Global Alliance
Powerfuels

Powerfuels Application Fields

Factsheets about powerfuels technologies
and their areas of application

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The Global Alliance Powerfuels

The Global Alliance Powerfuels was initiated by the German Energy Agency (dena) together with renowned corporate partners as founding members. Corporate partners are the core of the Alliance. They set the strategic agenda in the steering committee and define the working groups. As part of an extensive global network and through their active engagement in project development, they gain insights and strategic orientation in the upcoming global business field of green Powerfuels.

To reach its goals, the Alliance focuses on 3 strategic pillars

1 Strategy & Networking

Raise awarness and acceptance of Powerfuels as missing link to reach global climate targets.

2 Politics & Regulatory Framework

Support further enhancement of regulatory frameworks with a first focus on Europe as demand region.

3 Project Development Track

Stimulate project development to globally enable production capacities on industrial scale, thus increasing cost competiveness with fossil fuels.

Operational approach with focused activities

- Operate as think-tank, network, and information hub for partners and relevant decision makers.
- Provide politics, business, and civil society with the information needed for political agenda setting and further enhancement of regulation.
- Develop guidelines to enable a functioning market and prove the sustainability of powerfuels.
- Initiate projects with partners to build up global production capacity.
- Foster global cooperation on research and development by building an international scientific network.

What are powerfuels?

Powerfuels are synthetic gaseous or liquid energy carriers and feedstocks, based on renewable electricity. They deliver energy or basic materials for many use cases and are a renewable alternative to fossil resources to avoid CO_2 emissions.

Powerfuels are a game changer: By transforming electrons into molecules, they enable renewable energy to be stored over long periods and transported over long distances. They can be chemically identical to their respective fossil counterparts and can thus be used in any application area where fossil resources are consumed today.

Why do we need powerfuels?

In addition to energy efficiency and the direct use of renewable energy, powerfuels are the third pillar for a successful global energy transition. They will be necessary to fulfil the Paris Agreement and are a missing link to achieve the climate targets in 2050:

- They are climate-friendly solutions to applications without viable alternatives to replace fossil-fuel use from today's perspective.
- They can be transported and traded globally and thus open local potentials for renewable energy generation to a global market.
- They can reduce the economic costs of the energy transition by allowing the further use of existing infrastructures and devices, and by stabilizing the energy systems and providing longterm storage for renewable energy.
- They could accelerate the de-fossilization of existing consumer end-use equipment since they are green drop-in alternatives to fossil fuels.

What are the primary power-to-x technologies and fuel types?

Five technical processes build the basis to produce the entire powerfuels portfolio:

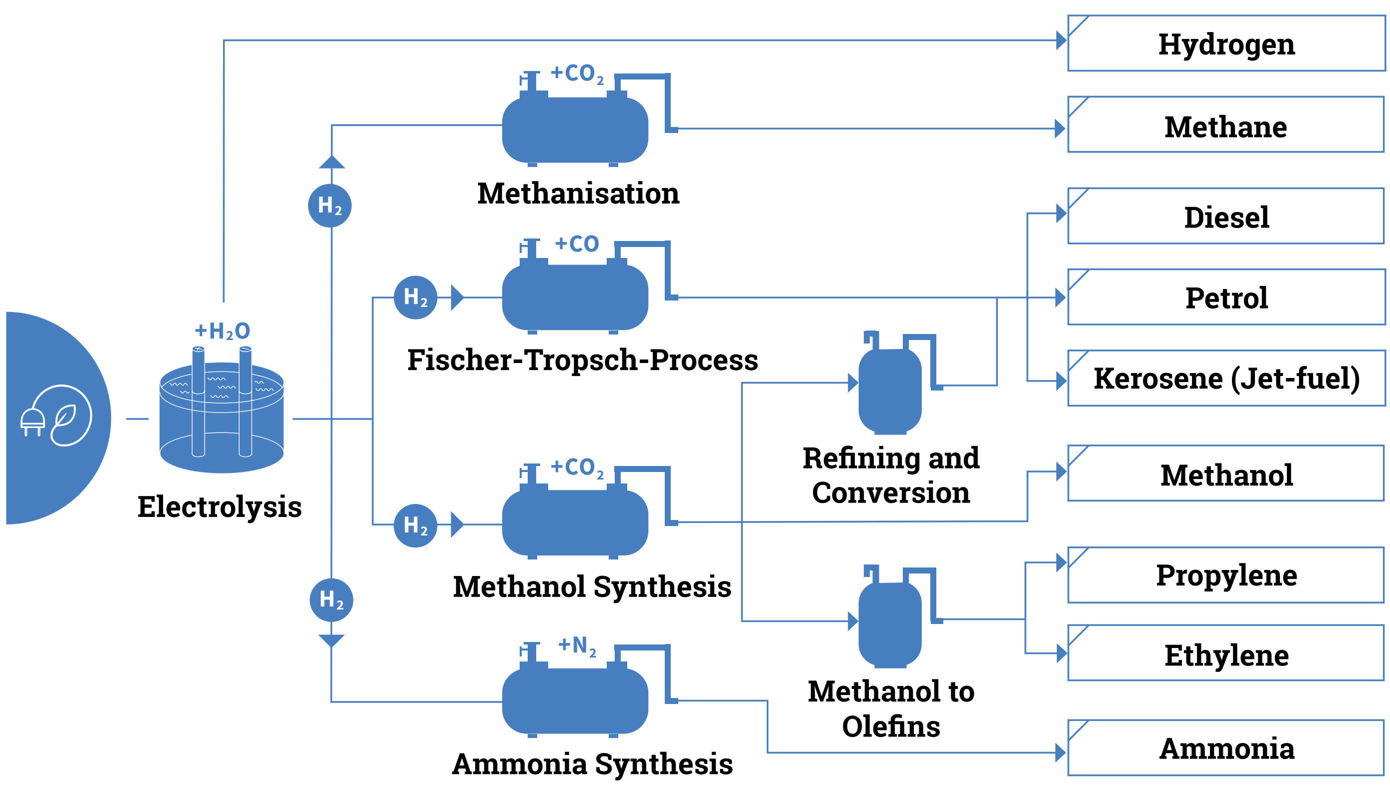
- Electrolysis
- Methanisation
- Fischer-Tropsch synthesis
- Methanol synthesis
- Ammonia synthesis

All powerfuel production processes start with electrolysis of water using renewable electricity to produce hydrogen and oxygen. **Hydrogen is the fundamental powerfuel which could be directly used as energy carrier or feedstock in a wide variety of applications.**

Hydrogen could also be further processed with carbon dioxide or nitrogen to obtain other fuels and chemicals. Carbon dioxide can be extracted from the atmosphere using Direct Air Capture technologies to close the carbon cycle. Nitrogen is extracted from the atmosphere using air separation technologies.

Both electrolysis and methanisation are established technologies since many years, but further increase in global capacities and deployment of industrial-scale systems will allow for further cost reduction through learning effects and economies of scale.

