinery hydrocracker. Its power requirement is ~120 MW. Its CO₂ consumption would be ~1/10 of the refinery’s total emissions, perhaps about the scale of small SMR. The second co-processing option (30% of hydrocracker feed) is 6 times larger, would need nearly 1 GW of electricity and would consume about half of the refinery’s CO₂. The final case completely fills the refinery HC with “e-crude” but its electricity consumption is really high, almost 2.5 GW and would require CO₂ to be imported from other facilities nearby as part of a potential hub (CO₂ network) or, in the long term, eventually from Direct Air Capture facilities. To put this in context, the world’s largest CO₂ capture plant today (on a coal-fired power station in the USA has a single train absorber-regenerator with a capacity of ~1.4 Mton/a of CO₂ say 3,800 ton/d.

Table 24 Indicative integration of “notional” Refinery with e-fuels
For reference: a “notional” 160 kbbl/day crude oil refinery would make ~9 kton/day of fossil diesel with direct CO₂ emission of ~4.5 kton/day.

Type of operation	Co-processing e-crude and fossil VGO in existing hydrocracker		Transformation of existing hydrocracker to 100% e-crude
	5% co-feed	30% co-feed	@ 100% of base capacity
Renewable Gasoline + Diesel, ton/day (kton/a at 100% utilisation)	120 (44)	715 (260)	2,350 (860)
Electrical Input, MW-e	120	730	2,430
CO ₂ input, t/day (kton/a at 100% utilisation)	430 (160)	2,600 (950)	8,600 (3,140)
Implications for refinery	Slight loss of crude capacity + re-optimisation of existing fossil units		Major loss of crude capacity with closure of many fossil process units

It is worth comparing the electrical demand with the scale of renewable energy facilities. Europe’s largest wind-farms have nameplate (peak) capacities in the range 0.5 to 1 GWe (although larger windfarms have been built in China and the USA). World scale solar farms also have nameplate capacities of 0.5 to 1 GW e.g. the 600 MWe Solar Star project in California. Both wind and PV generation vary with conditions leading to capacity factors of 20%-40%. This suggest that an e-fuel plant capable of converting roughly half of the refinery’s CO₂ emissions and providing enough product for 30% coprocessing in the refinery hydrocracker would require the peak output of what is today a world scale-wind or solar farm, and the combined outputs of several farms to ensure continuous operation.

In this *Refinery 2050* report [Concawe 2019], one case has been modelled to explore the e-fuel integration in the “notional” refinery in EU: Case based on Fischer-Tropsch technology + Hydrocracker upgrading.

The mass balance, assuming that the hydrogen required for e-fuels production and for upgrading in the Hydrocracker unit is produced from renewable electricity in electrolyzers within the battery limits of the refinery, is shown in **Table 25**.

Table 25. Mass balance for e-fuel production (considering CO₂ and water as feedstocks)

Feeds		Products					
CO ₂	Water	O ₂	FG	C ₃ +C ₄	Gasoline	Diesel/ Jet	Heavier
-100	-45.4	113.1	0.9	2.1	6.3	19.9	3.2

Note: The amount of H₂ used in the FT reactor is 0.3-0.4 kg H₂ per kg of product and in the hydrocracking section is <0.01 kg H₂ per kg of product.

The large co-production of O₂ shown suggests that co-location with a major industrial consumer of O₂ would be logical.

In the case of considering green hydrogen as an import, the mass balance is shown in **Table 26**.

Table 26. Mass balance for e-fuel production (considering CO₂ and imported green H₂ as feedstocks)

Feeds		Products						
CO ₂	H ₂	Water	O ₂	FG	C ₃ +C ₄	Gasoline	Diesel/ Jet	Heavier
-100	-14.1	81.8	0	0.9	2.1	6.3	11.8	3.2

Source: [Concawe 2019]

The modelled case, based on fossil feed co-processed with 1,020 kton/a of e-fuel produced by own CO₂ availability in refinery plus imported extra CO₂, is compared with a base case with only crude oil as feedstock in **Table 27**.

Both cases are based on 2050 demand scenarios when product demands are matched similarly.

Table 27. Base case versus e-fuel case in a “notional” refinery in UE

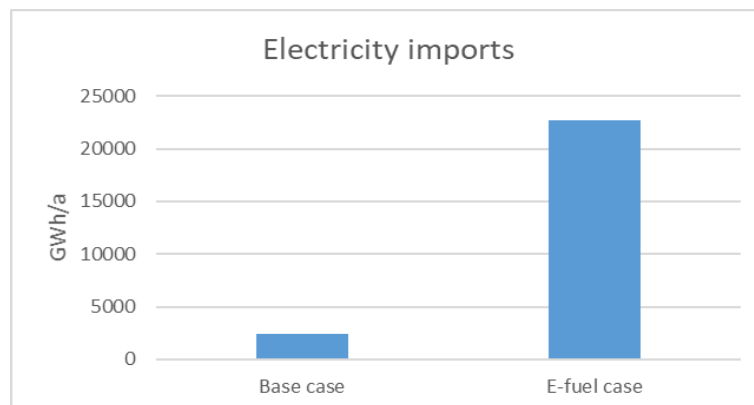
kton/a	Base case (2050)	E-fuel case (2050)
Crude	4,300 ⁽¹⁾	3,300
CO ₂ for e-fuel		
Own capture	0	466
Imported	0	2,700
E-fuel product	0	1,020

Source: [Concawe 2019]

Note (1): Base case defined according to 2050 demand scenario, assuming a decrease in demand versus current situation, as defined in Refinery 2050 report [Concawe 2019]. Details of the scenario demand can be found in chapter 3.3. of the report.

The **Figure 35** shows the electricity imports requirements. To produce 1 Mton/a e-fuel, 21,500 GWh/a are required. Half the EU refineries following this scheme would require about 25% of the entire EU electricity consumption today. This imported electricity has also a fossil component (40 g CO₂/kWh is considered).

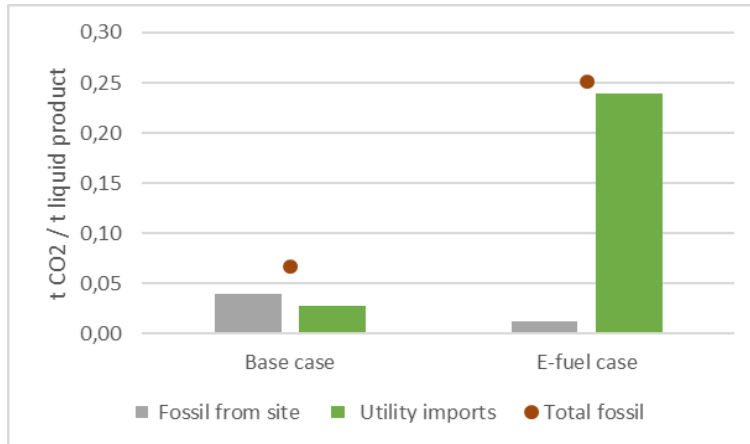
Figure 35. Electricity imports



Source: [Concawe 2019]

The **Figure 36** shows the direct and indirect refinery CO₂ emissions. In the e-fuel case, the total direct + indirect CO₂ emissions are much higher due to fossil component in imported electricity. Achieving complete renewability of electricity would remove the imported CO₂ emissions.

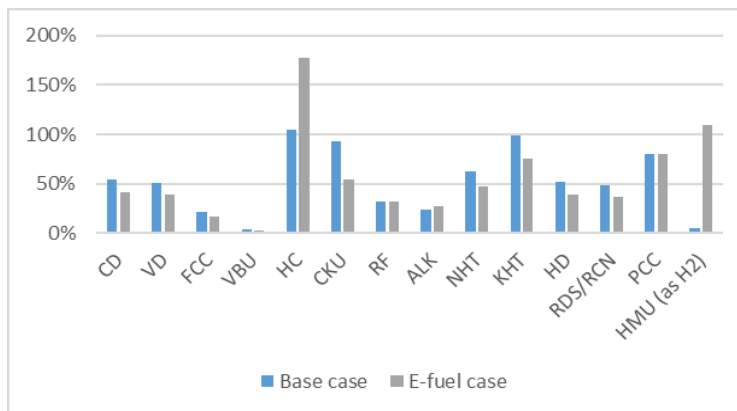
Figure 36. Direct and indirect refinery CO₂ emissions



Source: [Concawe 2019]

The **Figure 37** shows the process plant utilisation. In the e-fuel case, Hydrocracker and Hydrogen plant need extra capacity to hydrocrack the e-fuel (Fischer-Tropsch product), to produce a drop-in fuel.

Figure 37. Process plant utilisation



Source: [Concawe 2019]³⁷

Process plants abbreviation key

VD	Vacuum distillation
FCC	Fluid Catalytic Cracking
VB	Visbreaking
HC	Hydrocracking
CK	Coking
REF	Catalytic reforming
ALK	Alkylation
NHT	Naphtha hydrotreating
KHT	Kerosene hydrotreating
GHD	Gasoil hydrodesulphurisation
LDS	Atmospheric residue desulphurisation
RDS/RCN	Vacuum residue desulphurisation / conversion
HMU	Hydrogen manufacturing unit

³⁷ As an initial estimate, the simulations conducted aim to best match the yields of the different main fractions to the demand without precise consideration to product quality.

2.5. ENVIRONMENTAL IMPACTS AND SUSTAINABILITY

2.5.1. Environmental impacts

E-fuels can either be used as a finished fuel or they can be blended with other conventional refinery fuel components. To be compatible with the existing vehicles, e-fuels would have to meet existing fuel standards (i.e. EN 228 or EN 590).

Alternatively, e-fuels can be produced as fuels which do not comply with main fuel standards and require specifically designed vehicles. Vehicles designed for e-fuels should optimize combustion and/or emission performance irrespective of their drop-in capabilities (“non-drop-in fuels” [Shell 2018]).

2.5.1.1. Air Quality

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 in 2009 (Directive 2009/30/EC). As a result, lead (Pb) and sulphur (S) emissions from transport are no longer a concern for Air quality. The implementation of the Euro IV standard from 2005 has also been effective for Particulate Matter emissions. However, the situation regarding NO_x emissions is notorious and will only be effectively addressed with vehicles meeting the new Euro 6d standard for compliance under real driving conditions. It is worth noting that some of these pollutants (Pb and S) were due to the composition of the fuel, whilst others are due to the combustions conditions.

The temperature and pressure conditions and found in diesels engines are suited to the formation of NO₂/ NO_x from nitrogen and oxygen in the air intake.

Whereas the characteristics of most e-fuels are potentially favourable for air quality, there are some concerns with NO_x and NH₃ emissions when e-ammonia is used as a fuel. The formation of NO_x during combustion hardly depends on the abundance of nitrogen but rather on the temperature and pressure during combustion, the stoichiometry of the mix, etc. Ammonia is used in the selective catalytic reduction (SCR) process to convert NO_x into diatomic nitrogen and water. SCR catalysts are used to treat the exhaust in (SCR) process to convert NO_x into diatomic nitrogen and water. SCR catalysts are used to treat the exhaust in industrial boilers, gas turbines and diesel engines of all scales. Hence prospects for low-NO_x combustion of ammonia are high and has been confirmed in various experiments in Japan [IEA 2018].

SCR is considered to be the only technology currently available to fulfil the strictest NO_x requirements set by the International Maritime Organization (IMO) [Yara 2019].

The SCR process requires precise control of the ammonia injection rate. If this rate is insufficient unacceptably low NO_x conversions may occur. However, if the injection rate is too high, ammonia will be released to the atmosphere. These ammonia emissions from SCR systems are known as *ammonia slip*. The ammonia slip increases at higher NH₃/NO_x ratios. In practice, NH₃/NO_x ratios between 0.9 and 1 must be maintained to minimize the ammonia slip while still providing satisfactory NO_x conversions [Dieselnet Technology Guide 2005].

In general e-fuels would have positive environmental impacts because of the favourable combustion characteristics of the molecules produced - comparable to Gas to Liquid (GtL) fuels for which substantial literature is available on emissions benefits [Shell 2018]:

In passenger cars, testing (NEDC emissions test method) shows that e-fuels can improve on vehicles:

- NOx emissions by 2 - 10%
- Particulate emissions by 14 - 42%.

(on vehicles with lower Euro standards. Preliminary results, based on limited test data with a Euro 6 passenger car, showed even better performance under more stringent drive cycles (WLTP, RDE) [Shell 2018]).

In heavy duty vehicles,

- the NOx improvement is between 5 - 37%,
- PM reduction between 10-38 % depending on engine generation, from Euro-I to Euro-V.

Lower NOx emissions using e-DME (compared to diesel) are due to the shorter ignition delay which result in lower peak pressure and lower maximum combustion temperature.

E-OMEs are rich in oxygen and have no direct carbon-to-carbon chemical bonds. Recent studies with OME in a single-cylinder diesel engine demonstrated that soot and particulate number emissions can be reduced significantly compared to a paraffinic diesel fuel.

2.5.1.2. Water

Water is essential in any e-fuel scheme as the main feedstock for the production of e-hydrogen. It is also an important means of heat integration.

Synthesis of 1 litre of liquid e-fuel in a water cooled plant requires a water import of 3.7 - 4.5 l as feedstock.

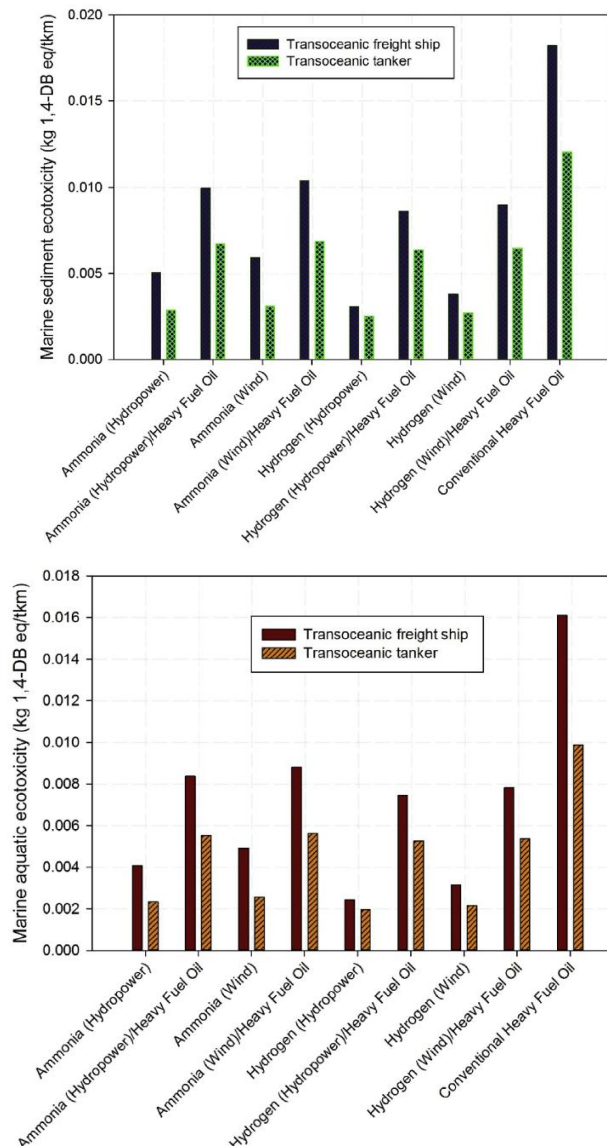
If all water produced is recycled back to the electrolyser, the net intake of water is 1.3 - 2.0 l per litre of e-fuel [Shell 2018].

It is important to ensure the sustainable use of the available water resources, including barren hot areas with limited water resources.

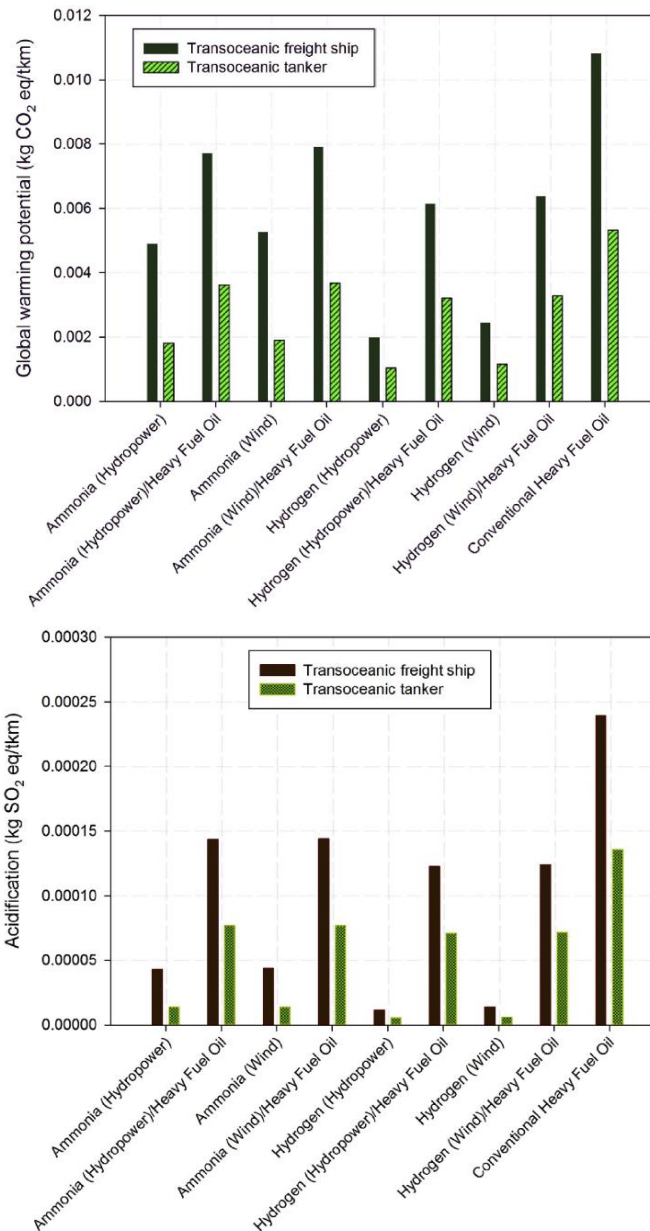
2.5.1.3. Others

Various environmental impact categories, such as global warming, marine sediment ecotoxicity, marine aquatic ecotoxicity, acidification and ozone layer depletion are selected in order to examine the diverse effects of switching to clean fuels in maritime transportation in one specific reference [Bicer, Y. and Dincer, I. 2017].