Powerfuels: Processes and fuel types

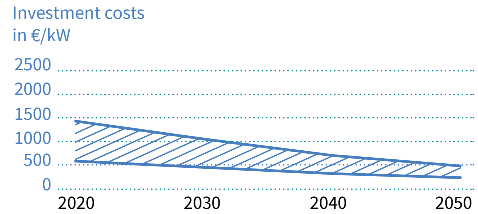


Technology overview and estimated investment costs reduction

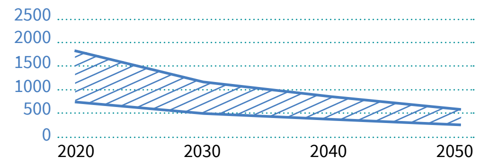
Electrolysis

Hydrogen electrolysis refers to the decomposition of water into hydrogen and oxygen through the use of electrical energy. It can be carried out either as a low-temperature or as a high-temperature process.
Right now the majority of processes used have already been developed with low temperature electrolysis such as alkaline electrolysis (AEL) or via proton exchange membranes (PEM).High temperature processes are gaining importance with the solid oxide electrolysis (SOEC) due to their high efficiency leading to a reduction in power consumption of the electrolysis.

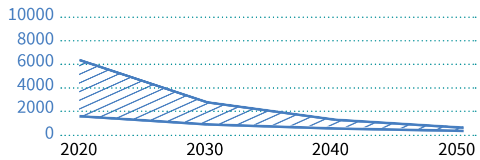
Alkaline Water Electrolysis
TRL 9
Efficiency increase from 82% to 84% by 2050



PEM
TRL 8,
Efficiency increase from 82% to 84% by 2050



SOEC
TRL 6,
Efficiency increase from 87% to 95% by 2050

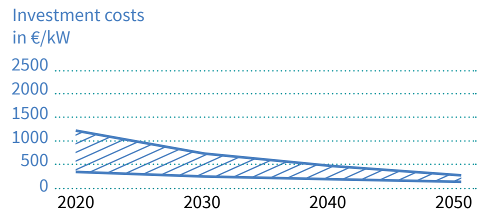


Source: dena (2017a), dena (2018b)

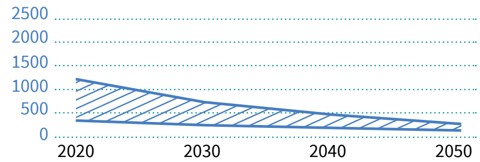
Methanisation

In the methanisation process, hydrogen and carbon dioxide are converted to methane. Catalytic methanisation requires a catalyst based on nickel and is already being used commercially. In addition, biological methanisation using microorganisms is also possible.

Catalytic
TRL 8,
Efficiency increase from 83% to 90% by 2050



Biological
TRL 8,
Efficiency increase from 80% to 90% by 2050

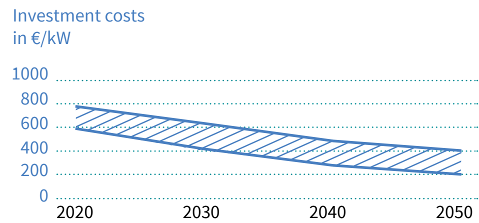


Source: dena (2017a), dena (2018b), Expertenbefragung

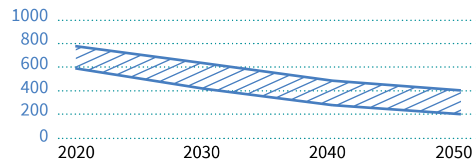
Methanol synthesis and Fischer-Tropsch process

Synthetic liquid fuels can be produced either by methanol or Fischer-Tropsch synthesis. In methanol synthesis, the first step is to produce methanol from hydrogen and carbon dioxide or carbon monoxide (CO). Methanol can be either used directly or further processed to produce synthetic liquid fuels (diesel, petrol, kerosene). In the Fischer-Tropsch synthesis carbon monoxide and hydrogen are used to produce a crude liquid fuel, which is then refined to produce the desired end product.

Methanol synthesis
including refinement and conversion
TRL 8,
Efficiency increase from 56% to 66% by 2050



Fischer-Tropsch-Synthesis
TRL 8,
Efficiency increase from 56% to 66% by 2050

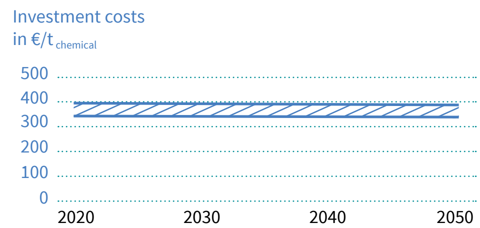


Source: Agora Verkehrswende, Agora Energiewende & Frontier Economics (2018), DECHEMA (2017), dena (2018b), LBST & BHL (2016)

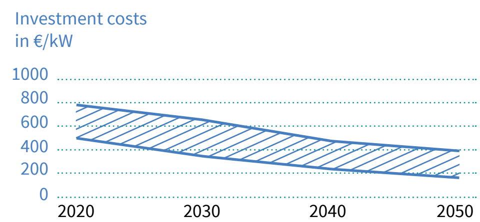
Ammonia synthesis and Methanol-to-Olefins process

Ammonia, methanol, propylene, and ethylene are widely used basic chemicals from which fertilisers, plastics and other chemicals are produced. At present fossil fuel feedstocks are used to produce these basic chemicals. Alternatively, green hydrogen (produced using electrolysis driven by renewable energy) could also be used as feedstock in order to produce ammonia or to produce methanol which can be further processed to produce propylene and ethylene using Methanol to Olefins process.

Ammonia Synthesis
TRL 7,
Decrease of the energy demand from 7,7 to 7,25 kWh/kg $_{chemical}$ by 2050



Methanol synthesis
TRL 8,
Efficiency increase from 70% to 78% by 2050



The Partners of the Global Alliance Powerfules are:

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Powerfuels in Aviation

The use of sustainable aviation fuels, notably powerfuels, is considered the only viable option for the aviation industry to meet its ambitious greenhouse gas reduction targets.

In 2017 the aviation sector worldwide accounted for 3 per cent of the global greenhouse gas (GHG) emissions[1]. If aviation were to be considered a country, its total amount of GHG emissions would make it into the world's top 10[2]. Thanks to increases in efficiency, it has been possible to decouple the increase in CO_2 emissions from traffic growth. However, following the current demand for air transport services, emissions will rise in the long term. Air transport in Europe has already been integrated into the Emission Trading System and from 2020 CORSIA (Carbon Offsetting a Reduction Scheme for International Aviation) will enter into force worldwide. As a consequence, air traffic is growing shall further grow CO_2-neutrally[3]. Due to high investment costs and long lifespans of airplanes, aviation requires a solution that also addresses carbon reduction for the current generation of fleets. High demand of energy combined with safety parameters, result in rigorous requirements for aviation fuels like high volumetric and gravimetric energy density and specific handling characteristics. Synthetic kerosene from electricity can be chemically identical to their respective fossil counterpart and meets all performance and safety specifications. Powerfuels kerosene can thus be both blended with conventional kerosene as drop-in fuel or replace it altogether.

3 % of global CO_2 emissions stem from Aviation, in 2017 a total of 859 Million tons[1]

50 % of the CO_2 emissions are to be reduced by 2050 compared to the 2005 level (IATA goals)[3]

Synthetic Kerosene

- ✓ Reduces greenhouse gases and pollutant emissions
- ✓ Allows sustainable, resource-friendly production in many regions globally
- ✓ Meets rigorous performance and safety fuel specifications (ASTM)
- ✓ Is usable as drop-in fuel for existing jet engines, refinery processes and distribution infrastructures

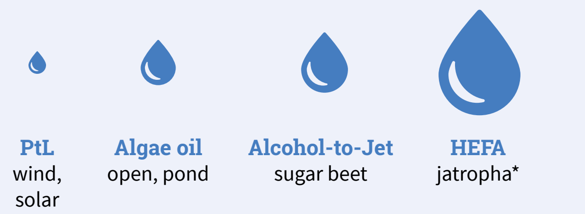
- ! Has still high overall costs: cost drivers are investment costs and cost of (renewable) electricity
- ! CO_2-neutrality depends on use of renewable electricity and renewable carbon sources

Comparison of sustainable aviation fuels

When comparing different options for production of sustainable aviation fuels (SAF), power-based kerosene (Power to Liquid, PtL) show significantly higher yields per hectare than biogenic SAF, whilst having a negligible specific water consumption. The International Council on Clean Transportation (ICCT) states that waste fats and oils are the most cost-effective SAF today. However, these sources for SAF are already widely used by the road sector and therefore their supply is limited. With about 800 to 900 Euro per ton of avoided CO_2, current carbon abatement costs of synthetic kerosene are about two times higher than that of second generation biofuels, but will strongly decrease with further market ramp-up of power-to-X production capacities.

Water demand per liter of jet fuel

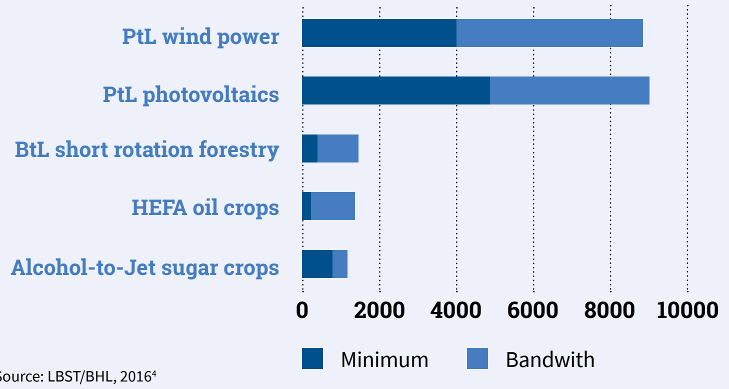
Powerfuels (PtL) water demand compared to selected biofuels
(volumes represetation, PtL water demand ~ 1.4 LH₂0/Ljetfuel)



Source: LBST/BHL, 2016[4]

*Hydro-processed Esters and Fatty Acid

Achievable air milage for an A320neo per ha of land (km/(ha-yr))

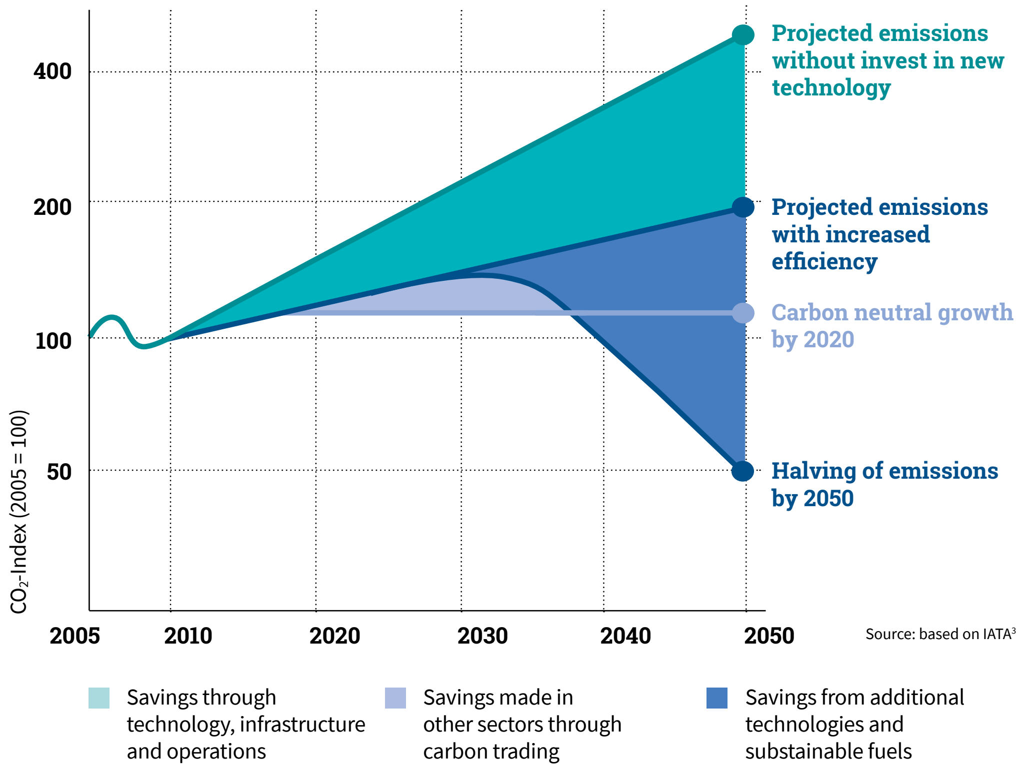


Source: LBST/BHL, 2016[4]

Self-commitment of the international aviation sector for CO_2 reduction

In 2009 various actors of the aviation sector agreed on a climate protection plan with the goal to halve the net CO_2 emissions by 2050 compared to 2005 levels. This will be achieved by incremental improvements by increasing engine efficiency, process and routes optimization, as well as the implementation of radical new technologies like new airplanes and alternative fuels[3].

In order to reach the goal of carbon-neutral growth from 2020, the aviation industry is expecting to use compensation as method of choice for the first years until new technologies show their carbon-reducing effect[3].