Figure 38. Environmental impacts of ammonia and hydrogen versus conventional fuel oil in maritime transportation³⁸



³⁸ Environmental toxicity is measured as two separate impact categories which examine water and land respectively. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecosystems. Ecotoxicity Potentials are calculated with the USES-LCA, which is based on EUSES, the EU's toxicity model. This provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterisation factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DB), and are measured separately for impacts of toxic substances on: Fresh-water aquatic ecosystems and terrestrial ecosystems. Source: [Bregroup 2019].



Reference: [Bicer, Y. and Dincer, I. 2017]

It is also important to mention the importance of process safety hazards, which could damage the environment, apart from the equipment and the personnel in an industrial facility. Process safety hazards typically include dust, gas or vapour contamination in processing plants, potential detonation of energetic materials and runaway exothermic chemical processes. Identifying and mitigating process safety hazards requires expert knowledge of the processes involved. It is also imperative that equipment be regularly maintained and inspected. Once a hazard has been identified, the level of risk is determined and the appropriate safeguards are put in place to provide a basis of safety [Safeopedia 2019].

2.5.2. Sustainability

2.5.2.1. Sustainable water and land use

Many areas with favourable conditions for PV solar and wind power generation have available land for e-fuels deployment but lack continuous sources of fresh water needed for the electrolysis step when producing e-fuels. Seawater desalination plants are one of the options to compete with other uses of precious water resources.

Moreover, large industrial facilities should not displace existing or less lucrative forms of land use. This is especially true of land used for food production, but it also includes space for settlements and nature reserves to protect endangered animals and plants.

The electricity generation and the e-fuels synthesis could be located in areas where no or only minor land use competition can be assumed (like deserts for solar photovoltaic). Renewable electricity generation is the most land intensive part of the e-fuel production. According to Transport & Environment, to power 50% of EU aviation with e-fuel in 2050, 8 million hectares of land would be required (the size of the Czech Republic) [Transport & Environment 2017].

Liquid e-fuels are then easily transported/imported from remote areas. Typically, for the annual production of 1 litre of e-fuel 0.05 to 0.18 m² of land (depending on the insolation) are required for power generation depending on the insolation of the location [Shell 2018].

2.5.2.2. Socially sustainable e-fuel production

Some sources also refer to the importance of e-fuel production not to negatively impact local communities. In developing countries, a portion of production revenues could go toward sustainable development. If countries in North Africa and in the Middle East produce e-fuels for other areas, efforts should be made to ensure inclusive benefits for local populations.

Besides, political stability may also play an important part in some of these areas.

3. ECONOMIC ASSESSMENT AND DEMAND SCENARIOS

3.1. COSTS AND INVESTMENT

3.1.1. Investment

The size of facilities and investment needs required for the production and deployment of e-fuels in Europe could be a profound challenge.

3.1.1.1. Exploring infrastructure implications in Europe

a) The case of Germany

In this aspect, FVV makes an interesting comparison for different energy paths for road transport in 2050 in **Germany**: 100% electric, 100% hydrogen and 100% e-fuels, to provide the current energy content of all fuels used in road transport in Germany in 2015 (560 TWh) [FVV 2018b].

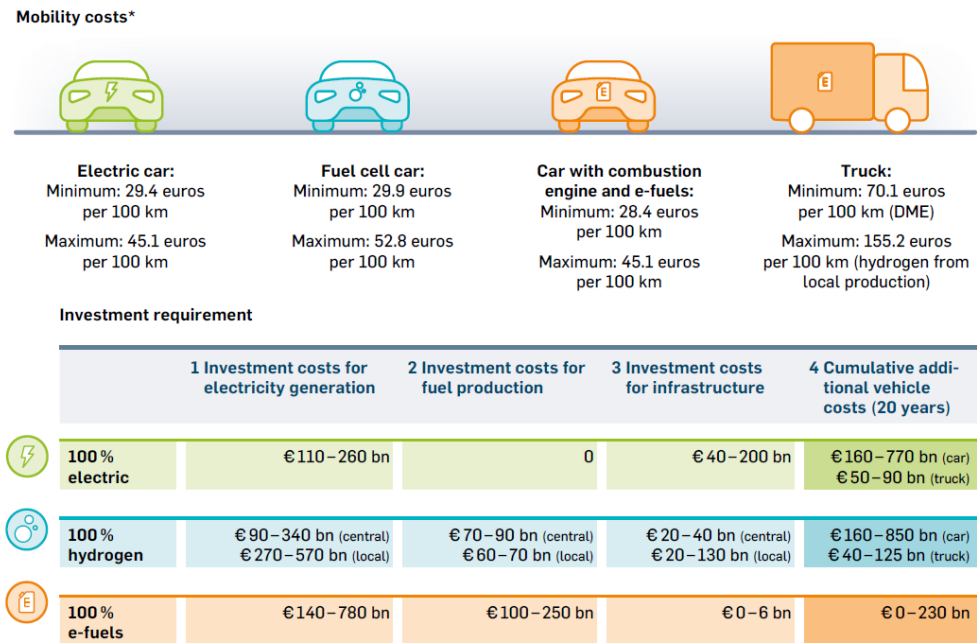
As part of this study, seven fuels in eight powertrain/fuel scenarios were inspected. The spectrum comprises two scenarios for methane, and one scenario each for methanol, DME (dimethyl ether), OME (oxymethylene ether), as well as e-gasoline, diesel and liquid petroleum gas based on the Fischer-Tropsch process.

The conclusion of its study is that the investment required for a 100% e-fuel pathway in Germany by 2050 with current fuel consumption, potentially ranges from **240 to 1,260 billion euros**³⁹. Investment in infrastructure and vehicles are significantly lower than in the other cases, but investment costs for electricity generation and for fuel production are higher.

When observing the lowest cost case for each of the three main paths (e-fuels, H₂ and BEVs), the minimum investment costs potentially required are in the same order of magnitude. The investment for the purely electric scenario could reach 1,230 billion euros. For the hydrogen scenario, investment of up to 1,640 billion euros could be necessary.

Taking into account that this study focused on Germany, the total investment for Europe will be much higher. As an example, FVV makes a rough extrapolation on e-fuels synthesis from 240 billion euros investment in Germany to around 2,100 billion euros in EU-28 [FVV 2018b].

³⁹ Not explicitly mentioned if inclusive of dedicated renewable power, or if there are renewable resources to make this power.

Figure 39. Different pathways CAPEX for Germany


Source: [FVV 2018b].

Notes:

-*The mobility costs comprise the costs for the energy source (without taxes and fees). 100% electric scenario assumes that only battery electric vehicles are used. For long-distance truck transportation, this scenario includes the installation of overhead lines on the highways.

-In the 100% electric scenario, the total electric energy requirement is at least 249 TWh per year, and at most 325 TW h per year (corresponding to 11,000 to 15,000 additional wind turbines (5 MW). This value includes the losses incurred when transporting electricity to the charging point and during charging, with figures ranging from 6 % to a maximum of 28 % incurred only during fast charging. (This could be one reason to not having a ratio of 1/5 (as in efficiency, explained in chapter 2.1.2.7.) in the investment costs of the electricity generation of 100% electric scenario versus 100% efuel scenario).

- In the 100% efuels case, the total electrical energy requirement is from a minimum of 625 TWh (methane, CO₂ source available), corresponding to 35,000-40,000 additional wind turbines, to a maximum of 1315 TWh (OME, CO₂ separation form air), corresponding to approx. 60,000 additional wind turbines.

More detailed CAPEX estimates for specific pathway are shown in these **Figures 40 and 41**:

Figure 40. Different pathways CAPEX for Germany (detailed)

	① Investment costs for power plants*	② Investment costs for fuel production	③ Investment costs for infrastructure	④ Cumul. add. vehicle costs** car (vs. gasoline) + truck (vs. diesel)
PtX	€137–526 bn (Pt-CH ₄)	€102–118 bn (Pt-CH ₄)	€3–6 bn (Pt-CH ₄)	€0–122 bn + €24 bn (CH ₄)
	€166–629 bn (Pt-MeOH)	€115–168 bn (Pt-MeOH)	< €1 bn (Pt-MeOH)	€0–20 bn + €0 bn (MeOH)
	€166–635 bn (Pt-FT)	€176–254 bn (Pt-FT)	€0 bn (Pt-FT)	€82 bn + €0 bn (FT)
	€149–570 bn (Pt-DME)	€103–151 bn (Pt-DME)	€1–2 bn (Pt-DME)	€163–231 bn + €1 bn (DME)
	€208–783 bn (Pt-OME)	€167–243 bn (Pt-OME)	< €1 bn (Pt-OME)	€163 bn + €0 bn (OME)
H₂	€89–342 bn (central)	€71–87 bn (central)	€19–38 bn (central)	€163–850 bn (car)
	€273–568 bn (local)*	€55–66 bn (local)	€19–128 bn (local)	+ €37–125 bn (truck)
BEV	€112–262 bn*	0	€38–198 bn	€163–768 bn (car) + €52–88 bn (truck)

← Energy supplier
← Fuel industry
← Automotive industry

Source: [FVV 2018a]. Note: (Pt = Power to)

Figure 41. Minimum and maximum potential investment in Germany by pathway

Scenario (cars + trucks)	Min. investment costs in € billion	Max. investment costs in € billion
Pt-CH₄	270	800
Pt-MeOH	280	820
Pt-FT	420	970
Pt-DME	420	960
Pt-OME	540	1,190
Pt-H₂ (central)	380	1,440
Pt-H₂ (local)	550	1,740
BEV	360	1,320

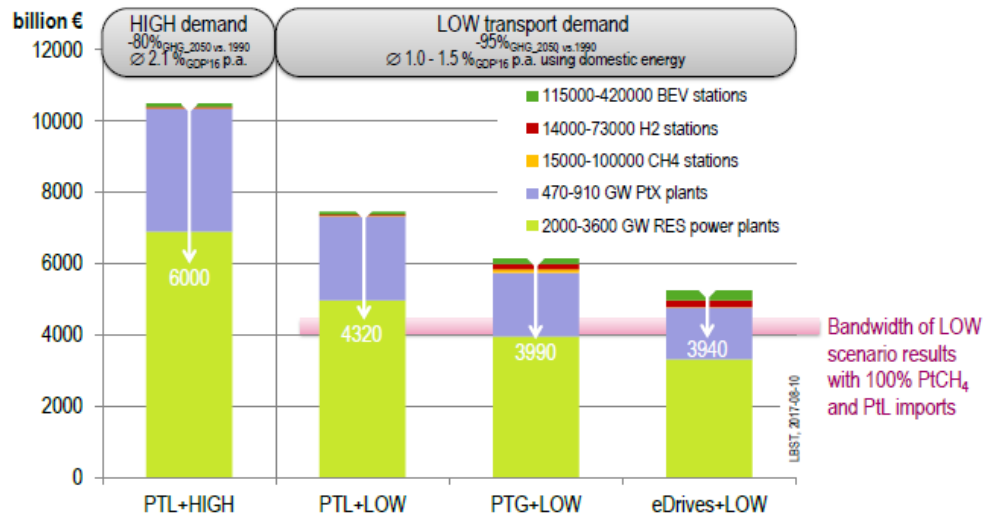
Source: [FVV 2018a]. Note: (Pt = Power to)

b) Europe

Dena (2017) estimates the cumulated investment for e-fuels over the whole of Europe in different scenarios of transport demand. Their high demand scenario ranges from **6,000 to 10,000 billion euros** whilst their low scenario ranges from **4,000 to 8,000 billion euros** (e-fuels imports from low electricity generation costs countries are considered)⁴⁰.

⁴⁰ To compare these figures with EU investment levels, it is remarked that, according to the EU Commission long-term strategy *A Clean Planet for all*, the average annual investment for 2021-2030 is 1081 billion euros₂₀₁₃ per year. EU GDP in 2018: \$19 trillion).

Figure 42. Potential cumulative investment in Europe to energy transition by 2050



Source: [dena 2018]. Note: White arrows assume 100% e-fuels imports

3.1.1.2. Current and forecast CAPEX per technology

All references allow for a progressive reduction in investment cost per technology over time, due to economies of scale and learning effects.

According to LBST and dena, electrolysis could represent almost half of the total investment for an e-fuel plant but falling to below 25% by 2050, where CO₂ supply becomes the main driver of total investment (DAC considered) [LBST and dena 2017].

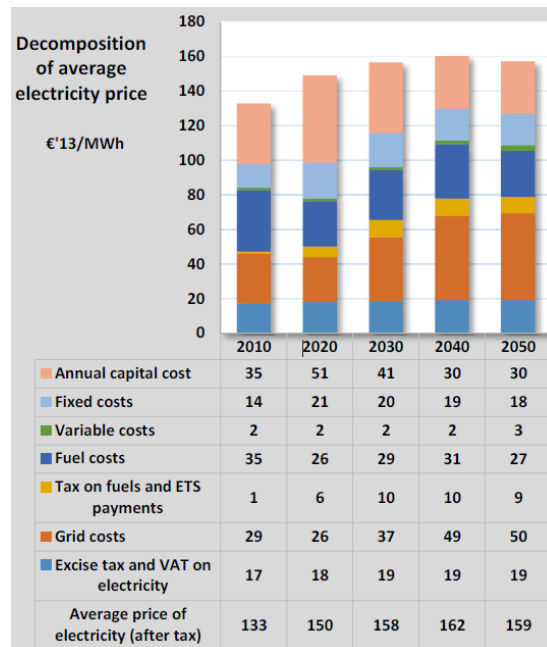
E-fuels synthesis, both via methanol or via Fischer-Tropsch route, are below 20% of the total investment⁴¹.

It is important to highlight that CAPEX for power generation 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.

In the EU reference scenario [Commission 2016], the electricity prices include CAPEX for power generation (see Figure 43).

⁴¹ Workup of the raw FT product not explicitly mentioned.

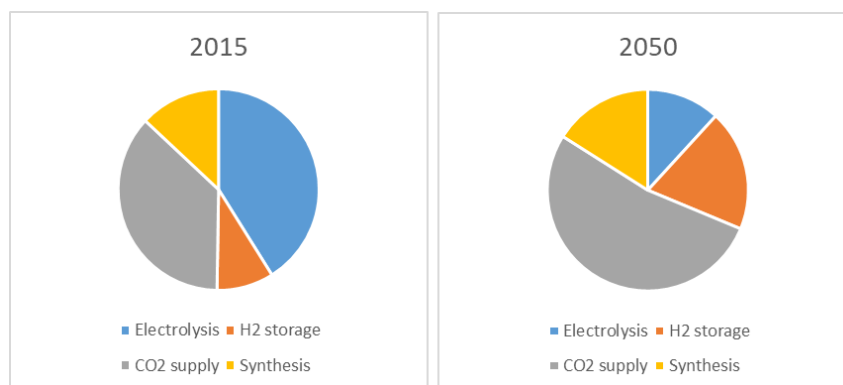
Figure 43. Electricity price projections for industry and composition in EU reference scenario



Source: [Commission 2016]

In *A Clean Planet for all*, when a massive e-fuels scenario (P2X) is considered [Commission 2018], the electricity price is higher (200 €/MWh by 2050) (see Appendix A1-6).

Figure 44. Distribution of e-fuel plant CAPEX from 2015 to 2050 (via FT and LT electrolysis)



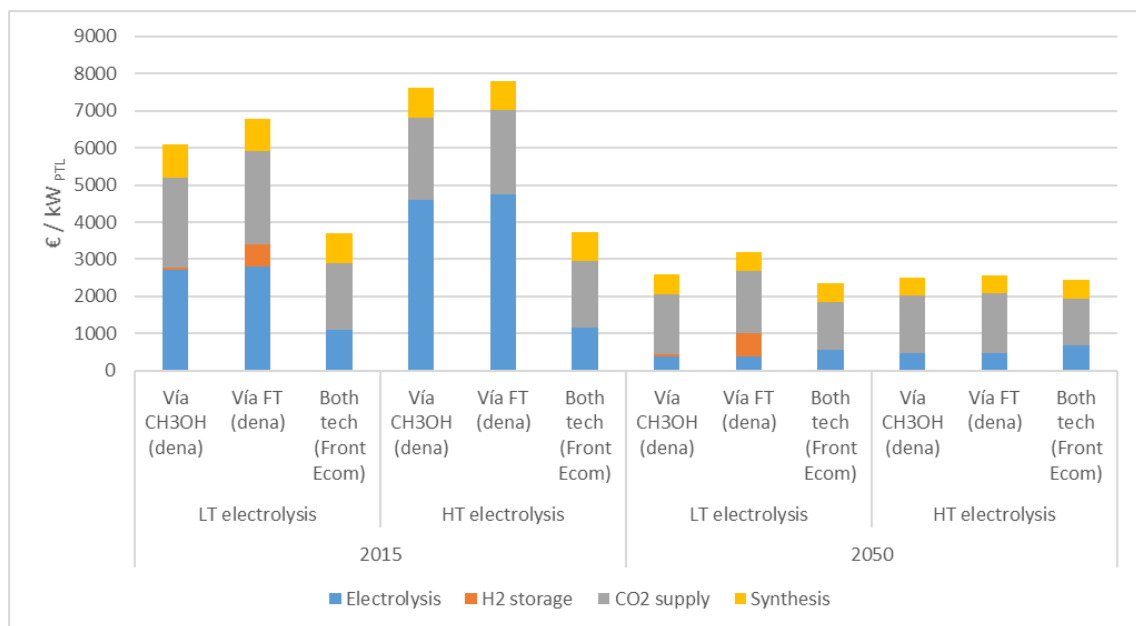
Source: [LBST and dena 2017]

Note: Investments for new hydrogen and hydrocracker capacity (needed as indicated in section 2.4.) are not explicitly mentioned in the LBST and dena report as part of the total e-fuel plant investment.