Source: based on IATA[3]

Legal Framework

Since the aviation sector is a highly competitive global market, the introduction of synthetic kerosene can only be achieved through international negotiations and agreements with binding GHG reduction targets. Currently there are no obligatory quotas for SAF usage or the abatement of emissions. Although the European air traffic is regulated in the European Trading System (ETS) since 2012, growing traffic demand avoided carbon reduction in the aviation sector[5]. In 2016 the ICAO implemented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to stabilize net CO_2 emissions from international aviation at 2020 levels. From 2021 until 2026, flights between volunteering countries will participate in CORSIA – 80 States, representing nearly 80 per cent of international aviation activity – while from 2027 all international flights will be subject to offsetting requirements with 90 per cent[6].

1 International Energy Agency 2 Reducing emissions from aviation, European Commission (https://ec.europa.eu/clima/policies/transport/aviation_en) 3 IATA Technology Roadmap, International Air Transport Association (IATA) 4 Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel, Umweltbundesamt 5 DIRECTIVE 2003/87/EC, 2003; European Parliament and Council 6 Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)-Frequently Asked Questions (FAQs), International Civil Aviation Organization (ICAO)

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Feedstocks for the chemical industry

Petrochemicals, which turn crude oil and natural gas into all sorts of daily products, are integral to modern societies. The growing role of petrochemicals is one of the key "blind spots" in the global climate mitigation debate.[1]

The chemical industry is unique in its fossil fuels use. While most industries use fossil fuels as energy source, the chemical industry uses about half of the sector's demand as feedstock: The fossil resources are used as raw material for a variety of widely used products like plastics, fertilisers, detergents or tyres. The chemical industry accounts for 14 per cent of the total primary demand for crude oil and 8 per cent for natural gas. Ammonia, methanol, ethylene, and propylene are the most important basic chemicals used as the starting materials for a large number of industrial downstream products. For example, nitrogen-based fertilisers are produced from ammonia, formaldehyde from methanol, and plastics using ethylene and propylene. In 2016, crude oil and natural gas represented 87 per cent of feedstocks in the carbon-based chemical industry.

All of these uses do also cause carbon emissions – during manufacturing, utilization, and/or at the end of useful life of these products. Thus, climate neutral substitutes are required to replace fossil fuels in the chemical industry in order to reach the overall goal of net-zero carbon emissions. Powerfuels can replace today's demand for fossil resources[2]. For some of the globally most widely used raw materials for the chemical industry like methanol, there already exist specific power-to-chemicals processes. Hence, powerfuels can significantly reduce the direct and indirect CO_2 emissions of many different product groups.

14 % of crude oil and 8 per cent of natural gas are globally consumed by the chemical industry, making it the largest industrial energy consumer[1]

1,5 gigatonnes of carbon emissions were emitted by the chemical industry in 2018 globally, making it the third-largest industrial CO_2 emitter[1]

Chances and challenges

- **Synthetic Ammonia**
- **Synthetic Methanol**
- **Synthetic Ethylene**
- **Synthetic Propylene**

Chances:

- Easy integration into existing production processes, technical devices, and infrastructures
- Continued use of mature technologies and proven industrial-scale processes
- Ensuring security of supply by increasing independency from by-products of fossil fuels refining

Challenges:

- Has still high overall costs: cost drivers are investment costs and cost of (renewable) electricity
- CO_2-neutrality depends on use of renewable electricity and renewable carbon sources

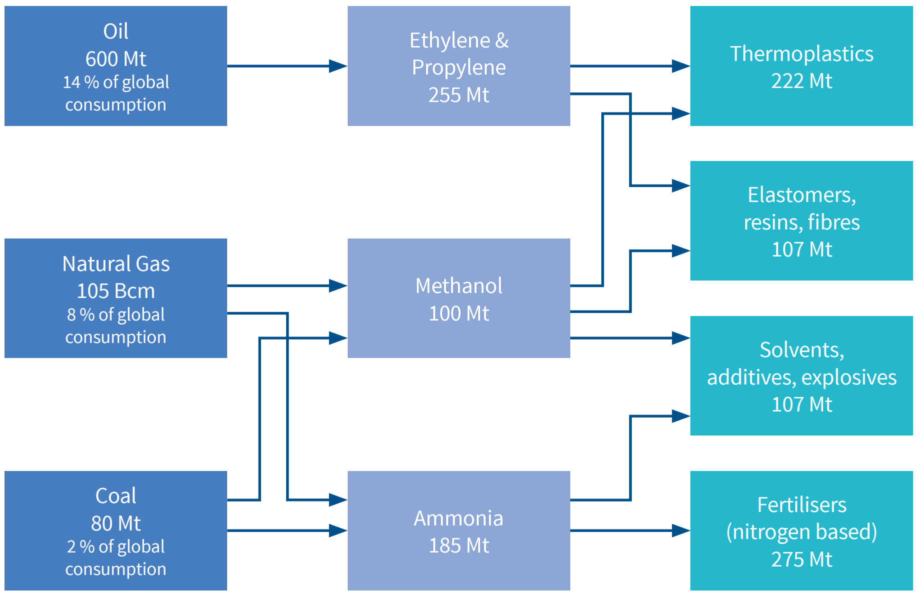
Alternative technologies

The synthesis processes currently used for the production of ammonia and methanol require hydrogen as basic material. Today, hydrogen primarily stems from CO_2-intensive steam reforming of natural gas. This can be substituted by green hydrogen, which is produced by electrolysers using renewable electricity. Ethylene and propylene, on the other hand, are mostly obtained in steam crackers by the thermal decomposition of hydrocarbon mixtures, such as those produced during conventional crude oil processing. Methanol produced from green hydrogen, can be catalytically converted into ethylene and propylene using the methanol-to-olefins (MTO) process, thus providing a green alternative to conventional ethylene and propylene. By using powerfuels, considerable amounts of CO_2 emissions can be reduced in the chemical industry.

About 60 per cent of global fertilisers are ammonia-based. As over 90 per cent of worldwide ammonia production is used for fertilisers and ammonia significantly consists of hydrogen, the world's agricultural industry depends heavily on hydrogen: 55 per cent of worldwide hydrogen demand is currently used for ammonia production.

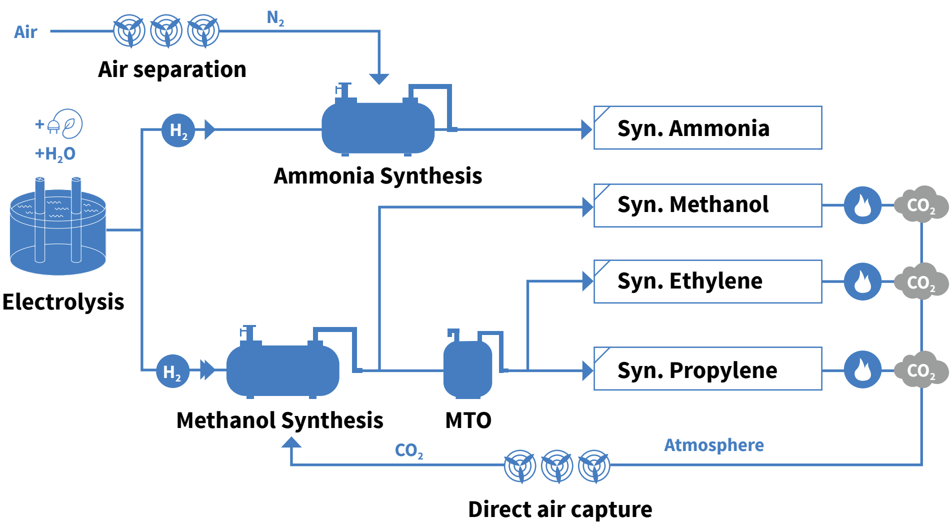
Another 10 per cent of worldwide hydrogen demand is currently used in methanol production, which has broad application areas. Almost 70 per cent of feedstock methanol is further processed into formaldehyde which is mainly used to produce synthetic resins.[3]

The four most-important basic chemicals are feedstock for the majority of all chemical products, thus having great relevance for both various industries and private life. Petrochemical products are everywhere and have become the fastest-growing source of oil consumption. Therefore, powerfuels have to play a major role in the decarbonisation of the chemical industry.



Source: IEA, 2018

Synthetic production processes



1 IEA 2018. **2** Further details of technologies described here can be found in [1, pp. 55–70]. **3** Hydrogen Europe **References:** A. Bazzanella and F. Ausfelder, Low carbon energy and feedstock for the European chemical industry. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie eV, 2017; IEA, "The Future of Petrochemicals: Towards more sustainable plastics and fertilisers", International Energy Agency (IEA), 2018; Hydrogen Europe (https://hydrogeneurope.eu/hydrogen-industry).

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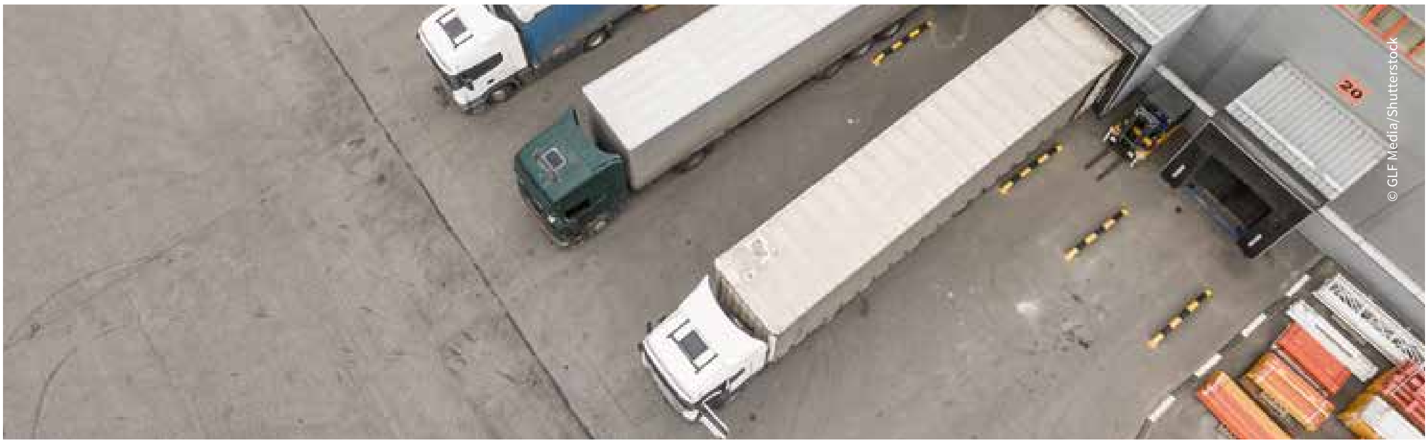

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Powerfuels in Heavy Transport

Powerfuels can play a major role in reaching the decarbonisation goals of heavy road transportation.

Road freight transport in the European Union has increased by 25 per cent since 1990. In 2016, heavy duty vehicles were responsible for 27 per cent of road transport CO_2 emissions and almost 5 per cent of total EU green-house gas (GHG) emissions. And EU freight transport is greatly dependent on road transport: 70 per cent of European freight is being transported by trucks, most of them being driven by diesel engines. As there is no major efficiency increase predicted for heavy duty vehicles, alternative propulsion systems and renewable fuels have to play a major role for the mitigation of GHG gases in the transport sector[1]. These include natural gas, hybrid-systems, battery electric vehicles, trolley-trucks and the usage of powerfuels.

Heavy duty transport is characterised by high transport capacity combined with long distances, this makes the direct use of electric energy difficult as battery driven trucks are lacking in range. The direct electrification by overhead lines comes with high infrastructural costs and is not cost-effective for less frequented routes.

Powerfuels offer a sustainable alternative to these challenges. Since they can be chemically identical to their fossil fuel alternatives, they could be used with existing infrastructure.

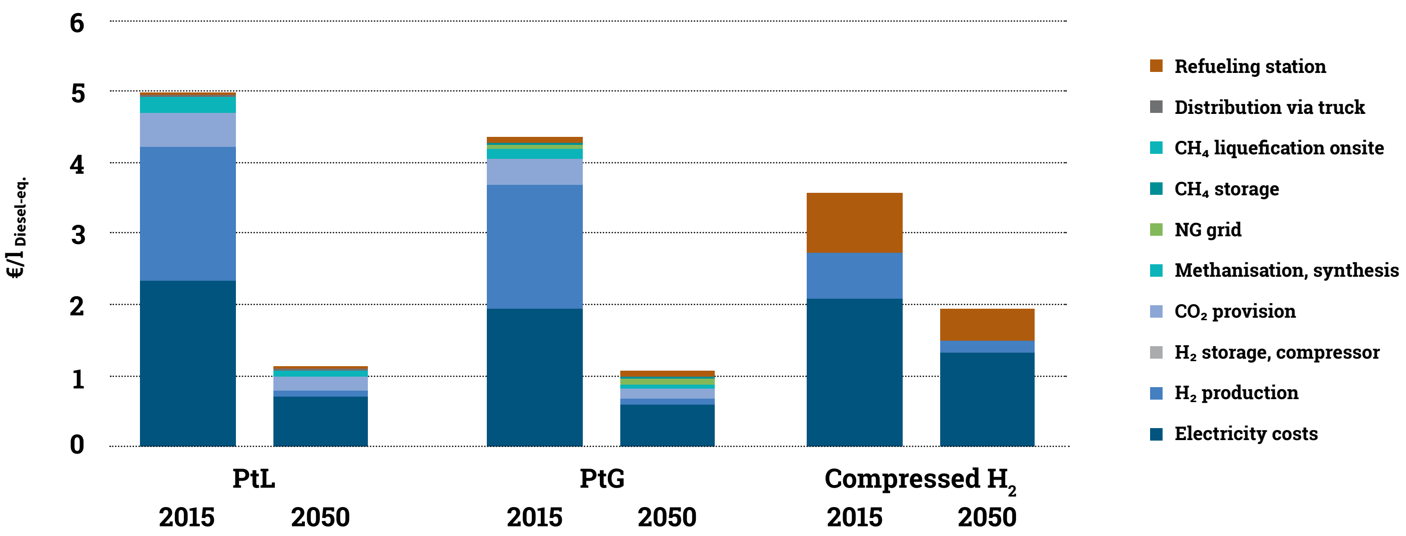
27 % of GHG emissions in the European traffic sector are emitted by heavy duty vehicles[1]