Although there is a wide range between figures cited in the literature today, there is an apparent consensus regarding the development of these costs over time ([Prognos 2018], [Frontier Economics/Agora 2018], [LBST and dena 2017], [Dechema 2017]).

Therefore, total CAPEX for an e-fuel installation could decrease from 4,000-8,000 (different range depending on the source) to 3,000 €/kWh_{efuel} (consensus among the sources) from 2015 to 2050.

Figure 45. E-fuels CAPEX



Sources: [Frontier Economics/Agora 2018] and [LBST and dena 2017]. Notes:

- CO₂ capture based on Direct Air Capture in both sources.
- 8,000 €/kW PtL (investment in 2015 according to dena, for a 70 Mton/a e-fuel plant corresponds to ≈850 million euros. This is in the order of magnitude of the Nordic Blue CAPEX reference for their future 8 kt/a e-fuel plant Heroya plant in Norway, estimated in 75 M€.
- LT: Low temperature, HT: High temperature

Although electrolysis is the technology where CAPEX is predicted to decrease the most in the coming years, the other technologies such as CO₂ supply and e-fuels synthesis CAPEX, either via methanol or Fischer-Tropsch⁴², are also likely to decrease by 2050 according to all references:

- Water electrolysis:

Frontier Economics (2018) shows an overview of the literature on investment costs for water electrolysis plants.

⁴² Fischer-Tropsch route is a more mature technology than methanol route, and the forward savings in CAPEX are likely incremental.

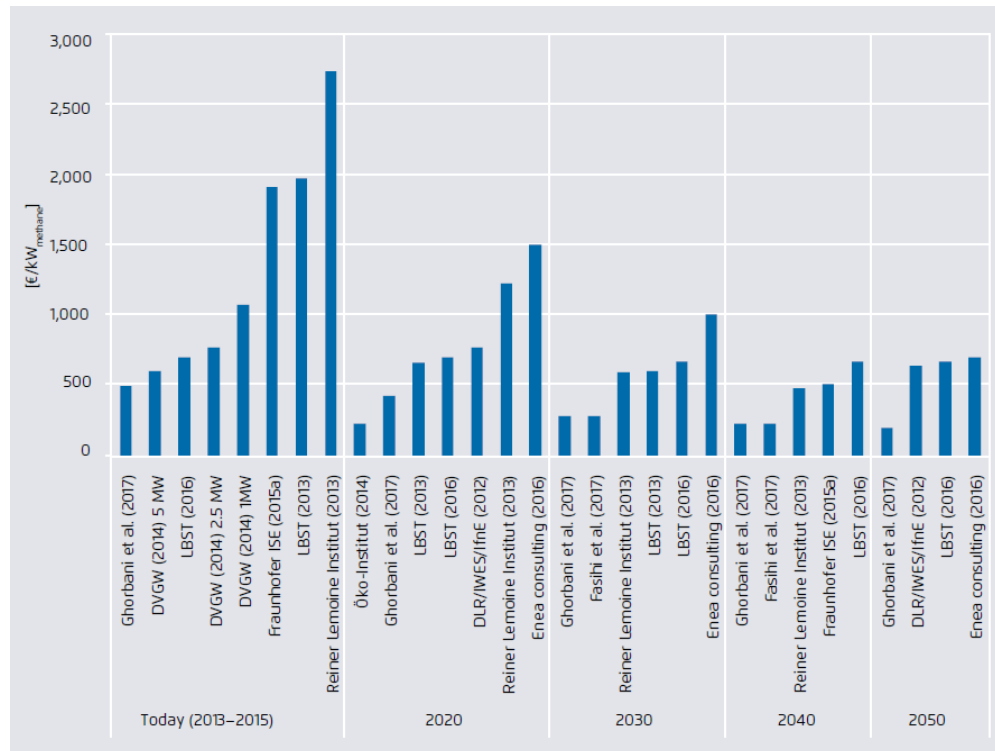
Figure 46. Decreasing investment cost for water electrolysis until 2050



Source: Frontier Economics (2018)

- Investment costs for CO₂ capture from the air are currently about 2,200 euros/kW_{PtL} and it is assumed that they will drop to 1,600 euros/kW_{PtL} until 2050.
- Synthesis investment costs are currently about 1,000 euros/kW_{PtL} and it is assumed that they will drop to 500 euros/kW_{PtL} until 2050.
 - Investments of Fischer-Tropsch synthesis and methanol synthesis do not differ fundamentally.
 - Investments for methanisation process varies significantly from today (500-2600 €/kW_{methane}, depending on the reference), to a convergent 700 €/kW_{methane} by 2050.

Figure 47. Methanisation CAPEX



Source: [Frontier Economics/Agora 2018]

Figures above are related to e-fuels synthesis process, but there are references, that goes beyond, not only calculating the investment required to the synthesis process, but also to the investment costs for electricity generation, infrastructure and vehicle costs.

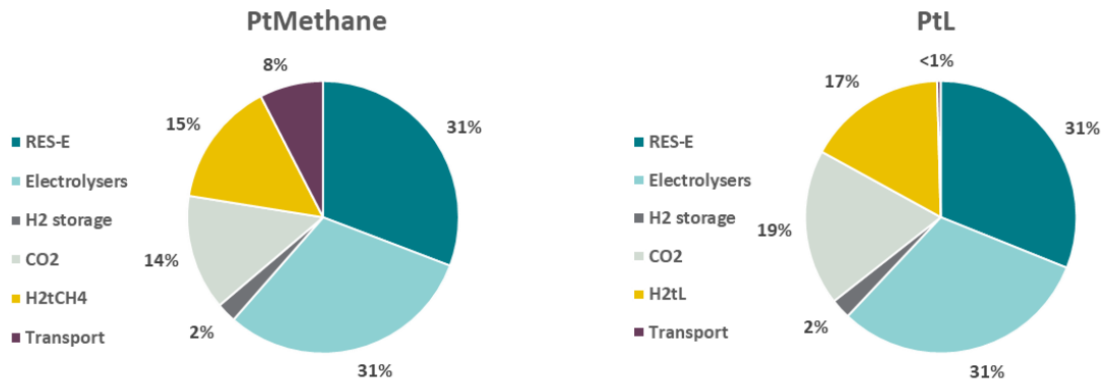
3.1.2. E-fuels production costs

The current high cost of e-fuel compared with conventional fuels, is likely to decrease due to the assumed reduction for investment costs of renewable electricity generation plants and conversion plants related to economies of scale and learning effects. The efficiency of hydrogen electrolysis is assumed to increase over time.

According to all references, the most important determining factors for the future cost of e-fuels are the costs of power generation and the capacity utilization of conversion facilities.

Frontier Economics gives a cost breakdown where costs for renewable electricity generation and electrolyzers make the major contribution [Frontier Economics/Agora 2018].

Figure 48. Cost breakdown of e-fuels



Source: [Frontier Economics/Agora 2018]

Note: All cost shares (in %) and absolute figures (ct/kWh) are rounded and associated with the following scenario: North Africa, reference scenario 2030, PV-Wind-combination, CO₂ from DAC, 6% WACC.

RES-E: Renewable energy sources for electricity

Costs for second-stage conversion processes (methanisation, Fischer-Tropsch synthesis, methanol synthesis): the costs for the synthesis of gaseous or liquid fuels (including H₂ storage and energy efficiency losses) account for around 15% to 17% of total costs - excluding the supply of CO₂.

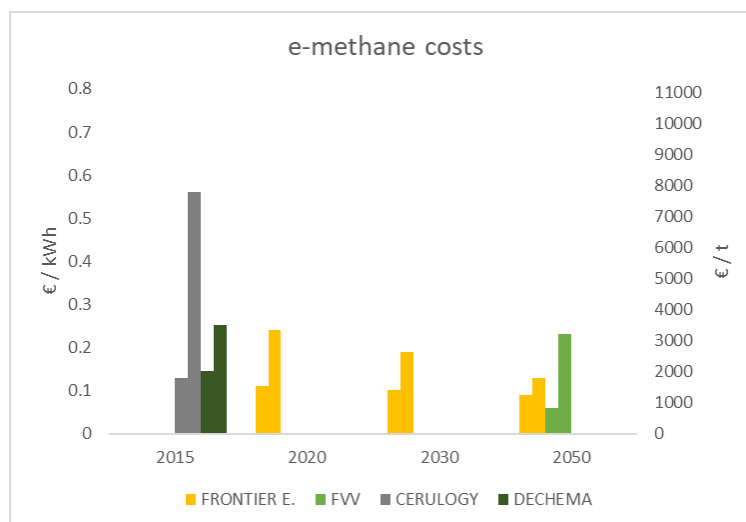
Costs for the supply of CO₂: the costs for the supply of CO₂ are around 14% to 19%, assuming that the CO₂ is captured from the air via DAC technology.

In the following figures, a comparison among all the references is done to see the cost ranges for all the e-fuels. Note that bars in the same colours represent the minimum and maximum cost estimates by each of the sources included in the comparison. Note also that the range is provided by different references, with different basis.

3.1.2.1. E-methane

E-methane cost ranges from 0,1 to 0,6 €/kWh (1,400-8,000 €/t) by 2015 to 0,1-0,2 €/kWh (1,400-3,000 €/t) by 2050.

Figure 49. E-methane costs (min/max) (€/kWh and €/t)

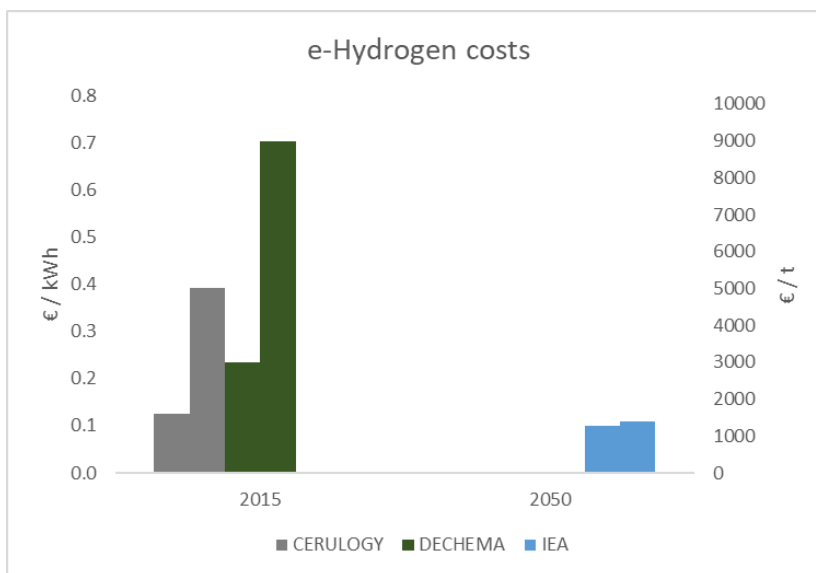


Note: As a reference, fossil natural gas price in 2018 (average EU-28): 0.065 €/kWh [Eurostat 2018]

3.1.2.2. E-hydrogen

E-hydrogen production costs range from up to 0.7 €/kWh (9,000 €/t) by 2015 to 0.11 €/kWh (1,500 €/t) by 2050.

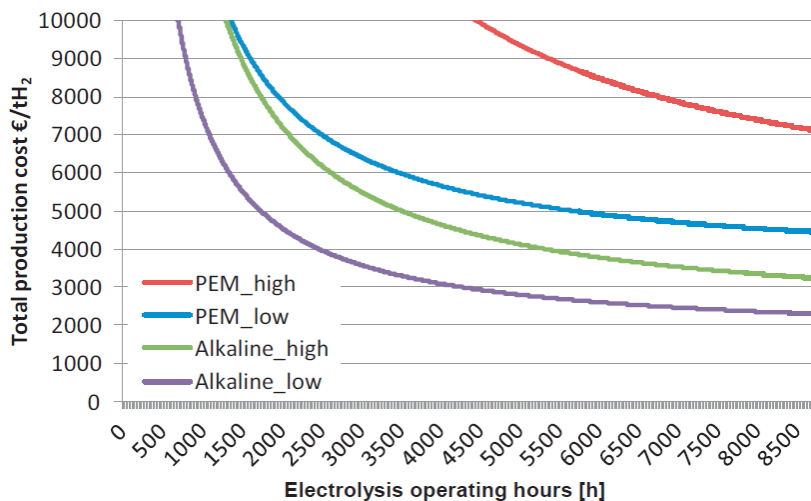
Figure 50. E-hydrogen costs (min/max) (€/kWh and €/t)



Note: Data not available by 2020 and 2030

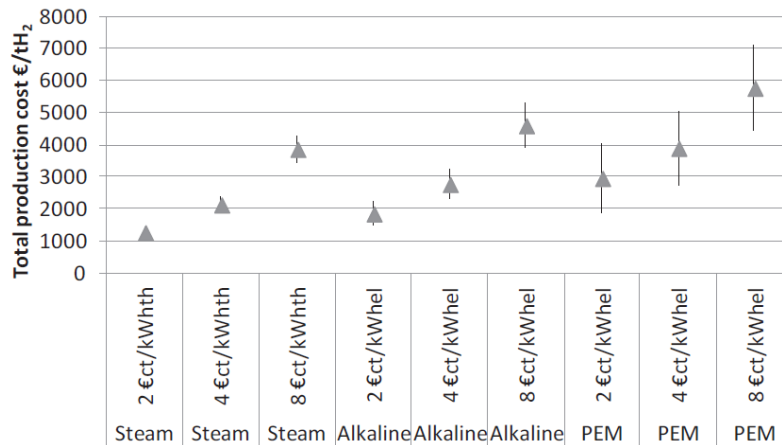
According to Dechema, production costs of hydrogen strongly depend on two main factors: i) electricity costs and ii) utilisation rate of the electrolyser (operating time, particularly relevant in case of a fluctuating renewable electricity). Hydrogen production costs are a function of the utilisation rate and other factors and showed a cost range of 0.23-0.70 €/kWh (3,000-9,000 €/t H₂) for different scenarios [Dechema 2017].

Figure 51. E-hydrogen costs, as a function of electrolysis operating hours (€/t H₂)



Source: [Dechema 2017]

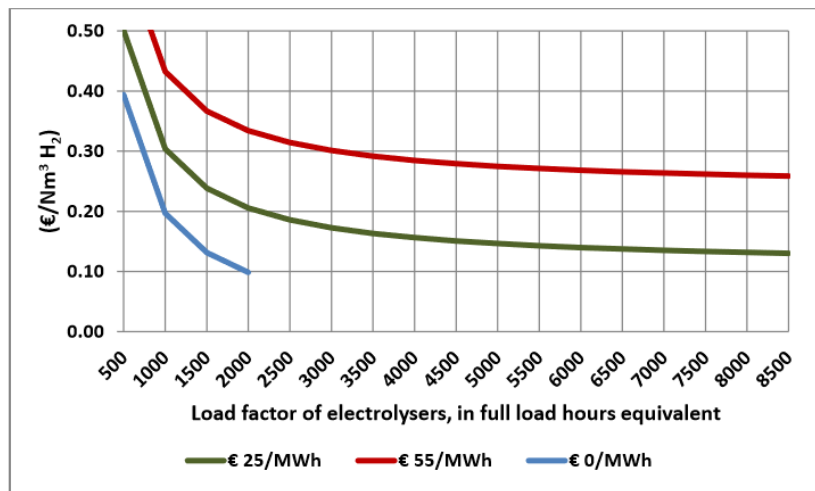
Figure 52. Hydrogen production cost for comparison between steam reformer and electrolyser



Source: [Dechema 2017]

According to IEA, in case of electrolysis of water, the major costs are those of electricity and of the electrolysers. The cost of electrolysers especially matters for capacity factors below 30%, while for higher capacity factors the cost of electricity is the predominant factor.

Figure 53. Cost of hydrogen from electrolysis for different electricity costs and load factors



Assumptions: Capex electrolysers USD 450/kW_m+30% installation +20% Opex; lifetime 30y; Weighted average capital cost 7%; efficiency 70%.

Source: [IEA 2018]

3.1.2.3. E-ammonia

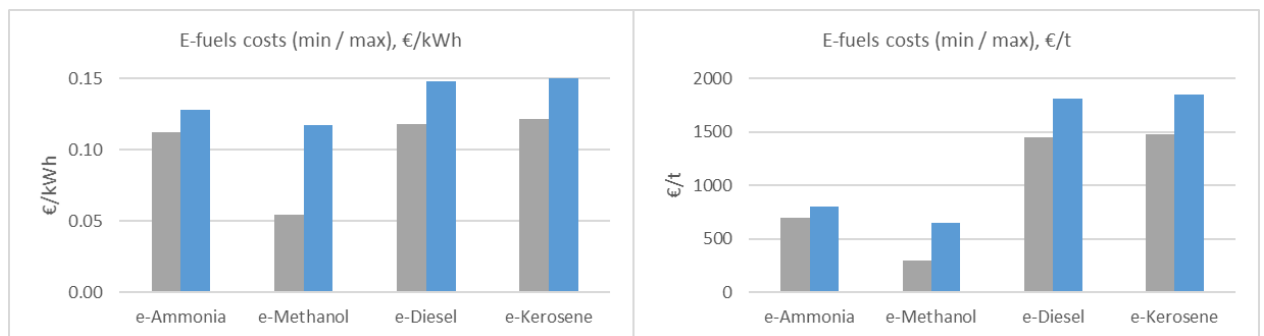
The cost of e-ammonia production is predicted to range between 0.04 and 0.13 €/kWh (255 - 800 €/t) by 2050, and is mainly determined by the electricity price (10-50 €/MWh), assuming continuous operation and adding capital and operating expenses.