40 % of the oil demand growth and 15 per cent of the increase in global energy-sector CO_2 from 2015 until 2050 will be accountable to trucks without further policy efforts[2]

H_2 **Hydrogen**	No local pollutant and CO_2 emissions	High efficiency of the fuel cell	Hardly any supply and refuelling infrastructure
Synthetic Methane	Significantly lower CO_2 and local pollutant emissions	Usage of existing vehicles and refuelling infrastructure for RE-CNG	No existing refuelling infrastructure for LNG
Synthetic Diesel	Possible usage of existing refuelling infrastructure and vehicles	"Drop-in" character makes it able to gradually substitute conventional Diesel	No substantial efficiency increase predicted for Diesel engines

Actual and projected cost structure of relevant powerfuels for public transport

Actual (2015) and predicted (2050) prices for different powerfuels in €/l $_{Diesel-eq.}$



Hydrogen is provided by high temperature electrolysis for PtG and PtL, Hydrogen for compressed hydrogen is provided by low temperature electrolysis, Powerfuels are produced with EU domestic energy in 2015 and are imported for the year 2050, Carbondioxide is provided by direct air capture technology Source: "e-fuels" study (LBST and dena)[3]

Comparison of technology and infrastructure for different propulsion types

	Technology readiness level	Infrastructure
FCEV-truck Hydrogen	First fuel cell trucks (FCEV) are already been produced; high tank capacities needed; high overall efficiency of the fuel cell; high cost reduction possible	Almost no existing infrastructure; Development of modern logistic procedures, like liquid organic hydrogen carriers (LOHC) and liquefaction of hydrogen
CNG/LNG-truck Synth. Methane	High technology readiness level of the whole powertrain; Usage of CNG rather in the light vehicle area; LNG for trucks not yet widespread	CNG-infrastructure available widespread; LNG not yet disseminated
Diesel-truck Synth. Diesel	Further use of existing and disseminated technology	Further use of existing and disseminated infrastructure
BEV-truck Renewable electricity	BEV-trucks are yet in prototype stage; not yet suitable for long distances; high weight of the battery	Recharging infrastructure in under construction
Trolley-truck Renewable electricity	Overhead line hybrid trucks are yet in prototype stage	Capital-intensive construction of infrastructure needed; disseminated usage and border-crossing traffic problematic

Existing political instruments can foster powerfuels ramp-up

The admission of powerfuels to the national implementations of the EU RED-II (Renewable Energy Directive) as carbon-neutral variant of alternative fuels could draw more attention to powerfuels. Instruments on national or local level like road tolls or congestion charges, as well as existing taxes and duties like energy taxes or vehicle taxes can be further evolved to take GHG emissions into account. Another possibility is allowing powerfuels to count towards achieving EU fleet average emission targets for heavy duty vehicles. These are amongst others promising possibilities for policy makers to boost the market ramp-up of powerfuels.

1 Carbon dioxide emissions from Europe's heavy-duty vehicles, European Environment Agency. **2** CO_2 emission standards for heavy-duty vehicles, European Parliament. **3** The future of trucks – Implications for energy & the environment, IEA. **References:** The potential of electricity-based fuels for low-emission transport in the EU, dena and Ludwig Bölkow Systemtechnik.

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Powerfuels in Industry: Process Heat

Powerfuels will have to play an important role for decarbonizing industrial heat. This particularly holds true for processes where no efficient electrothermal alternatives exist.

Industrial heat accounts for almost one-fifth of global energy consumption and two-thirds of industrial energy demand. Since the vast majority of industrial heat originates from fossil-fuel combustion, it constitutes around 30 per cent of the industrial and 12 per cent of the total global CO_2 emissions[1].

Improving energy efficiency is crucial to reduce the overall energy demand for industrial heat, therewith directly avoiding greenhouse gas (GHG) emissions. For the production of low and medium temperature heat, direct use of renewable energies like solar or geo thermal, as well as the use or renewable electricity with heat pumps or electrode boilers are able to further reduce GHG emissions. For high temperature heat applications, biofuels are the currently most-used renewable option. However, since biofuels on a global scale have a limited volume potential[2], powerfuels are essential to reach climate goals while fulfilling energy demands in application areas like high process heat as well as for example air and sea transport.

Powerfuels offer a sustainable alternative to these challenges. They can be chemically identical to currently used fuels, thus replacing fossil resources in existing processes, infrastructures and technical devices to produce high temperature heat.

20 % of global energy is consumed for industrial heat[1]

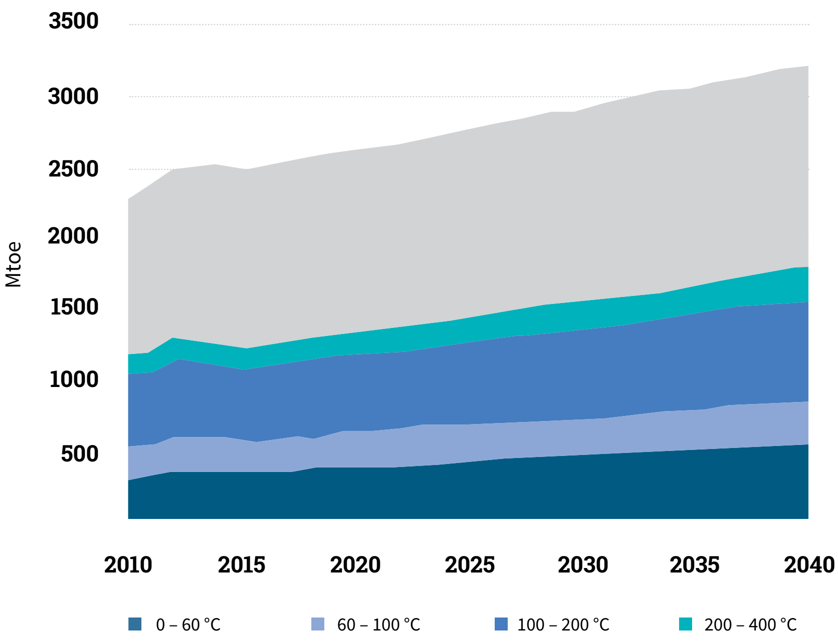
12 % of global greenhouse gas emissions stem from fossil fuel use for industrial heat[1]

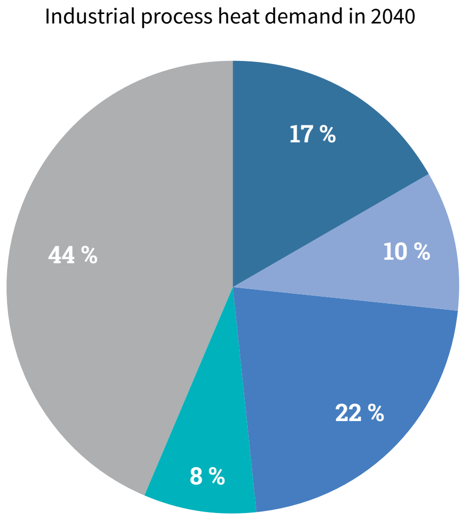
H_2	**Hydrogen**
	Synthetic Methane
	Synthetic Methanol

- ✓ Opportunity to decarbonise high temperature and other not-easily electrifiable industrial applications
- ✓ Easy integration into existing production processes, technical devices, and infrastructures
- ✓ Continued use of mature technologies (e.g. industrial furnaces and furnace burners) and proven industrial-scale processes

- ! Has still high overall costs: cost drivers are investment costs and cost of (renewable) electricity
- ! CO_2-neutrality depends on use of renewable electricity and renewable carbon sources

Global industrial demand by temperature level and sector





Energy demand for industrial heat is expected to raise by around 40 per cent from today's 2250 Mtoe[3] – about 20 per cent of worldwide energy demand – to 3250 Mtoe in 2040[1].

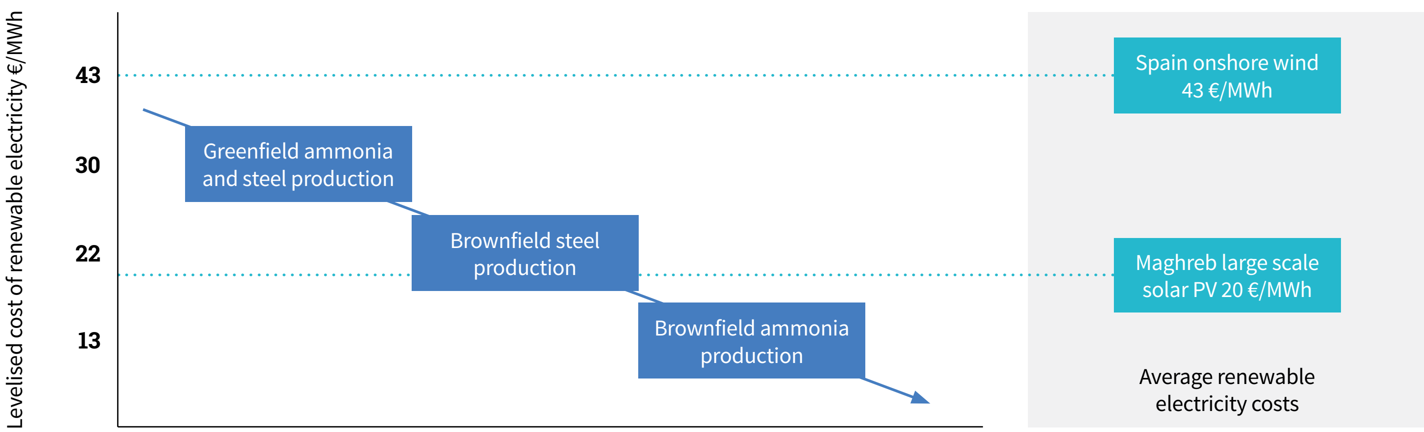
Industrial heat demand can be classified based on the required temperature levels. About 50 per cent of the demand is for high temperature heat (temperatures over 400 °C), around 25 per cent for medium temperature heat (100 to 400 °C) and the remaining 25 per cent for low temperature heat (less than 100 °C)[4]. High temperature processes are mostly used in energy-intense industry sectors like ceramics, glass.

From today's technological perspective and in order to meet the future demand of high temperature process heat in a climate friendly manner, fossil fuels have to be replaced by carbon-neutral fuels like powerfuels.

Decarbonisation approaches based on industrial electricity prices[5]

Today, the use of Carbon Capture and Storage (CCS) is considered the most economic decarbonisation option for industrial installations. However, in many countries worldwide, CCS is either technologically not feasible and/or socially not fully accepted. At the same time, with levelised cost of electricity (LCOE) from renewable energy sources continuously decreasing, decarbonisation by powerfuels gains more and more attractiveness over the use of fossil resources combined with CCS. With LCOE between 20 and 40 EUR/MWh for new power generation plants from renewable energy sources in favourable regions globally, powerfuels have reached cost-competitiveness in many applications in ammonia and steel production. It is then for example cheaper to use green hydrogen for fuel at newly-built ammonia or steel plants designed around hydrogen than to use CCS.[5]

Powerfuels will thus play an important role in decarbonisation of important industrial sectors like manufacture of non-metallic mineral products, including manufacture of ceramics as well as glass and glassware.



Cost competitive green hydrogen industrial usage compared to CCS

Source: McKinsey, 2018

1 IEA, 2018. **2** Schmied, Wüthrich, Zah, & Friedl, 2015. **3** Mtoe – Million tonnes of oil equivalent. **4** IEA, 2017. **5** Results presented are based on (de Pee, Pinner, & Roelofsen, 2018).

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Global Alliance *Powerfuels*

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Powerfuels in Public Road Transport

Powerfuels can be a complement to direct electrification of buses, and hence play a major role to decarbonise public transport.

In highly populated urban areas, public transport contributes to CO_2 emissions as well as local air pollutants. The most widely used means of public transport are diesel buses, thus the introduction of alternative propellants for buses becomes an important issue in terms of reducing greenhouse gases (GHG) and improving local air quality. Alternative propulsion systems and renewable fuels that could lead to a decrease in GHG emissions for buses include natural gas, hybrid-systems, battery electric vehicles, trolleybuses and the usage of powerfuels.

The use of powerfuels is necessary for routes with high capacity utilisation and compliment the mobility sector's shift towards direct electrification. The advantages of powerfuels compared to battery electric vehicles is the longer range and the significantly lower time for refuelling. This makes powerfuels an interesting application for public fleets in transport as well as in other crucial public services (e.g. fire department, police, etc.). Due to a centralised procurement strategy of public fleets, a faster market ramp-up of powerfuels driven vehicles as well as powerfuels production infrastructure could be achieved. The central refuelling characteristics of public fleets and transportation in general makes it possible to build up the refuelling-infrastructure for hydrogen or gas before they are covering a wide public scope. This leads to lower infrastructural costs compared to private vehicles running on hydrogen or synthetic gas.