Table 29. E-ammonia costs (min/max) (€/kWh)

Low-carbon electricity price (€/MWh)	10	30	50
Ammonia production costs (€/t) min	255	450	735
max	380	590	800
Ammonia production costs (€/kWh) min	0.04	0.07	0.12
max	0.06	0.09	0.13

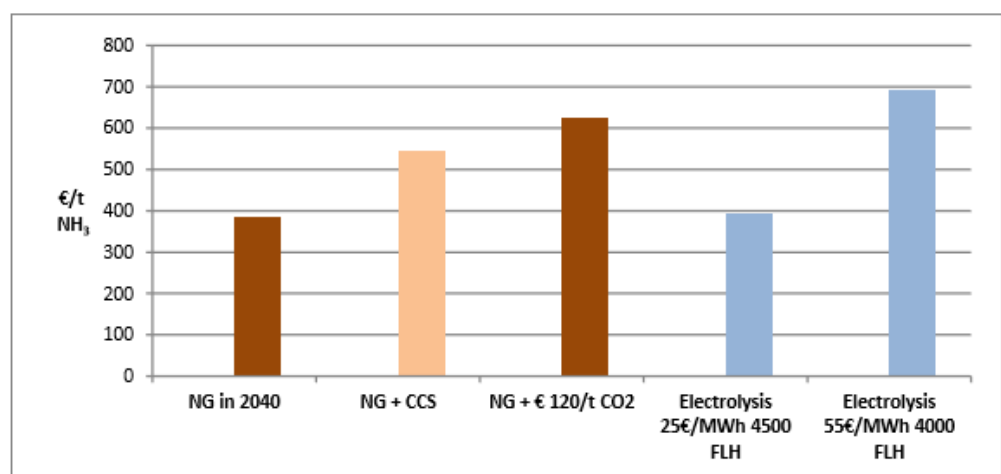
Source: [Dechema 2017]

Dechema compares e-ammonia production costs versus other e-fuels in the same basis (50 €/MWh electricity price):

Figure 54. E-ammonia production costs versus other liquid e-fuels (min / max)


Source: [Dechema 2017]. Note: min values in grey, max value in blue

According to IEA, the following figure compares the cost of producing ammonia from natural gas with those of producing ammonia from electrolysis. The natural gas price used is assumed to represent the European market. The conditions for electrolysis illustrate two situations, “average” renewable resources at 55 €/MWh, and world’s best.

Figure 55. Cost of e-ammonia from NG reforming vs electrolysis of water


Source: [IEA 2018]

The IEA analysis suggests that producing ammonia from renewables in world’s best resource areas can compete with natural gas reforming in Europe, especially if carbon emissions are constrained or taxed.

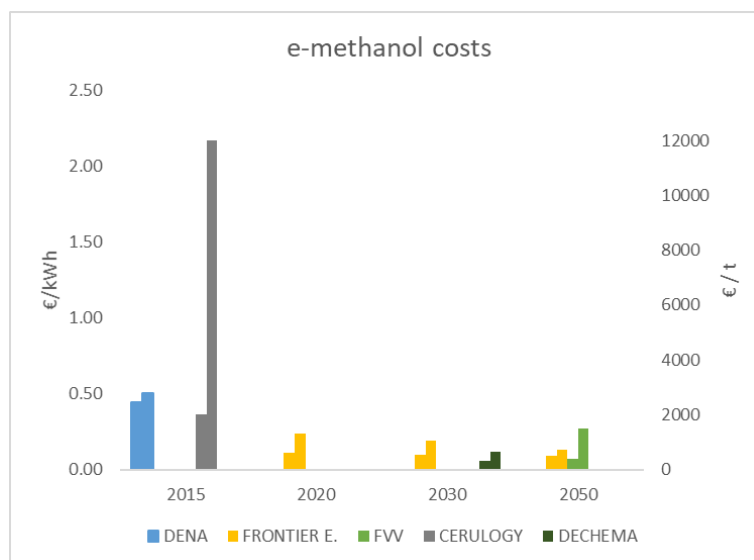
This analysis bears several interesting conclusions. If ammonia is needed for its own sake, e.g. as feedstock for industry, or because a long-duration storage is needed, imports from best renewable resource areas will likely dominate over local production and (as seen above) natural gas reforming. However, if hydrogen gas is required either as feedstock or energy carrier for most fuel cells, the costs of turning it into ammonia, transporting it and turning it back to hydrogen gas significantly reduce the price advantage over local hydrogen production from renewables. Furthermore, neither routes are cost competitive with natural gas reforming combined with CCS.

According to the University of Maritime Advisory Service [UMAS 2019], e-ammonia would be competitive versus biofuels for current ships if electricity is below 0.05 \$/kWh.

3.1.2.4. E-methanol

E-methanol cost ranges from below 0.5 €/kWh (3,000 €/t) by 2015 (except for the Cerulogy high scenario) to below 0.05 - 0.27 €/kWh (300 - 1,500 €/t) by 2050 [Cerulogy 2017].

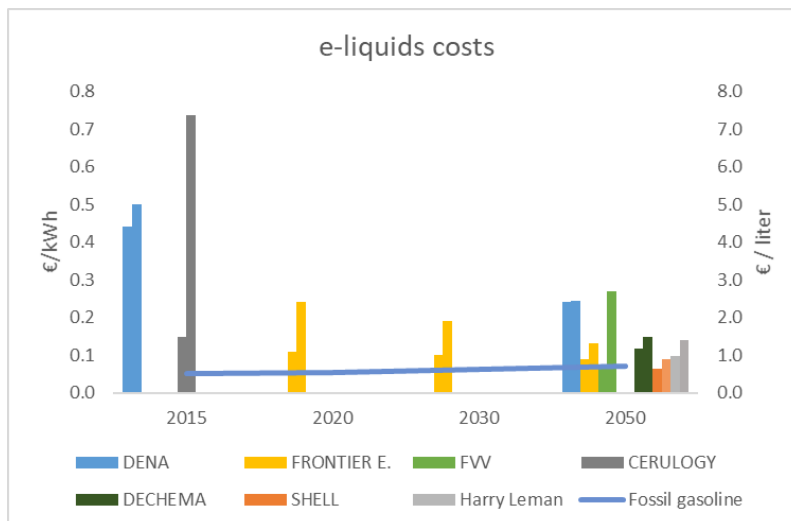
Figure 56. E-methanol costs (min/max) (€/kWh and €/t)



3.1.2.5. E-gasoline, e-diesel, e-kerosene

Liquid hydrocarbon e-fuel costs ranges from up to 0.8 €/kWh (7 €/l) by 2015 to around 0.1-0.3 €/kWh (1-3 €/l) by 2050.

Figure 57. Liquid hydrocarbon e-fuel costs (min/max) (€/kWh and €/l)



Note: Cerulogy data based on low and high cases [Cerulogy 2017]

In comparison with conventional fossil fuel, e-fuel costs are currently much higher but they tend to converge over time, so that in 2050 they are around 1-3 euros/litre (without taxes). In the less optimistic scenarios, cost of e-fuels could be up to three times higher than fossil fuels by 2050.

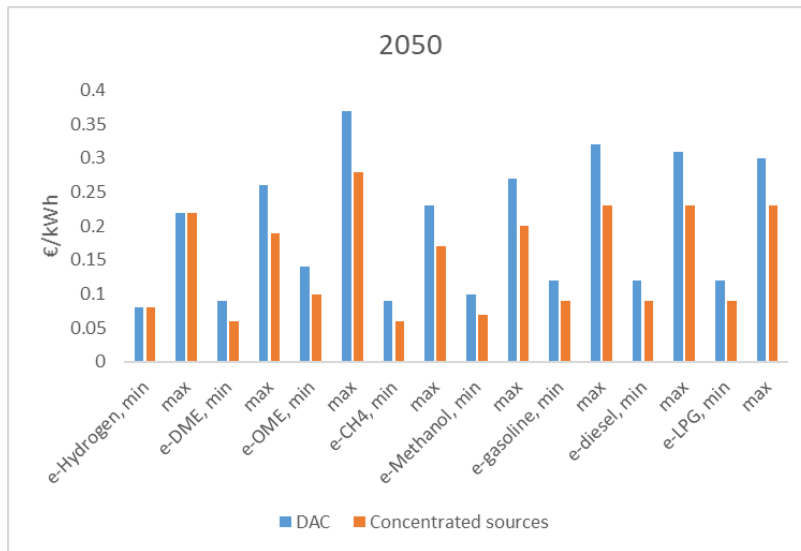
Estimates by Bosch are aligned with the above outlook, suggesting that the fuel could cost between 1 and 1.4 euros a litre in the long run.

3.1.2.6. CO₂ source impact

The following **Figure 58** compares all of them in the same basis. According to FVV [FVV 2018a], it is shown that by 2050, all e-fuels would be below 0.25 €/kWh (with CO₂ from concentrated source) or below 0.4 €/kWh (with CO₂ from the air). That means CO₂ source impact is around 0.15 €/kWh in the total e-fuel price (<40%)⁴³.

⁴³ FVV in these data seems far more optimistic than other literature sources prediction.

Figure 58. E-fuels costs (min/max) per type of e-fuel (€/kWh e-fuel), by 2050



Source: [FVV 2018a]

Note: for every e-fuel, the first set of bars are minimum and the second set of bars are maximum costs.

In the next **Table 30** the CO₂ costs employed by different sources for their assessment are shown. There is a difference in 10 times the cost of CO₂ depending on the origin (DAC or Concentrated source (Conc)).

Table 30. CO₂ costs (€/t CO₂), by 2050

		2015	2030	2050
[dena 2017]	DAC	380		277
[Frontier Economics/ Agora 2018]	DAC		145	100
[FVV 2018a]	DAC			124-293
[ICCT 2018]	Conc		34	
	DAC		513	
[Cerulogy 2017]	Conc	30		

Bellona 2017 claims that only if CO₂ were to be captured from ambient air would the resulting fuels not increase the concentration in the atmosphere [Bellona 2017].

However, while there are still industries that emit CO₂ as part of the process, it is still more energy/CO₂ efficient to capture the CO₂ from enriched streams. DAC is the most expensive option.

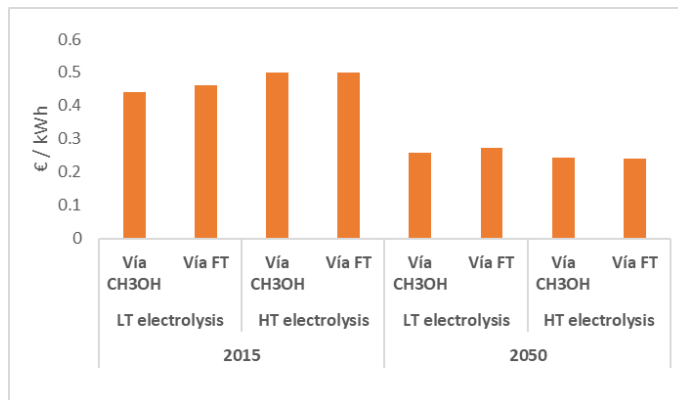
In conclusion, there is a high variety of expected costs for DAC and concentrated CO₂, depending on the different literature sources.

See a detailed comparison of CO₂ costs from different sources in **Appendix A1-4**.

3.1.2.7. Technology impact

In the **Figure 59**, the impact of different technologies in the final e-fuel price is shown (Methanol or FT route, or LT or HT electrolysis). It is below 0,05 €/kWh in the total e-fuel price (<10%).

Figure 59. Cost of e-liquid fuels made from different technologies, by 2015 and 2050 (€/kWh e-fuel)



Source: [dena 2017]

Note: dena quotes electricity costs, including transport and distribution, amounting to about 11 c€/kWh of electricity in 2015, and about 8.4 c€/kWh of electricity in 2050.

3.1.2.8. Operating costs

References estimate the operating costs as a percentage of the investment costs:

- Hydrogen electrolysis plants: 3% for low-temperature electrolysis, and 3.5% for high-temperature electrolysis, of investments costs per year.
- Methanisation plants: 3% of investments costs per year.
- Methanol synthesis and Fischer-Tropsch synthesis: 3% of investments costs per year.
- CO₂ Capture from the air: 4% of investments costs per year.

3.1.2.9. Water supply costs

The costs of supplying water are negligibly low, even in countries in which the water must be obtained from desalination plants.

The synthesis of 1 litre of liquid e-fuel in a plant requires a raw water import of 3.7 - 4.5 l as feedstock.

If all water produced is recycled back to the electrolyser, the net intake of water is 1.3 - 2.0 l per litre of e-fuel [Shell 2018].

The investment costs of desalination plants are 1,150 euro/m³ per day (420 €/m³ per year)⁴⁴; the operating costs are four per cent of the investment costs; and the electricity consumption is 4.1 kWh el/m³.

⁴⁴ This means between a 10% (if water is recycled to the electrolyser, where -2 l of water / l of e-fuel is required) to a 20% (if water is not recycled, where -4 l of water / l of e-fuel is required) of the current e-fuel production cost (-7 €/l).

3.1.2.10. Transport costs

Transport costs are of secondary importance in the total e-fuel costs. According to Frontier Economics, the costs for the transportation of the e-fuels from exporting to importing countries (e.g. Germany/Europe) range from 0% for transporting e-liquid fuels up to 8% for transporting gaseous fuels like methane. If existing infrastructure for transporting these gases already exists, for example gas pipelines from Norway, Russia or North Africa to Europe, these costs are negligibly low [Frontier Economics/Agora 2018].

Transport costs are estimated like it is shown in **Table 31** and **Table 32**:

Table 31. E-methane transportation costs

	ct€/KWh
Liquefaction	0.61- 0.69
Transport from Iceland	0.08
Transport from North Africa	0.12
Transport from the Middle East	0.36
Regasification	0.15
Total	0.84 -1.19

Source: [Frontier Economics/Agora 2018]

Table 32. E- Liquid fuels transportation costs

Production country	Port of departure	Sea distance to Hamburg (km)	Transport costs (ct/kWh)
Iceland	Reykjavik	2,332	0.014
North Africa	Algiers, Agadir, Casablanca	3,600	0.022
Middle East	Muscat, Dubai	11,000	0.067

Source: [Frontier Economics/Agora 2018]

3.1.3. Cost drivers

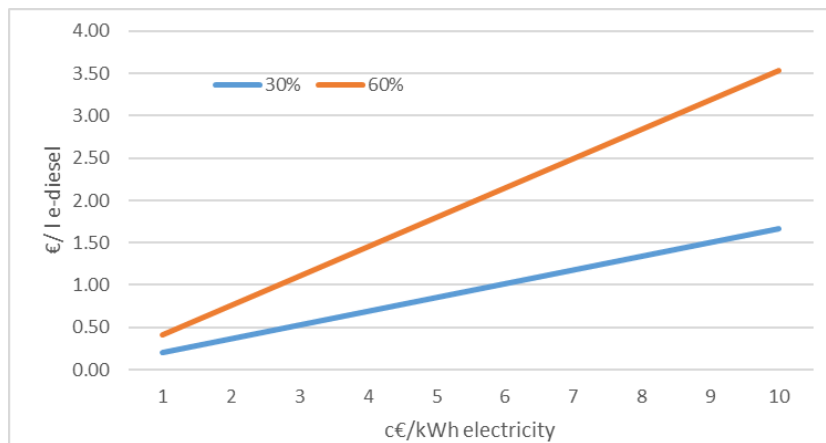
The most important cost drivers for the future cost of e-fuels are the costs of power generation and the capacity utilization of conversion facilities. Costs of power generation include the CAPEX required to increase the power facilities. Also an important driver is the capital cost recovery of the e-fuels plants themselves.

3.1.3.1. Costs for renewable electricity generation

Renewable electricity costs account for around one third of the total e-fuel costs (Frontier Economics (2018)). Therefore, electricity cost and efficiency of the processes is a key driver of e-fuel costs.

The cost of the e-fuel is proportional to the electricity cost as it is shown in **Figure 60** [Cerulogy 2017].

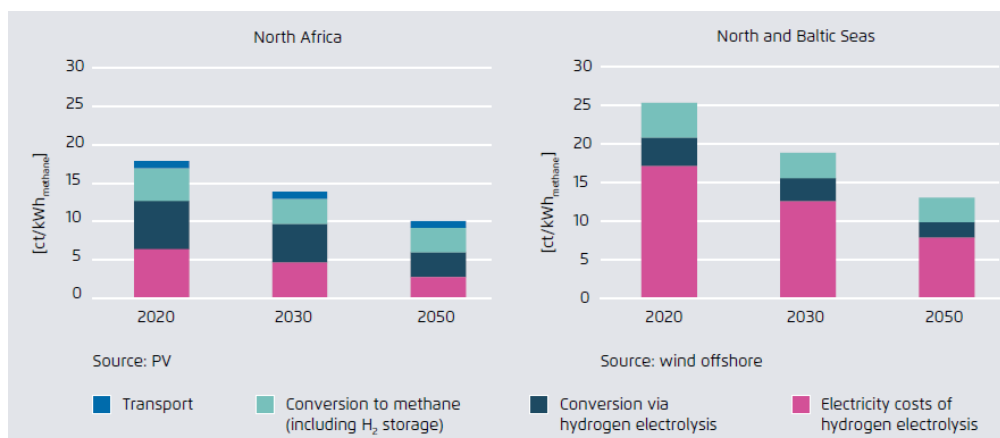
Figure 60. Contribution of electricity costs to e-fuel cost for overall electricity conversion efficiencies from 30 to 60%.



Source: [Cerulogy 2016]

Although electricity generation costs are expected to fall until 2050, they will continue to make up a significant fraction of total costs in 2050, as it is shown in Figure 61.