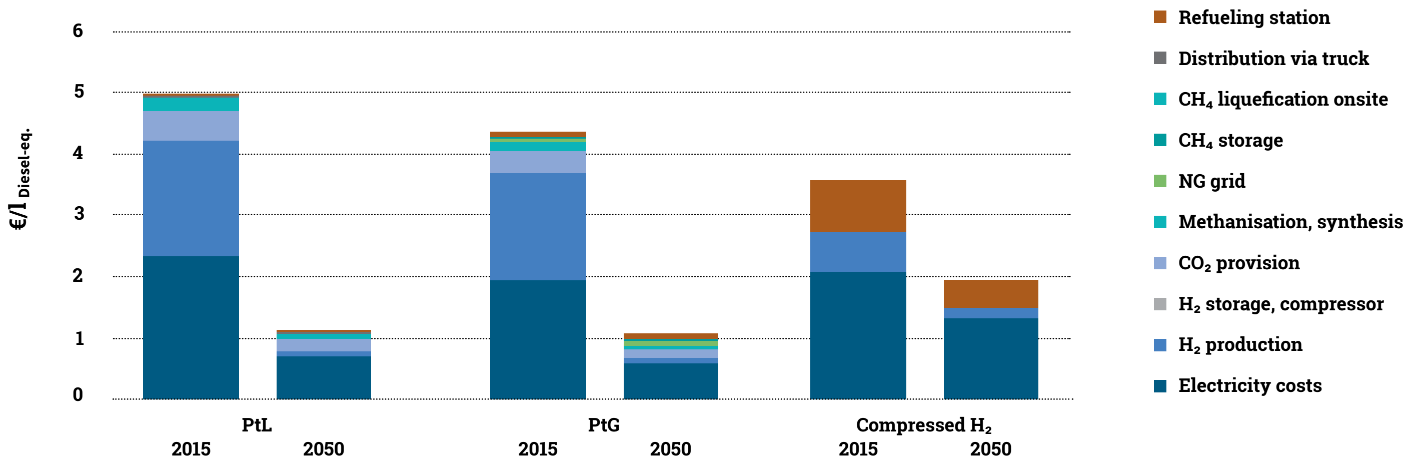
50 – 60 %
of total public transportation in Europe is satisfied by buses[1]

95 % of buses run on Diesel[1]

H_2 **Hydrogen**	No local CO_2 and pollutant emissions; less noise pollution compared to conventional combustion engines	Higher range than BEV-buses; possibility for centralised refuelling infrastructure; short refuelling cycle	
Synthetic Methane	Significantly lower CO_2 and local pollutant emissions compared to diesel driven buses	Higher range than BEV-buses; possible usage of existing centralised refuelling infrastructure; short refuelling cycle	
Synthetic Diesel	Possible usage of existing refuelling infrastructure and vehicles; short refuelling cycle	Higher range than BEV-buses; “drop-in” character allows it to gradually substitute conventional diesel	No broad incentives yet to implement powerfuels into public transport sector

Actual and projected cost structure of relevant powerfuels for public transport

Actual (2015) and predicted (2050) prices for different powerfuels in €/l $_{\text{Diesel-eq.}}$



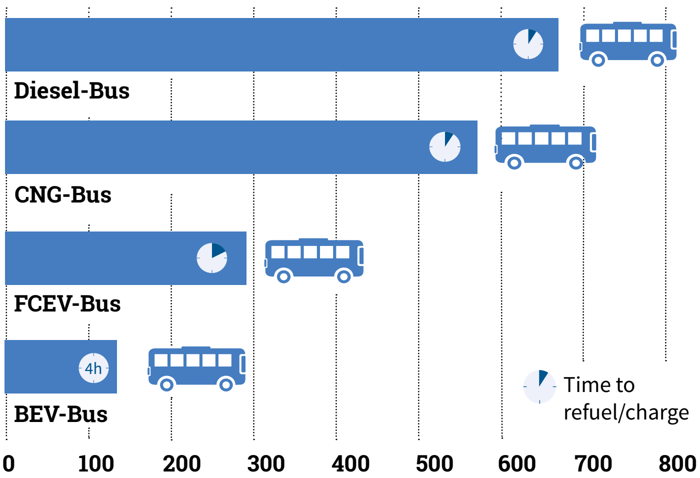
Hydrogen is provided by high temperature electrolysis for PtG and PtL, Hydrogen for compressed hydrogen is provided by low temperature electrolysis, Powerfuels are produced with EU domestic energy in 2015 and are imported for the year 2050, Carbon-dioxide is provided by direct air capture technology Source: "e-fuels" study (LBST and dena)[2]

From today's perspective, **hydrogen** is the energy carrier, which has comparatively lowest production costs in the range of powerfuels. On the other hand, hydrogen triggers high investments in vehicle technology and infrastructure. A significant decline of the costs is expected with ramp-up of global electrolyses capacities.

The production of **synthetic methane** is associated with slightly higher energy demands compared to the hydrogen production. Synthetic methane has "drop-in" character and can thus immediately substitute natural gas. This establishes significant financial benefits.

The production of **synthetic diesel** is associated with slightly higher conversion losses than the production of synthetic methane. Its major advantage is, that the usage of existing infrastructure and combustible ready vehicles is possible. This can establish significant financial benefits.

Range of typical public buses depending on different powertrains*



*Example calculation for public buses of the model series Mercedes-Benz Citaro. Used parameters (Energy storage, consumption) – BEV-bus: Range according to manufacturer; FCEV-bus: 35 kg, 12 kg/100 km; CNG-bus: 209,2 kg (1360 l), 38,25 kg/100 km; Diesel-bus: 260 l, 38,7 l/100 km.

All powerfuels-driven vehicles have a significantly longer range compared to battery electric buses, whilst having shorter refuelling durations.

Synthetic diesel has highest fuel costs compared to other powerfuels, but its "drop-in"-character allows the immediate use of this decarbonized fuel in any existing diesel vehicle today without the need for any modification in infrastructures or vehicles. Synthetic diesel thus allows immediate GHG reduction in existing vehicle fleets.

Gas-driven buses have significantly reduced local pollutant emissions compared to diesel buses. Production process for synthetic methane needs less energy and has therefore lower fuel costs than synthetic Diesel.

Fuel-cell electric buses (FCEV-buses) have a significantly higher well-to-wheel energy efficiency compared to combustion engine vehicles. In addition, FCEV-buses have the advantage of no tailpipe emissions, which is especially interesting for highly populated urban areas with a high exposure of air pollutants (e.g. NOx).

Public transport as ideal early adopter for powerfuels

Public transport usually uses centralised infrastructures for maintenance and refuelling. Public transport can forecast its specific transport demand, leading to a continuous and predictable fuels demand. Therefore, long-term planning stability is given, making power-to-X production investments feasible and thus favours the use of powerfuels. In addition, public transport operation has to undergo a competitive tendering process, in which public policy makers can include GHG emission targets to the tender conditions. These make such public fleets perfect for early market ramp-up of powerfuels.

1 Decarbonisation: the public transport contribution, International Association of Public Transport.
2 The potential of electricity-based fuels for low-emission transport in the EU, dena and Ludwig Bölkow Systemtechnik.

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