Figure 61. Comparison of the generation and transport costs of e-methane in North Africa (photovoltaic) and in the North and Baltic Seas (offshore wind)



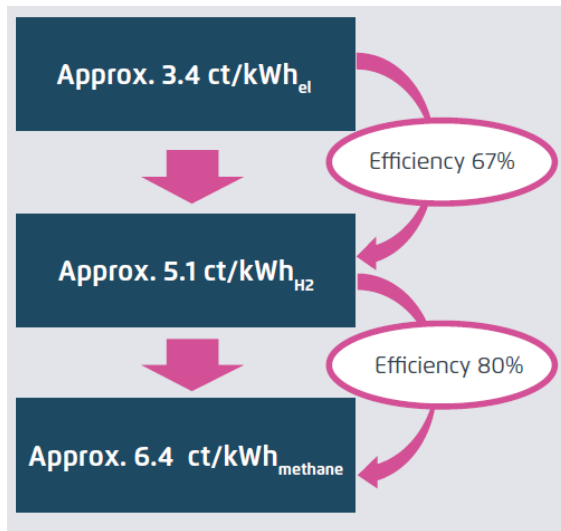
Source: [Frontier Economics/Agora 2018]. Note: Although in the original source, it is mentioned that CO₂ capture costs are included in the calculation, they are not shown as an independent block in the chart.

Renewable power is becoming increasingly cost competitive with power generation from fossil fuels, but depends very much on the region. Latest estimates for levelised cost of electricity (LCOE) are around 5 ct€/kWh; an LCOE of 1 ct€/kWh is needed to achieve e-fuel costs of 1 €/litre [Shell 2018], which is still higher than a fossil fuel.

The large influence of the electricity generation costs on the cost of e-fuels is primarily linked to system inefficiencies across the e-fuel value chain. The illustrative example in Figure 62 demonstrates the resulting conversion losses: If electricity generation costs are 3.43 ct€/kWh el and the system efficiency is 67% for the water electrolysis and 80% for the second-stage conversion processes

(methanisation, Fischer-Tropsch or methanol synthesis), the electricity cost for the final product are 6.39 ct€/kWh e-fuels.

Figure 62. Illustrative example of conversion losses.

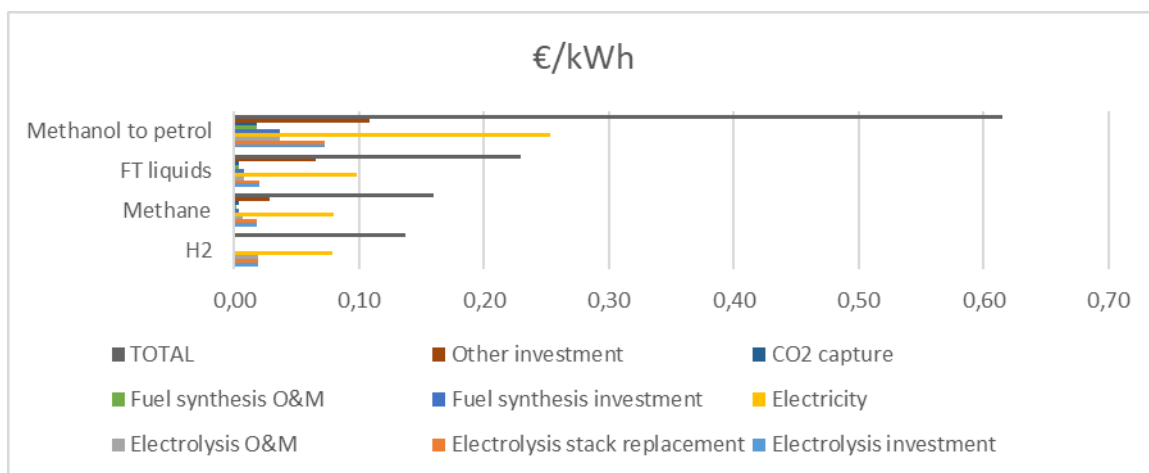


Source: [Frontier Economics/Agora 2018]

Note: Reference case for e-fuels in North Africa based on photovoltaic in 2020.

Figure 63 shows that electricity costs account for around 33% of the total e-fuel cost, which is why importing e-fuels from regions with cheap renewable electricity could decrease the e-fuels costs significantly.

Figure 63. E-fuels production costs in 2015



Source: Ceruly with Concawe own assessment, based on LHV and density values. Data based on Ceruly's base case [Ceruly 2017]

Notes:

PEM electrolyser: 5 ct€/kWh electricity, CO₂ from industrial concentrated source; capacity factor >80%, 5% interest rate.

Power generation CAPEX is not included. Depending on the level of deployment of e-fuels, additional power generation CAPEX could have an impact on electricity price.

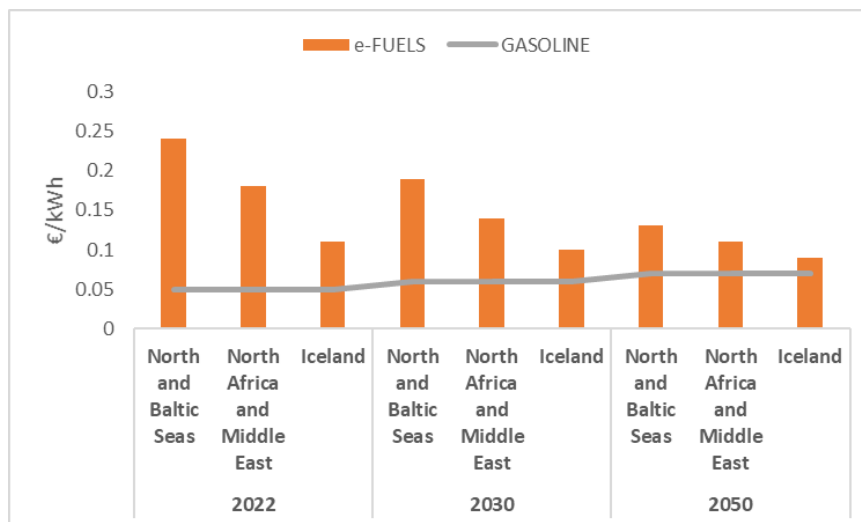
"Methanol to petrol" is referring to liquid e-fuels via methanol route instead of the FT route.

Investment costs are expressed as part of the production costs using factors. E.g.: for low temperature electrolysis, a factor of 600 - 3700 €/kWe in the short term is used, reducing to 300 - 1300 €/kWe in the longer term. For large facilities on the 100 MWe scale investment requirements could be 250 €/kWe. High temperature electrolysis is unlikely to be available at commercial scale until 2030 or so - predicted investment requirements are of 400 - 1000 €/kWe. Other investment may include hydrogen storage and grid connectivity costs.

Table 33. LHV and density values utilised for e-fuels production costs Concawe assessment

	e-hydrogen	e-methane	e-diesel	e-methanol
Density (kg/l)			0.83	0.79
LHV (MJ/kg)	46	50	44	20

Figure 64. Cost of e-methane and liquid fuels produced in different world regions (€/kWh e-fuel)



Source: [Frontier Economics/Agora 2018]

Notes:

- North and Baltic seas based on offshore wind power, North Africa and Middle East on 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
- Costs could potentially fall to those values by 2050 if global e-fuel capacity reaches around 100 gigawatts. The 100 gigawatts of electrolysis capacity needed for affordable e-fuels corresponds to a five-fold increase in the world's current installed capacity of about 20 gigawatts. Such an increase in capacity would cost between 10 and 100 billion euros by 2050.
- DAC considered (See variability of captured CO₂ costs in Appendix A1.4.)
- Electricity prices considered:

Electricity prices considered (ct/kWh)	2020	2030	2050
North and Baltic seas (Offshore wind)	7-12	5-11	4-8
North Africa - Middle East (PV)	3-4	2-3	1.1-2.7
Iceland (Geothermal/hydropower)	2.8	2.7	2.6

Source: [Frontier Economics/Agora 2018b]

According to Frontier Economics, in the medium and long term, the import of e-fuels from all export regions will be cheaper than producing them in Germany with offshore wind energy [Frontier Economics/Agora 2018].

The impact could be up to 0.15 €/kWh in the total e-fuel price (up to 50%). FVV has a more moderate view, claiming that e-fuels imports from these geographies could be some 20% lower in costs [FVV 2016].

The most favourable production option for e-fuels is based on geothermal power and hydropower in Iceland.

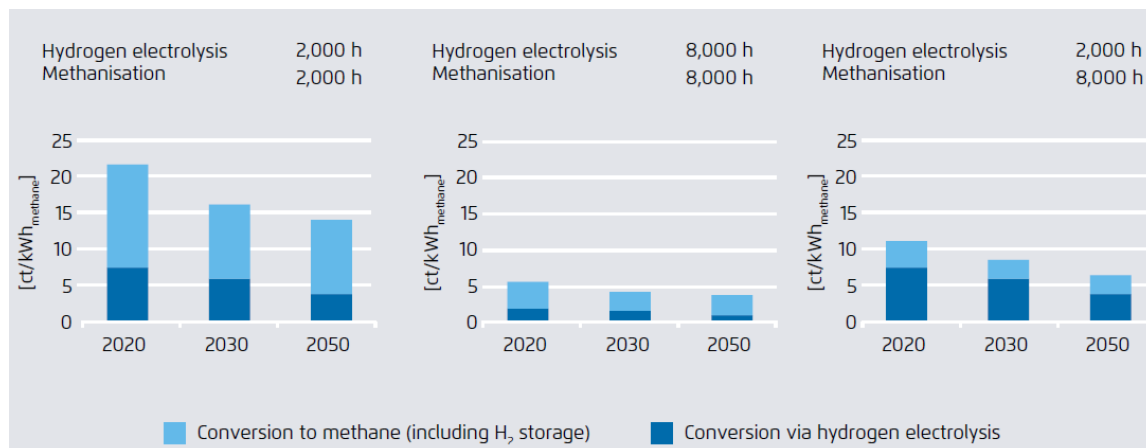
In the **Figure 64**, Frontier Economics state that the cost of the individual site and technology options converges over time. This is because the investment costs for photovoltaic power plants and offshore wind turbines are assumed to fall more sharply than the CAPEX for established technologies such as onshore wind, geothermal and hydropower.

3.1.3.2. Impact of utilisation rate for conversion plants

The utilisation rate of conversion plants are also a considerable cost driver. These represent the second most important cost component after electricity generation costs, as it is shown in **Figure 65** from Frontier Economics (2018). The impact from a 2,000 h to 8,000 h utilization rate could be up to 0.15 €/kWh (up to 75%).

There is a general concern whether 2,000 hours of full-load operation is operationally manageable for an e-fuel process plant and can give adequate returns on investment.

Figure 65. Impact of utilisation rates



Source: [Frontier Economics/Agora 2018]

3.2. FUTURE DEMAND SCENARIOS

3.2.1. Potential future demand (2030/2050)

European scenarios for 2020, 2030 and 2050 are used by several references with each in Europe by different references, each of them following a different approach.

However, there does appear to be a consensus that e-fuels will not play a significant role by 2020. By 2030 and increasingly, by 2050, a high variability of potential demand in Europe is foreseen by different sources. By 2050, estimates for e-fuels demand range from the more conservative references who suggest e-fuels demand may be in the order of <50 Mtoe/a ([Prognos 2018], [DG R&I and Ecorys 2017]) to the more optimistic references who suggest it may reach 300-

380 Mtoe/a ([Dechema 2017], [FVV 2018]). This is of course dependent upon the ability to reduce the production cost as anticipated.

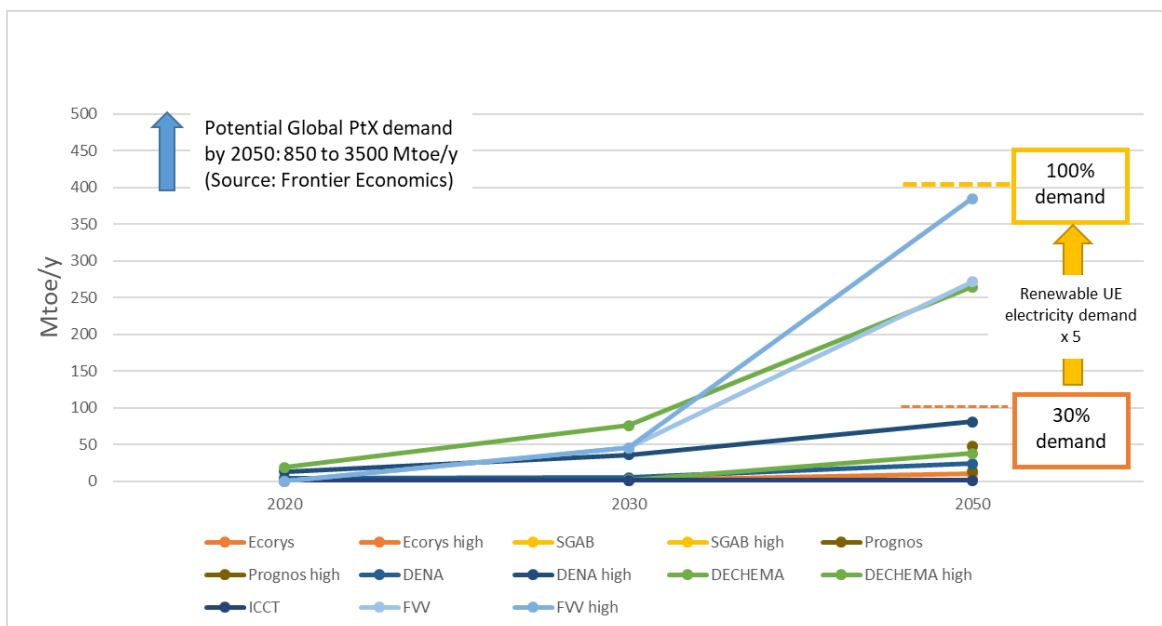
For comparison, the energy demand for transport forecasted in the European Commission EU reference scenario [European Commission 2016], is suggested to be around 350 Mtoe/a by 2030-2050.

In summary, the e-fuels potential contribution by 2030 is below 15% of predicted total EU transport demand by 2030, and below 30% of total EU predicted transport demand by 2050, according to most references (with the exception of Dechema and FVV high scenarios, which estimate it could potentially reach up to 100% contribution of total EU predicted transport demand by 2050).

This compares with prediction for the global e-fuels demand in the range 850 to 3,500 Mtoe/a by 2050 [Frontier Economics/Agora 2018].

The **Figure 66** and **Table 34** summarize the different approaches followed by different sources:

Figure 66. European Potential Demand for e-fuels (base and high scenarios) according to different references (2020-2050)



Source: [European Commission 2016]

Note: 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)

Table 34. E-fuels EU demand estimation approach followed by different references

Main references	Main approach followed
[Frontier Economics/Agora 2018]	Based on percentage shares of e-fuels of final energy demand by sector
[DG R&I and Ecorys 2017]	Based considering extensive R&I efforts and development of conversion technologies
[European Commission 2017. SGAB]	Based on what the industry can deliver from the conversion facilities point of view, given the appropriate policy framework and financing structure
[Prognos 2018]	Minimum equivalent to air and sea traffic, max to all sectors. Based on Germany demand
[LBST and dena 2017]	Based on demand scenarios competing with other transport technologies
[Dechema 2017]	Based on different scenarios competing with chemical production technologies
[ICCT 2017, 2018]	Based on future electricity prices and financial parameters
[FVV 2016]	E-fuels replace today's fossil fuels

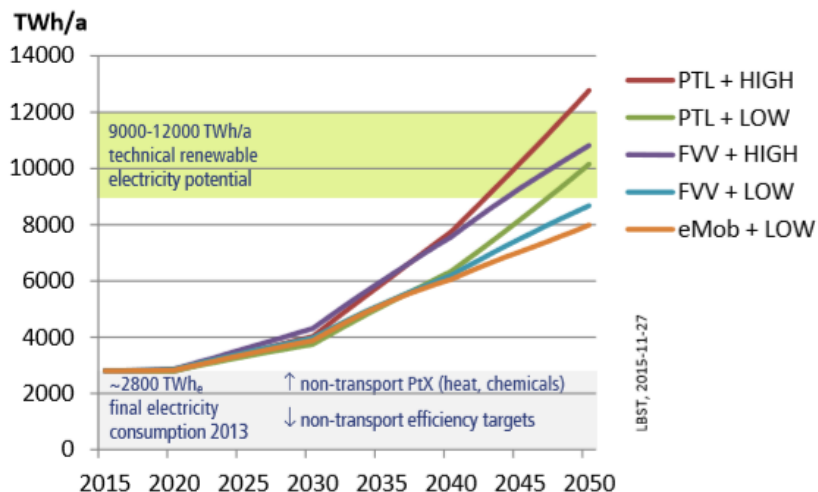
The potential scale of e-fuels coverage of transport fuel demand could reach even 100% in some cases - this is unrealistic and these proposals are more as what we might call "normative scenarios" (this is what would need to happen) as distinct from what credibly might happen.

Looking only at demand does not give a robust answer of what is realistic or achievable, because demand could theoretically be 100% covered by e-fuels. So, would it be possible to look at this in a different way i.e. what are realistic implementation scenarios for ramping up e-fuel production (e.g. as a function of availability of fully renewable electricity)?

The answer depends on the investment and operation costs reduction of the different sustainable fuels technologies and on the technical potential supply for renewable considered. For example, FVV 2050 high scenario (where e-fuels could provide up to 100% of potential demand in transport in Europe) implies an increase from 2,800 TWh (today's electricity consumption in the EU-28), to values up to 9,000-12,000 TWh/a, which means a multiplier factor of 3 to 5 of today's total European electricity demand [FVV 2016]⁴⁵.

⁴⁵ This electricity requirement is to cover transport only, and that it does not include the requirements of other industries which will also probably need additional electricity to decarbonize their emissions.

Figure 67. FVV Renewable electricity demand from the transport sector versus technical renewable electricity potential for Europe

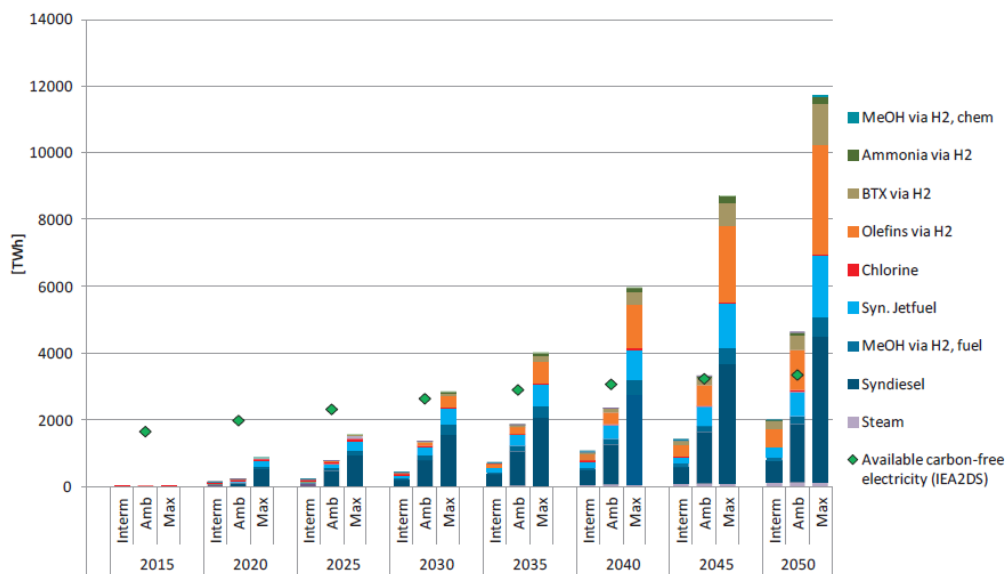


Source: [FVV 2016]

Note from the original source: This chart compares the EU-28 transportation electricity demands from different scenarios. Transportation electricity demands are shown on top of today’s electricity demand. Today’s electricity demand is kept constant because a discussion of new electricity consumers - like power-to-heat, power-to-chemicals, etc. - versus electricity demand reductions induced by energy efficiency targets would merit a modelling study of its own.

This conclusion is also aligned with Dechema 2050 high scenario, where the available renewable electricity should be at least 5 times the available today, and at least 4 times the predicted available in 2050 by IEA2DS scenario.

Figure 68. Dechema demand scenarios versus carbon-free electricity availability



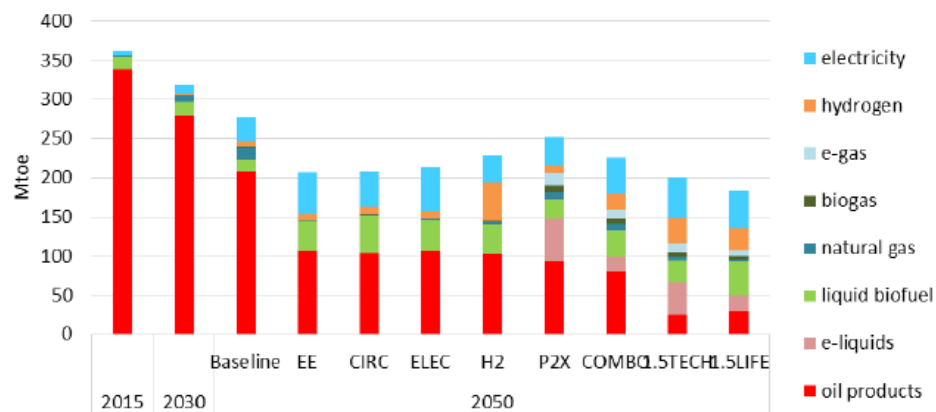
Source: [Dechema 2017]

In conclusion, e-fuel (e-liquids and e-gas) production by 2050 in Europe (according to what different sources claimed that could be considered “realistic”) with the expected ramp-up of available carbon-free electricity in Europe by 2050, could reach from 0 to 50-80 Mtoe/a (from 0 to 30% of the total transport demand expected in Europe by 2050⁴⁶). Values over this percentage would require a huge increase in renewable electricity infrastructure, which seems to be extremely challenging with significant uncertainties regarding the potential impact on electricity costs.

The percentage of 30% is aligned with the fuel consumption scenarios in the transport sector in 2050, reported by the European Commission in the Long Term Strategy *A Clean Planet for all* [European Commission 2018].

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), which is the only scenario reducing by -80% by 2050, that shows a significant uptake of e-fuels.

Figure 69. Fuels consumed in the transport sector in 2050



Source: PRIMES.

Source: [European Commission 2018]

Note: This scenario considers a total transport demand of 250 Mtoe/a by 2050, differently to EU reference scenario [European Commission 2016], that claims a 350 Mtoe/a by 2050.

3.2.2. Domestic production vs import

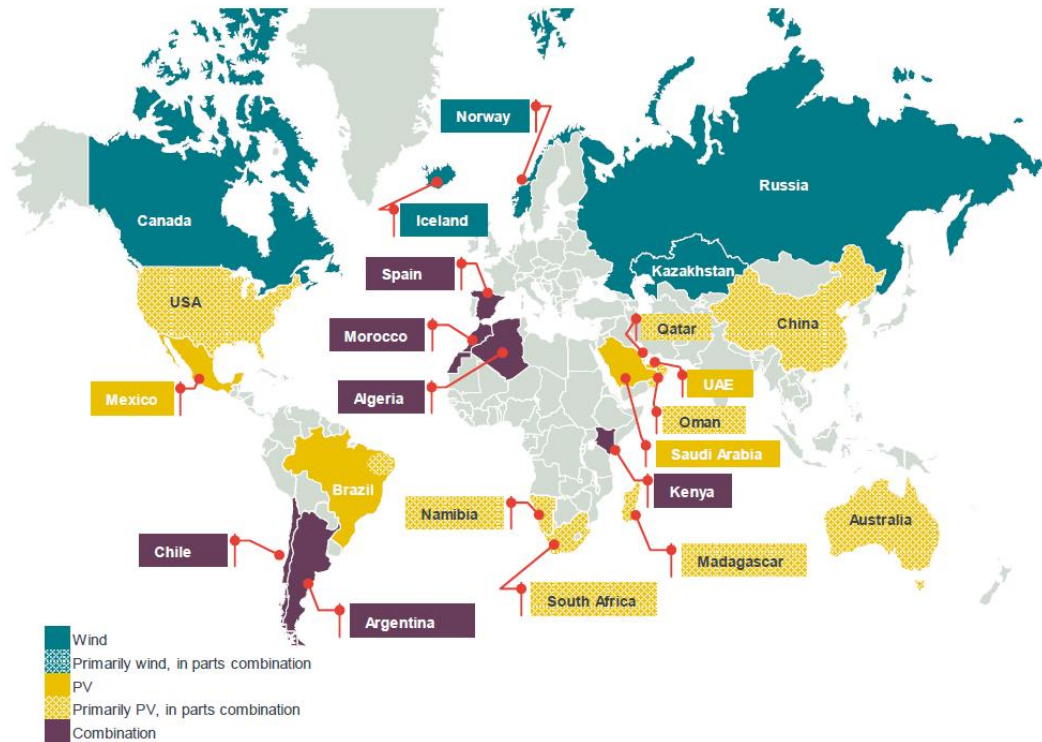
There are references, such as Frontier Economics, who focus their study on the option of importing e-fuels to cover demand in the heating and transport sectors [Frontier Economics 2018].

Importing e-fuels could become an important element of the energy transition if the availability of renewable energy produced in some European countries, cannot meet demand over the long term. The import of e-fuels also has the advantage of allowing the use of highly favourable sites for generating renewable electricity (i.e. locations with excellent wind and solar resources), with a potential reduction in the associated cost.

⁴⁶ Efficiency considered from electricity to e-fuel: 44%. Source: [Frontier Economics/Agora 2018].

Frontier Economics 2018 suggests that a global e-fuels market will emerge, with exports from many potential e-fuels producing countries. Countries and regions with favourable conditions for renewable energies and a high technical potential for producing power from renewable energy sources are strong candidates for e-fuels production and exports.

Figure 70. Strongest potential e-fuels producer worldwide



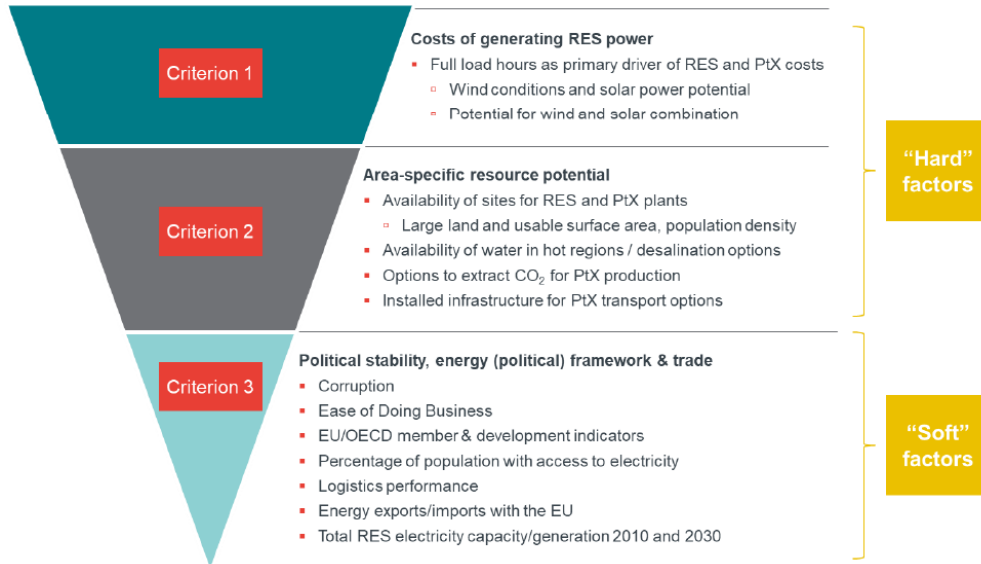
Source: [Frontier Economics 2018]

Besides Frontier Economics, references such as FVV also claims that e-fuels imports from world region with favourable conditions for renewable electricity production, including North Africa and the Middle East are likely to be 20% lower in costs, including transportation costs to Europe [FVV 2016]⁴⁷.

According to Frontier Economics, in order to capture the benefits of international production and trade of e-fuels and realise investments in e-fuels facilities and infrastructures, potential e-fuels exporting countries need to fulfil a number of requirements. These can be sub-divided into “hard” and “soft” factors:

⁴⁷ Note that this comparison is done on a DAC technology in every region. The reduction in renewable cost of electricity could be somewhat compensated by the CO₂ capture cost reduction if coming from concentrated sources.







Figure 71. Overview of factors for identifying potential e-fuels producers



Source: [Frontier Economics 2018]

The potential e-fuels suppliers are currently at different levels of readiness and willingness to participate and in this emerging market. However, Frontier Economics, for illustrative purposes and to provide a concept on how these countries might be clustered with regard to their part in a global e-fuels market, identify several types of “e-fuel stories” and a selected example of a country that may fall within each of these categories, and is considered representative for a wider group of potential suppliers.

Table 35. Type and examples of e-fuels production in different regions of the world

Type	PtX motivation and readiness	Selected example
 Frontrunners	<ul style="list-style-type: none"> ▪ PtX already on countries (energy) political radar ▪ Export potential and PtX readiness evident ▪ Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration 	Norway
 Hidden Champions	<ul style="list-style-type: none"> ▪ Fundamentally unexplored RES potential ▪ Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ PtX could readily become a serious topic if facilitated appropriately 	Chile
 Giants	<ul style="list-style-type: none"> ▪ Abundant resource availability: massive land areas paired with often extensive RES power ▪ PtX readiness not necessarily precondition, may require facilitation ➢ Provide order of PtX magnitudes demanded in mature market 	Australia
 Hyped Potentials	<ul style="list-style-type: none"> ▪ At centre of PtX debate in Europe with strong PtX potential ▪ Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation 	Morocco
 Converters	<ul style="list-style-type: none"> ▪ Global long term conversion from fossil to green energy sources ▪ PtX to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for PtX export technology development; may require political facilitation and partnership with the EU/DE 	Saudi Arabia
 Uncertain Candidates	<ul style="list-style-type: none"> ▪ Partially unexplored RES potentials, possibly paired with ambitious national climate change policies ▪ PtX export in competition with growing national energy demand ➢ PtX export motivation and potential unclear – may drive PtX technology development, however export uncertain 	China

Source: [Frontier Economics 2018]

In any case, Frontier Economics claims that the development of new energy infrastructure will require the support and facilitation from local politicians and administrations. This is particularly relevant to gain public acceptance and to be able to finance the necessary infrastructure investments. Consequently, the success of an implementation of new energy systems also relies on energy strategies developed by governments in energy-consuming countries.

4. CONCLUSIONS

In this final section of the paper, the main takeaways from the report explore: Pros/cons, potential role, key enablers, advantages and disadvantages per type of e-fuel / use / technology.

4.1. PROS, CONS, CHALLENGES AND OPPORTUNITIES

E-fuels have numerous advantages:

- They achieve a significant CO₂ reduction versus their equivalent fossil-based fuels offering a compelling complementary alternative for low-CO₂ mobility in Europe.
 - The main CO₂ abatement potential is ~ 85-96% (WTT basis) or 70% (LCA analysis)
 - The CO₂ abatement potential (WTT basis) is similar if CO₂ comes from direct air capture or from a concentrated fossil source⁴⁸.
- E-fuels have a higher energy density compared to batteries, and can thus be used in mainstream aviation and shipping sectors where no electricity-based alternatives can be found.
- E-fuels are easy (and relatively inexpensive) to store compared to electricity:
 - E-fuels can be kept in large-scale stationary storage over extended periods, and mobile storage in vehicle tanks, allowing to compensate seasonal supply fluctuations and contribute to enhance energy security⁴⁹.
- Existing infrastructure can remain in use for transporting and storing (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 of the e-fuels could be deployed immediately across the whole transport fleet without any major change in engine design.
 - In the case of liquid e-fuels, they offer an alternative technology to reduce GHG emissions in both old and new vehicles without requiring the renewal of the fleet.
- For blending, a blending ratio of up to 100% is possible when adding methane to natural gas, and e-liquid fuels to gasoline and diesel, providing they are meeting their corresponding specifications.
- Regarding air quality, e-fuels would have positive environmental impacts, because of the favourable combustion characteristics of the molecules produced.
- E-fuels routes are more favorable in terms of land use than biofuels routes. Advanced lipids and biomass biofuels efficiency in terms of land use (m² land) is up to 1000 times lower than e-fuels for the same fuel production.

⁴⁸ Although there are controversial opinions about the total “carbon-neutrality” of the CO₂, because some sources as Bellona or Transport & Environment state that the use of concentrated CO₂ sources does not close the carbon cycle while CO₂ from DAC does.

⁴⁹ Strategic petroleum reserve within the territory of the E.U. equal to at least 90 days of average domestic consumption.

E-fuels have also disadvantages:

- The inherent thermodynamic conversion inefficiency that occur when producing e-fuels, which result in a significant amount of new renewable generation plants requirement⁵⁰.
 - The overall energy efficiency of electricity use in battery electric vehicles is 4-6 times higher than e-fuels in combustion engines.
- The current low scale of the technology, still in a pilot/demo scale.
 - Some really profound challenges could be discovered as the facilities are scaled up by a factor of 100,000 times (compared to what has been demonstrated so far, in a demo scale) or 100 times (compared to a new announced project in Norway starting up in 2021) to reach a large-scale commercial plant⁵¹.
- The massive amount of capital-intense equipment, which is necessary to deploy the technology.
- High e-fuels production costs in comparison with conventional fossil fuels.
 - E-fuel costs are currently high (up to 7 euros/litre) but they are expected to decrease over time due to economies of scale, learning effects and a reduction in the electricity price, being in 2050 around 1-3 euros/litre (without taxes). Therefore, cost of e-fuels could be from one to three times higher than fossil fuels by 2050.

In comparison with direct use of electricity:

- Direct electrification of the transport sectors (such as passenger cars) would allow the direct use of renewable electricity.
 - The advantage of this approach is that electricity does not have to be converted into another type of energy, which entails conversion inefficiencies.
 - The disadvantages of this approach include the losses associated with transporting, distributing and particularly with storing electricity. Furthermore, beyond the costs that would arise from constructing new renewable generation capacity, widespread electrification would entail significant investment in additional electricity transport grids, distribution grids and electricity storage infrastructure.
 - There could also be issues with the supply raw material for batteries which would impose limits on the transition of the entire EU passenger car fleet to battery electric vehicles [Bosch 2018], besides unpredictable developments of battery costs, infrastructural stresses and recycling challenges [VDA 2017]. This also has to be considered in the context of the degree of transition of the global vehicle fleet and competition with other regions in the drive for electrification.

Some opportunities/synergies e-fuels deployment could benefit from are:

- Industrial clusters, within industrial producers of CO₂ to produce e-fuels (as a concentrated source)

⁵⁰ E.g. to supply 1% of the total EU expected demand in transport by 2050 with e-fuels, it is required 6% of the total EU-28 current installed wind power capacity (178 GW) or 100% of, e.g. the Netherlands + Sweden current installed wind power capacity (11.88 GW) [WindEurope 2018].

⁵¹ Shell's Pearl facility, the largest synthetic liquids (GtL) plant in the world, located out of Europe -Katar-. Only this part of the e-fuels route has been commercialised producing fuels at a scale comparable to conventional refining.

- In the future, it is likely that there will still be industry sectors that emit large amounts of CO₂ for process-related reasons (for example, refineries, production of steel, cement or biogas).
- A “notional⁵²” refinery in the European Union (EU) in 2050, where a high penetration of energy efficiency, electrification and CO₂ capture is assumed, would reduce their direct CO₂ emissions from around 1,600 kt/a to 500 kton/a. To produce 1,000 kton/a of e-fuel, 3,000 kton/a of CO₂ are required. Therefore, to produce 1,000 kton/a of e-fuel in a 2050 notional refinery, 15% of the CO₂ would be produced within the refinery, and 85% would have to be imported from another CO₂ producer
- The expected CO₂ generation from large point sources is expected to exceed the amount of CO₂ required for the e-fuels demand.
- OEMs-Industry alliances
 - Some OEMs (Original Equipment Manufacturer), such as Audi, are developing an e-fuels strategy to support their compliance pathway.
- Business models based on regions with large and cheap renewable energy sources
 - The import of e-fuels from geographically privileged regions is relatively simple.
 - Importing e-fuels from low-electricity cost regions in the world could reduce costs up to 20-50%.
 - Dependency on external EU countries could be diversified compared to current fossil fuel dependency on a restricted list of countries beyond Europe.

Some of the e-fuels strengths, opportunities, challenges and concerns, and a comparison versus other options are summarized in **Figure 72** and **Table 36**.

Figure 72. Strengths, opportunities, challenges and concerns of e-fuels

Strengths	<ul style="list-style-type: none"> • Drop in capability • High energy density • Near zero GHG emissions
Opportunities	<ul style="list-style-type: none"> • Business perspective for regions with large wind and solar potentials • Industrial clusters within industrial producers of CO₂ to produce e-fuels / OEMs
Challenges	<ul style="list-style-type: none"> • Costs of fuel production • Accessibility to CO₂ sources (concentrated versus DAC) • Significant more need for renewable electricity
Concerns	<ul style="list-style-type: none"> • Lock-in of established combustion engines technologies • Acceptance of extensive renewable power plants

Source: Concawe based on German Environment Agency [German Environment Agency 2016].

⁵² Notional or “average” mid-range refinery (160,000 bbl/d of crude oil intake, assumed throughput - current demand - and process unit capacities consistent with the European average refinery configuration, with a current direct CO₂ emission of 1,600 kt/a. This is a hypothetical refinery used for illustration and is not intended to represent a “typical” refinery). See **section 2.4**.

Table 36. Different options versus different key parameters

	Transport sectors	Infrastructure	Storage	Investment	GHG reduction
Fossil fuels	All	Existing	Easy	Low	Low
Electricity	LDV / HDV	New	Difficult	High	High
Biofuels	All (limited by availability and cap in demand)	Existing	Easy	Medium	High
E-fuels	All	Existing ⁽⁵³⁾	Easy	High	High

4.2. POTENTIAL ROLE OF E-FUELS IN MID-CENTURY EUROPE

In *A Clean Planet for all* [European Commission 2018] different scenarios have been presented to meet EU objectives of -80% GHG reduction by 2050.

In the EU's vision, e-fuels play a role, with a specific scenario focused on them (PtX scenario, with e-fuels in all modes of transport and other sectors).

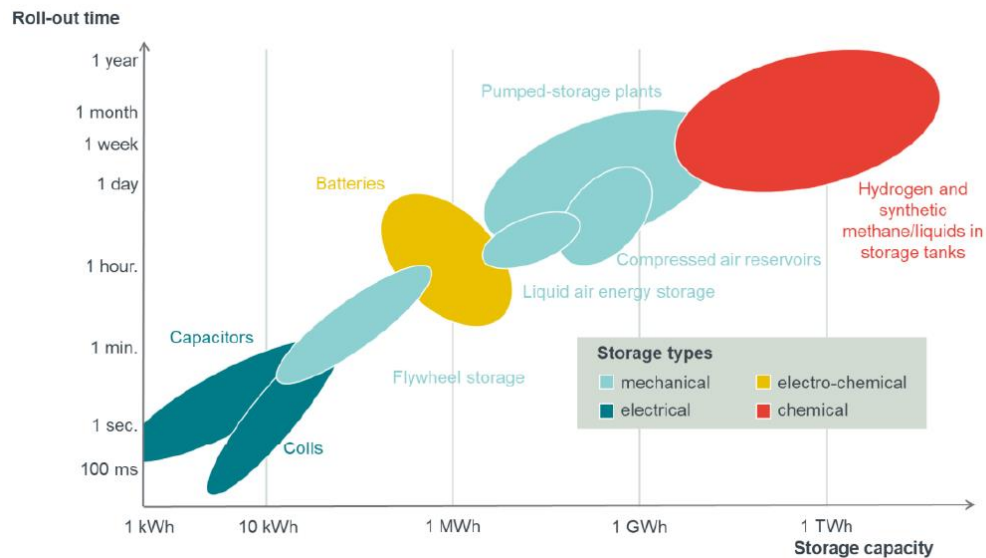
All sources analysed agree that e-fuels will play a role in sectors where no realistic, efficient alternative is foreseeable, such as **maritime and aviation sectors** (where experts claim mainstream electrification is not viable in a medium-long term).

E-fuels are also taken into account as an **energy storage** for renewable energy, as [Frontier Economics/Agora 2018] explicitly states in their report

- *“Power is increasingly produced from renewable energy sources in Europe, in particular from wind and photovoltaic. This fundamental development makes energy storage indispensable because wind and sun are only capable of providing fluctuating energy. This applies at short notice, i.e. within or between individual days and over weeks, as well as seasonally, i.e. over several months (e.g. from summer to winter for heating)”.*
- *“Electricity can efficiently be stored for seconds, hours, days and weeks e.g. in batteries and pumped hydro storages. However, there is a lack of viable affordable solutions for seasonal electricity storage to date. In contrast, due to their energy density, e-fuels and hydrogen are well placed for seasonal storage of renewable energy. E-fuels will therefore inevitably become a central part of the transition towards a system in which renewable energy production has to be stored in large volumes and over a long period of time (seasons)”.*

⁵³ 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.

Figure 73. Technologies to economically store energy will require e-fuels



Source: [Frontier Economics/Agora 2018]

“Additionally, huge storage capacities for oil and gas are already available. According to Frontier Economics (2018), for example in Germany, existing facilities for storing liquid fuels have a volume of more than 535 TWh (this corresponds to around 42% of annual demand for oil, 62% of annual demand for the main fuel products gasoline, diesel and heating oil or 90% of the gross electricity consumption). Gas storage capacities in the existing facilities in Germany are around 260 TWh (this corresponds to more than 33% of annual gas demand)”.

“In comparison, the volume of all German power storage systems is only about 0.04 TWh. The electricity storage capacity of all German power plants is therefore currently sufficient to serve the average electricity demand for 41 minutes”.

E-fuels can also enhance energy security of a country: in the European Union, according to Council Directive 68/414/EEC of 20 December 1968, all 28 member states are required to have a strategic petroleum reserve within the territory of the EU equal to at least 90 days of average domestic consumption. E-fuels can be stored in the existing infrastructure to guarantee these 90 days of energy security.

4.3. KEY ENABLERS

Some of the main key enablers to deploy e-fuels are:

- Policy framework

All references agree that a suitable regulatory framework is needed to ensure that EU refineries industry remain competitive. As it is stated in Fuels Europe Vision 2050 [Fuels Europe 2018], policymakers at EU and national level have a crucial role in making this happen, by creating the right regulatory framework to encourage and enable investments and the development and implementation of innovative technologies.

As an example: E-fuels have an expanded role in the regulatory framework proposed for the RED II, but the proposed framework raises some important questions. Flexibility is provided in the regulation, so there is not a requirement of a direct connection between the renewable electricity and the renewable fuel production site, but the modalities of such flexibilities still need to be defined (delegated act by the end of 2021 at the latest).

According to Frontier Economics, one of the possible measures could be to raise the price of carbon emission credits. Other potential measures may include market acceleration programmes such as a credit system between first-of-a-kind plants and vehicle manufacturers to incentivise the development of the technologies [Frontier Economics/Agora 2018] and the WTW recognition.

- Technical development and scale-up
 - Scale-up of the current demo-scale technology to available commercial plants, highlighting the magnitude of the assets and investment needed in a new value chain (electrolysers, carbon capture, syngas and e-fuels conversion facilities).
 - Electrolysis capacity is a key enabler to deploy e-fuels technology. According to Frontier Economics, 100 gigawatts electrolysis capacity will be needed across Europe for affordable e-fuels. This figure corresponds to a fivefold increase in the world's current installed capacity of about 20 gigawatts. Such an increase in capacity would cost between 10 and 100 billion euros by 2050. This broad range is indicative of the uncertainty surrounding technological advancements [Frontier Economics/Agora 2018].
 - Also as key enablers, we can consider the critical minerals and factories requirement for electrolysers, and their durability and replacement life.
 - Adding to the costs of electrolysis are the investment costs for the construction of methanisation and e-fuel facilities. Additional R&D would also be required as Carbon capture from air (Direct Air Capture) technology are not currently commercially viable. Since the Direct Air Capture pilot facilities are still in their early testing stages, current cost assumptions for these technologies are fraught with uncertainty.
- High full load hours
 - E-fuel facilities are capital intensive and have high fixed costs. Accordingly, each additional operational hour has a strong impact on the cost of e-fuels, as this defrays the high fixed costs.
 - E-fuel facilities need to achieve high full load hours, dealing with the intermittency of renewable power supply to achieve efficient and economic operations. Frontier Economics estimate that e-fuel facilities need to achieve 3,000 to 4,000 full load hours annually (although this assertion is debatable regarding the 8,000 - 8,600 full load-hours operation in industrial sites as refineries, and the intermittency patterns of renewable power supply) [Frontier Economics/Agora 2018].
- Accessibility to affordable renewable energy price
 - Due to conversion losses, the price of electricity is the major determinant of the variable cost for e-fuels. Accessibility to a sustainable and affordable renewable power is thus essential for the economically viable operation of power-to-gas and power-to-liquid production facilities. Importing e-fuels could become an important

element, allowing the use of highly favourable locations for generating renewable electricity with a positive impact on cost reduction for e-fuel production.

- Other issues: Specifications / Labelling
 - Another important key enabler to deploy the e-fuels production is to certify its use in commercial applications, so technical approval would be an important step before deployment could begin.
 - The specification for kerosene use as a jet fuel are very strict. Cerulogy indicates the production of jet fuel from Fischer-Tropsch synthesis has already been demonstrated and approved for use in commercial aviation in blends of up to 50% with conventional jet fuel, by the American Society for Testing and Materials (ASTM) [Cerulogy 2017]. The jet fuel pathway via methanol, however, is still to be demonstrated and has not yet been certified by ASTM for use on commercial flights.

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6. GLOSSARY

AEC	Alkaline Electrolysis
ASTM	American Society for Testing and Materials
CAPEX	Capital expenditure
°C	Degree Celsius
CBP	Chemical Biotechnological Processes
CCS	CO ₂ Capture & Storage
CCU	CO ₂ Capture & Utilisation
CH ₄	Methane
CH ₃ OH	Methanol
CHP	Combined heat and power
CN	Cetane number
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRI	Carbon Recycling International
CSIRO	Commonwealth Scientific and Industrial Research Organization
ct€	Euro cents
CTL	Coal-to-liquids
DAC	Direct Air Capture
DME	Dimethyl-Ether
EU	European Union
EUCAR	European Council for Automotive R&D
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FG	Fuel gas
FT	Fischer-Tropsch
FQD	Fuel Quality Directive
JEC	JRC-EUCAR-CONCAWE consortium
GHG	Greenhouse gases
GTL	Gas-to-Liquids
HDV	Heavy Duty Vehicle
HT	High temperature
HTFT	High-temperature Fischer-Tropsch
ICE	Internal Combustion Engine
IEA	International Maritime Organisation
IMO	International Energy Agency
kW _e	Kilowatt of electricity
LCA	Life Cycle Analysis
LCOE	Levelized cost of electricity
LCP	Low Carbon Pathways
LDV	Light Duty Vehicle (i.e. car)
LEL	Lower Explosive Limit
LHV	Lower Heating Value
LH ₂	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LPC	Low-Carbon Pathways
LT	Low Temperature
LTFT	Low-temperature Fischer-Tropsch
MEA	Monoethanolamine
MTG	Methanol-to-Gasoline
MOF	Metal-organic frameworks

MPa	Megapascal
NH ₃	Ammonia
NO _x	Nitrogen oxides
OEM	Original Equipment Manufacturer
OME	Oxymethylene-ethers
PEM	Polymer Electrolyte Membrane
PSA	Pressure Swing Adsorption
PtG	Power to gas
PtL	Power-to-liquids
PtX	Power-to-x
PV	Photovoltaic
RED	Renewable Energy Directive
RES-E	Renewable energy sources for electricity
RON	Research Octane Number
rSOC	Reversible Solid Oxide Cell
RWGS	Reverse water-gas shift reaction
SCR	Selective Catalytic Reduction
SMR	Steam-Methane Reforming technology
SOE	Solid Oxide Electrolysis
SOEC	High-temperature solid-oxide electrolysis
SOFC	Solid Oxide Fuel Cell
SO _x	Sulphur oxides
toe	Ton of oil equivalent (= 10 Gcal or 41.868 GJ)
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
TTW	Tank-to-Wheel
UEL	Upper Explosive Limit
UK	United Kingdom
USA	United States of America
USD	USA Dollar
VGO	Vacuum Gasoil
VOC	Volatil Organic Compound
WT	Weight
WTT	Well-to-Tank
WTW	Well-to-Wheel
WWFC	World-Wide Fuel Charter

Synonyms:

E-fuels, e-fuels, efuels, Power-to-X, PtX, Power-to-liquids, PtL, Power-to-gas, PtG, Synthetic fuels, electrofuels

AUTHOR	YEAR	DEMAND SCENARIOS	IMPORTATION	CO2 source	INVESTMENT	COSTS
DETAILED ASSESSMENT						
Frontier Economics						
FVV	2018	Efuels replace today's fossil fuels	Mentioned	DAC	Efuel Synthesis: 2300-3500 euro/kWh PTL	0.92-2.44 euro/l
FVV	2018	Demand based on the real fuel in Germany in 2015	Mentioned	DAC + Concentrated source	All the chain: 240-1260 bill euros, Germany	0.07-0.37 €/kWh
FVV	2018	100% efuel scenario theoretically feasible but more expensive than combined scenarios with EV	-	DAC	All the chain: 240-1260 bill euros, Germany	0.07-0.37 €/kWh
ICCT	2018	0 demand without subsidy. Up to 0.87 Mtoe/y by 2030 with 3 €/l subsidy	-	DAC + Concentrated source	-	-
Frontier Economics / Agora						
Prognos	2018	Determined by economics: inexpensive renewable electricity and high full load hours	Mentioned	DAC	Efuel Synthesis: 2300-3500 euro/kWh PTL	0.92-2.44 euro/l
Cerology	2017	From 13 Mton/y (equivalent to air and sea traffic) to 45 Mton/y if PTL is used in all sectors, by 2050 in Germany. Theoretically in large volumes. In practice, difficult to implement	-	DAC	Efuel Synthesis: some data, page 138	1.2-2.2 euros/l
LBST and dena	2017	Based on demand scenarios competing with other technologies. From 24 to 81 Mtoe/y by 2050	-	Concentrated source	Implied in Efuels production costs	0.1-0.6 euros/kWh
Dechema	2017	Based on demand scenarios competing with other technologies. From 38 to 265 Mtoe/y by 2050	-	DAC	Efuel Synthesis: 2500-8000 euro/kWh PTL. All the chain, 4.000 to 10.000 bill euros, EU	2.5-2.8 euros/l
ICCT	2017	0 demand without subsidy. Up to 0.36 Mtoe/y by 2030 with 1.5 €/l subsidy	-	Concentrated source	Efuel Synthesis: 800-2000 euro/kWh PTL	1.2-1.5 euros/l
Yusuf Bicer	2017	-	-	Concentrated source	Efuel Synthesis: some data, page 13	-
LBST and Hincio	2016	-	-	-	-	-
UBA. GEA	2016	-	-	-	-	-
FVV	2016	Efuels replace today's fossil fuels	Mentioned	DAC	Efuel Synthesis: 250-445 bill euros, Germany. CO2 investment: page 5-98	0.07-0.37 €/kWh

A1-2 ADVANTAGES AND DISADVANTAGES PER TYPE OF E-FUEL

e-METHANE	
IMPACT ON	PROS
USE	Heating and industry sectors
AIR QUALITY	
HEALTH	
SAFETY	
PRICE	e-methane cost ranges from 0,1 to 0,6 €/kWh by 2015 to 0,1-0,2 €/kWh by 2050
STORAGE	It could use all or most existing logistics, including transportation, storage and distribution systems, on top of final application, of natural gas logistics
TRANSPORT	It could use all or most existing logistics, including transportation, storage and distribution systems, on top of final application, of natural gas logistics
PROPERTIES	Methane contains 83% of the energy of the hydrogen (LHV).
EFFICIENCY	51% (in a WTW basis)
PRODUCTION PROCESS	In the process of methanisation, methane (CH ₄) and the by-products water (H ₂ O) and heat are generated from carbon dioxide (CO ₂) and e-hydrogen (H ₂).
	CONS

e-HYDROGEN	
IMPACT ON	
USE	<p>PROS</p> <p>At present, about 70-80 Mt H₂ are produced annually for industrial uses, mostly for refining oil products (removing sulfur) and producing ammonia, itself feedstock of nitrogen fertilizers, explosives, cleansers and refrigerant. Its current use as a fuel is marginal, in rockets and some thousands of hydrogen vehicles</p> <p>Injection in existing gas grids, in mix with natural gas, would be a relatively easy first step to develop the use of some hydrogen in buildings, small industries, etc.</p> <p>CONS</p> <p>It is not exactly clear which proportion could be injected today with no or very minimal changes at users' level. Current regulation limit the share of hydrogen to 6% in France (in volume), or even 2% in Germany, while some studies and tests suggest 20% could be achieved. These percentages apply to volumes, but given the lower energy density of hydrogen compared to methane, they should be divided by three to represent the energy content of the mix – thus ranging from less than 1% to about 7% in the best case.</p>
AIR QUALITY	-
HEALTH	-
SAFETY	The high inflammability of hydrogen creates difficulties for direct combustion if not in mixes. Its best energy use is in fuel cells for electricity generation.
PRICE	Synthetic hydrogen or e-hydrogen cost ranges up to 0,7 €/kWh (9000 €/t) by 2015 to 0,1 €/kWh (1300 €/t) by 2050.
STORAGE	Storing hydrogen is no simple matter. Small amounts are usually stored as compressed gas, usually at 35 to 70 MPa. Embrittlement of metals by H ₂ dictates specific choices of materials. Onboard vehicles and stationary storages for building blocks or refuelling stations (up to about one tonne) would use metallic or composite-reinforced polymer tanks. Other stationary options include metal hydrides, which store H ₂ in a solid under moderate temperature and pressure that gives them a safety advantage. But they are heavy and can only store 1.8% hydrogen by weight. Large amounts of hydrogen gas can be stored in underground salt caverns, at various pressure levels. Air Liquide operates the world's largest (300 000 m ³) such storage in Texas. In Europe, a number of smaller salt caverns currently storing natural gas could be adapted for hydrogen storage. Hydrogen can also be stored as a liquid, although liquefaction at minus 253° C is a complex and energy-intensive process. Maintaining the fuel at low temperature requires continuous energy use.
TRANSPORT	Transporting hydrogen is also difficult. Its low volumetric density makes transport mode relatively energy-intensive in pipelines. Transport over long distances in large amounts would presumably take one of the three roads identified by the Japanese cross-ministerial program "SP Energy carriers": cryogenic, liquid hydrogen; bound with carbon atoms in organic hydrides ³ , or bound with nitrogen in ammonia. The distribution cost of gaseous hydrogen (compressed) by trailers can be assessed at USD 1 to 4/kg – roughly doubling the price from large hydrogen producing plants. This may justify decentralized production from electrolysis, even if small-scale is more costly than large-scale. Another option is to inject hydrogen in mix with natural gas in existing natural gas networks, also benefitting from existing natural gas storage capacities. However, the implied decarbonisation remains limited. ²
PROPERTIES	It has a very high specific energy (or gravimetric energy density), but a rather low (volumetric) energy density. Even heavily compressed or liquefied, it still occupies four to seven times the volume of gasoline.
EFFICIENCY	Hydrogen generates more energy per mass in comparison to liquid fuels 67% (in WTW basis)
PRODUCTION PROCESS	From electrolysis of water. ²
PRODUCTION PROCESS	It is mostly (95%) produced from fossil fuels (coal gasification in China, natural gas steam reforming in most other places, and some naphtha partial oxidation in refineries), with only a small contribution of electrolysis, mostly during the production of chlorine and caustic soda.

e-AMMONIA	
IMPACT ON USE	CONS
<p>IMPACT ON USE</p> <p>NH3 can be combusted in gas turbines, industrial furnaces or internal combustion engines, most likely after partial or complete thermal cracking into nitrogen and hydrogen.</p> <p>Green ammonia today appears as the prime candidate for replacing maritime fuels in long haul ocean-going ships. The Lloyd's register together and the University of Maritime Advisory Services show that biofuels and green ammonia are better option to green long haul maritime transportation than green hydrogen and electricity, which may be considered for shorter trips.</p> <p>While ammonia is heavier and bulkier than fossil fuels and biofuels, this inconvenience may not be as problematic on ships as it might be on aircrafts. Additional storage tanks would not actually create significant inefficiencies or reduce the useful load. Existing internal combustion engines could use ammonia as a fuel with relatively minor modifications.</p>	<p>A concern frequently expressed relates to the formation of nitrogen oxides (NOx) which the presence of nitrogen in ammonia could increase. However, the formation of NOx hardly depends on the abundance of nitrogen but rather on the temperature and pressure during combustion, the stoichiometry of the mix, etc. Furthermore, ammonia has a known ability to convert NOx into diatomic nitrogen and water in selective catalytic reduction process (SCR: over 99% NOx reduction can be achieved. Reference (3)). This property is widely used to reduce the NOx emissions due to combustion of fossil fuels in industrial boilers, gas turbines and diesel engines of all scales. Hence prospects for low-NOx combustion of ammonia are high and start being demonstrated with various experiments undertaken in Japan, the UK and other countries.</p>
<p>AIR QUALITY</p>	<p>Ammonia is biodegradable as it quickly diluted and carries no danger to wildlife since it is degraded by the living organism.</p>
<p>HEALTH</p>	<p>Ammonia is toxic for lungs and eyes, but its pungent smell is an important safety feature</p>
<p>SAFETY</p>	<p>Stored as a liquid at about 1 MPa, a very low pressure which does not require special high pressure tanks</p>
<p>PRICE</p>	<p>E-ammonia cost is predicted to range between 0,04 and 0,13 €/kWh (255 – 800 €/t) by 2050</p>
<p>STORAGE</p>	<p>Ammonia is also likely to continue to cost less than electrofuels containing carbon and produced with direct air capture, if only because carbon is about 2 000 times less abundant than nitrogen in the air. Ammonia has good chances to prevail over carbon fuels when carbon neutrality is required</p>
<p>TRANSPORT</p>	<p>Ammonia is more easily liquefied, transported, stored and distributed than hydrogen</p>
<p>PROPERTIES</p>	<p>Ammonia is more easily liquefied, transported, stored and distributed than hydrogen</p> <p>Its liquid form contains more hydrogen than the liquid form of dihydrogen, as reflects their relative energy densities: 15.37 MJ/L for NH3 vs. 9.98 MJ/L for H2</p> <p>It is a molecule that composes of 3 atoms of hydrogen and 1 atom of nitrogen. The capability to convert a liquid at adequate pressure permits ammonia to store more hydrogen per unit volume than compressed hydrogen/cryogenic liquid hydrogen</p>
<p>EFFICIENCY</p>	<p>Ammonia's toxicity or its lower specific energy constitute major impediments for its success.</p> <p>15% (WTW basis)</p>
<p>PRODUCTION PROCESS</p>	<p>The principal commercial method of producing ammonia is by the Haber-Bosch process: $N_2+3H_2 \rightarrow 2NH_3$. To synthesize e-ammonia or green ammonia, hydrogen is obtained from an electrolyser, using renewable electricity and water, as in the other e-fuels routes.</p> <p>Another way to synthesize ammonia, is based on a conventional natural gas reformer plus a CCS (carbon capture and storage). This is called blue ammonia, but it is not considered an e-fuel.</p>

e-METHANOL	
IMPACT ON	CONS
USE	Used in gasoline blending or after transformation in dimethyl ether (DME) or gasoline. It is primarily used as a feedstock in the chemical industry.
AIR QUALITY	It forms much less air pollutants than gasoline or diesel fuel burning.
HEALTH	
SAFETY	
PRICE	e-methanol cost ranges from below 0,5 €/kWh (3000 €/t) by 2015 (except from Cerulogy high scenario) to below 0,25 €/kWh (1500 €/t) by 2050.
STORAGE	Methanol is liquid at normal temperature and pressure, and thus very easy to store and ship
TRANSPORT	Methanol is liquid at normal temperature and pressure, and thus very easy to store and ship
PROPERTIES	Methanol has just half of the (volumetric) energy density of gasoline (15,8 vs. 32,1 MJ/l based on the LHV); i.e. 2 litres of methanol contain the same energy as 1 litre of gasoline. Its density (0,792 kg/l at 20°C) corresponds to the density of most other liquid fuels, its boiling point is at 64,7°C.
EFFICIENCY	14% (in a WTW basis)
PRODUCTION PROCESS	Methanol can be produced from CO ₂ in one or two steps. In the latter case, CO ₂ is converted to CO with the reverse water gas shift (RWGS) reaction, followed by hydrogenation of CO into methanol. In one step, these two reactions take place simultaneously with direct methanol synthesis. The resulting product mixes methanol and water that needs then to be distilled. Global demand of about 80 Mt/y.
	Dominantly produced from fossil fuels, it is primarily used as a feedstock in the chemical industry.

e-DME/e-OME	
IMPACT ON	CONS
USE	
AIR QUALITY	
HEALTH	
SAFETY	
PRICE	
STORAGE	
TRANSPORT	
PROPERTIES	
EFFICIENCY	
PRODUCTION PROCESS	

CONS
PROS

DME, also known as methoxymethane, is the simplest ether. It is used as propellant in aerosol sprays, but is also a potential substitute fuel for (modified) diesel engines (Shell, 2018).

For DME service in vehicles, only moderate modifications of engine and injection systems are required. So far mainly small commercial vehicle fleets (buses and heavy duty vehicles) have used DME as a transport fuel, especially to address air quality issues.

Due to their high oxygen concentration, they suppress pollutant formation in combustion. As diesel fuels, they reduce the emission of carbon black and NOx.

0.2-0.25 €/MWh by 2050

Deviating from current European diesel specifications (EN 590; EN 15940), neat OME fuels are not compatible with the existing fuel infrastructure nor with today's diesel engine technology. Hence OMEs could only be used in small quantities as drop in fuels, which is limiting any of their emission reduction potentials. Also, the materials compatibility of OMEs is unknown and approval would be needed for their use in existing vehicles. For high concentrations of OMEs, engine and fuel systems have to be fully adapted.

As a diesel substitute DME has a cetane number of 55 – 60 which is higher than the European diesel specification EN 590. Despite moderate octane ratings, DME could in principle be used as admixture to Liquefied Petroleum Gas (LPG) for spark ignition engines.

The lower heating value of DME is 28.4 MJ/kg and 19.0 MJ/l and thus lower than diesel's LHV (43.1 MJ/kg and 35.9 MJ/l). DME's boiling point is at -24.8°C, i.e. DME is gaseous at room temperature. Therefore, for transport and use as fuel DME must be compressed. Its vapour pressure at room temperature is 5.1 bar, which is even lower than propane's vapour pressure at 20°C (8.4 bar).

OMEs' chemical properties depend on their chain length. Common features of OME fuels are: no carbon-carbon linkage and a high oxygen content between 42 – 48 m-%. Their volumetric energy density of 20 – 21 MJ/l is low, but still exceeds that of methanol (15.8 MJ/l) and of DME (19 MJ/l).

DME can be readily synthesized through dehydration of methanol over ordinary solid acid catalysts such as phosphoric acid modified alumina g-Al2O3. As potential alternative options that are yet to be commercially proven, DME can also be produced directly from syngas in a single reactor – with MeOH still as an intermediate molecule in the reaction – or from CO2 hydrogenation over a bifunctional catalyst with both methanol synthesis and methanol dehydration activity.

Alternatively, methanol can be converted into poly(oxymethylene) dimethyl ethers, also called Oxymethylene ethers (OMEs).

e-LIQUID HYDROCARBONS	
IMPACT ON	CONS
USE	
Drop in fuels (gasoline, kerosene, diesel) for road vehicles, maritime and aviation	
AIR QUALITY	
Efuels don't generate SOx (no sulfur in the feedstock), and they generate 80% less particles than conventional fuels	If emission particles in cities are going to be prohibited, no matter is if comes from renewable or not.
HEALTH	
SAFETY	
PRICE	PTL cost ranges from up to 0,8 €/kWh (1,1 €/l) by 2015 to around 0,1-0,3 €/kWh (1-3 €/l) by 2050.
STORAGE	
They could use all or most existing logistics, including transportation, storage and distribution systems, on top of final application	
PTL fuels can also enhance energy security of a country	
TRANSPORT	
They could use all or most existing logistics, including transportation, storage and distribution systems, on top of final application	
PROPERTIES	
High specific energy	While synthetic liquid hydrocarbons are often categorized as "drop-in" fuels, i.e. fuels that could replace oil products with no change in the customer applications, the reality is more complex. Commercial fuels are usually complex blends, and end-use applications may have different levels of flexibility in accommodating possible variations, even minor, in the fuel composition.
EFFICIENCY	Very low: 13% (WTW basis) from renewable power to final combustion engine. Large volumes of electricity are needed due to conversion losses
PRODUCTION PROCESS	Most of these processes are proven or even commercial today, although based on fossil fuels other than oil, i.e. gas to liquid and coal to liquid technologies.
Their production could take two different paths: the first is based on methanol, which is then converted and upgraded in gasoline, kerosene or diesel, the other uses the Fischer-Tropsch (FT) process. The FT process directly produces hydrocarbons which can be further upgraded into the same fuels.	

A1-3 TRL DESCRIPTION

Technology Readiness Level	Description
TRL 1.	basic principles observed
TRL 2.	technology concept formulated
TRL 3.	experimental proof of concept
TRL 4.	technology validated in lab
TRL 5.	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6.	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7.	system prototype demonstration in operational environment
TRL 8.	system complete and qualified
TRL 9.	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Source: [Cerulogy 2016]

A1-4 CAPTURED CO₂ COSTS FROM DIFFERENT ORIGINS AND SOURCES

CO ₂ source	Capture cost	Year available	Units	Reference
Natural gas power plant	21-64 10-64	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Coal power plant	32-180 10-110	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Petroleum refining/ petrochemical	64-150 32-95	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Cement Industry	75-160 32-53	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Iron and steel	53-75 32-64	2028-033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Ammonia production	<21 <21	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Bioethanol/biogas	<21 <21	2028-2033 2038+	2018 €/tCO ₂ captured	Brynolf et al., 2017
Biomass w/ carbon capture	55	—	2018 €/tCO ₂ captured	Keith, Ha-Duong, and Stolaroff, 2006
Direct air capture	140	—	2018 €/tCO ₂ captured	Keith, Ha-Duong, and Stolaroff, 2006
Direct air capture	53	—	2018 €/tCO ₂ captured, but does not include regeneration costs of the sorbent	Holmes and Keith, 2012
Direct air capture	90	—	2018 €/tCO ₂ captured	Lackner, 2009
Direct air capture	915	—	2018 €/tCO ₂ avoided	House et al., 2011
Direct air capture	"Estimates of \$100/tC (\$27/tCO ₂) to \$500/tC (\$136/tCO ₂) found in the literature for direct air capture are just not believable. Absent a technological breakthrough that departs from humankind's accumulated experience with dilute gas separation, direct air capture is unlikely to be a serious mitigation option until the price on CO ₂ is measured in thousands of dollars per tonne of CO ₂ ."			Ranjan and Herzog, 2011
Direct air capture	400-595	—	2018 €/tCO ₂ captured, just the energy costs no capital recovery costs included	Ranjan, 2010
Direct air capture	551-742	—	2018 €/tCO ₂ avoided	Socolow et al., 2011
Coal power plant	75	—	2018 €/tCO ₂ avoided	Socolow et al., 2011

Source: [ICCT 2018]

CO ₂ source:		Gas power plants	Coal power plants	Petroleum	Cement	Iron and steel	Ammonia	Bioethanol	Ambient capture
Short term	Low	20	30	60	70	50	10	10	n/a
	Mid	35	71	92	102	59	14	14	n/a
	High	60	170	140	150	70	20	20	n/a
Long term	Low	10	10	30	30	30	5	5	20
	Mid	24	32	52	39	42	10	10	138
	High	60	100	90	50	60	20	20	950

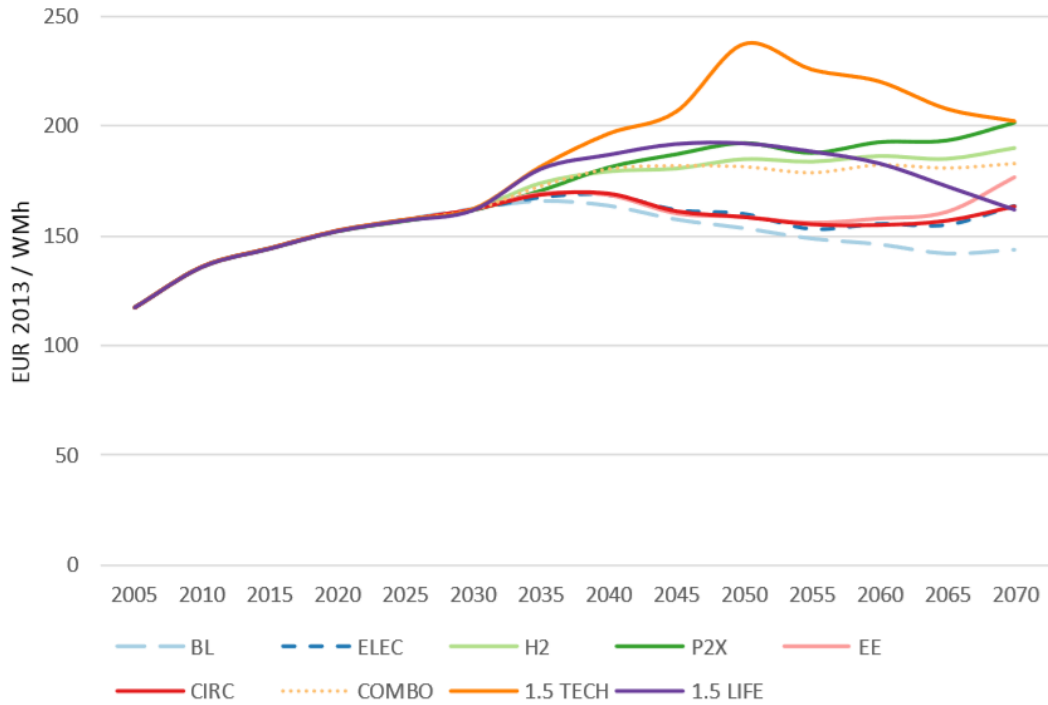
Source: [Cerulogy 2017]

A1-5 A CLEAN PLANET FOR ALL SCENARIOS DETAIL

Long Term Strategy Options								
	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5.TECH)	1.5°C Sustainable Lifestyles (1.5.LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks)		-80% GHG (excluding sinks)		-90% GHG (incl. sinks)		-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	<ul style="list-style-type: none"> Higher energy efficiency post 2030 Deployment of sustainable, advanced biofuels Moderate circular economy measures Digitilisation 		<ul style="list-style-type: none"> Market coordination for infrastructure deployment BECCS present only post-2050 in 2°C scenarios Significant learning by doing for low carbon technologies Significant improvements in the efficiency of the transport system. 					
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)		CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings	COMBO but stronger		CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			<ul style="list-style-type: none"> CIRC+COMBO but stronger Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid			Limited enhancement natural sink		<ul style="list-style-type: none"> Dietary changes Enhancement natural sink

Source: [European Commission 2018]

A1-6 PROJECTED AVERAGE ELECTRICITY PRICES IN DIFFERENT SCENARIOS



Source: PRIMES.

Source: [European Commission 2018]

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