Global Alliance POWERFUELS

Powerfuels: Missing link to a successful global energy transition

Introduction to technologies, applications, markets and policy

powered by

dena German Energy Agency

Imprint

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Members of the Global Alliance Powerfuels

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Content

Executive Summary

The Global Alliance Powerfuels
The Global Alliance Powerfuels was initiated by the German Energy Agency (dena) in late 2018 together with various renowned corporate partners as founding members. It currently comprises of 16 members and 22 partners forming a global network. The strategic objective of the Alliance is to foster the development of a global market for powerfuels.

Powerfuels are gaseous or liquid fuels and feedstock produced from renewable electricity. This includes, but is not limited to, hydrogen, synthetic gas and synthetic liquid fuels (also known as Power-to-Liquid). 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 represent an alternative to store renewable energy 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

Main Goals of the Alliance:

1. **Raise awareness and acceptance of powerfuels as missing link to reach global climate targets**
2. **Support the further enhancement of regulatory frameworks with the initial focus on Europe as region of demand**
3. **Stimulate project development to globally enable production capacities on industrial scale, thus increasing cost competitiveness with fossil fuels**

Global cooperation is needed to address climate change
Human influence on the global climate system is widely known. A global cooperation is needed to address climate change - as evidenced by the 196 countries that have signed the Paris Agreement. For the first time, from 2024 onwards, there will be common and binding minimum standards for states to report on their greenhouse gas emissions and climate protection measures. The energy transition to yield climate goals presents both wide-ranging challenges and opportunities for societies around the

world. Governments are called upon to promote policies that safeguard competitiveness, economic growth, and employment. These will enable companies to use their innovative capabilities to protect the climate and make the transition to a sustainable global economy possible.

Powerfuels are an essential building block for reaching climate targets
Powerfuels are synthetic gaseous or liquid energy carriers and feedstock, based on renewable electricity. They are a missing link for reaching climate targets due to four key reasons:

- Powerfuels are a climate-friendly solution **for applications that have limited or inexistent low carbon emission alternatives** from today's perspective
- Powerfuels utilise the worldwide potential for renewable energy systems as they **can be transported and traded globally**
- Powerfuels can reduce the overall cost of energy transition by **utilising existing infrastructures and providing long-term storage options** for renewable energies
- Powerfuels could accelerate the defossilisation of existing consumer end-use equipment, because they are **green drop-in alternatives to fossil fuels**

Technologies are market-ready – and costs will fall further with economies of scale
The necessary **technologies for the production of powerfuels are already demonstrated and tested**, however the business models are not available yet, as total costs are still high. Electricity is the main cost driver, followed by carbon capture (for hydrocarbons) and the electrolysis of hydrogen. Through economies of scale, the costs of powerfuels production technologies could significantly be reduced. Sufficient demand for powerfuels can be triggered by policies that recognise the carbon-neutral nature of powerfuels compared to fossil fuels.

An international powerfuels market provides value for everyone – producers, consumers and enabling countries
In countries with abundant renewable energy sources, the costs of renewable electricity are expected to decrease rapidly with increased capacity. Those countries are particularly suited for powerfuels production. Depending on the country, powerfuels could be used for their own demand first to replace fossil fuel imports or could be exported to countries that are willing to pay for the carbon-neutral nature of powerfuels.

Powerfuels will play an important role in the major industry sectors becoming carbon neutral. Powerfuels can be applied to all industry sectors as they can be tailored to have the same molecular structure as fossil fuels, allowing powerfuels to be used in existing infrastructures until more sustainable alternatives could be developed.

Join the discussion about the perspectives of a global market for powerfuels. Contact us at www.powerfuels.org or through powerfuels@dena.de. We are eagerly looking forward to your opinions, insights and opportunities to work towards a sustainable global energy future.

1 What are powerfuels and why are they relevant?

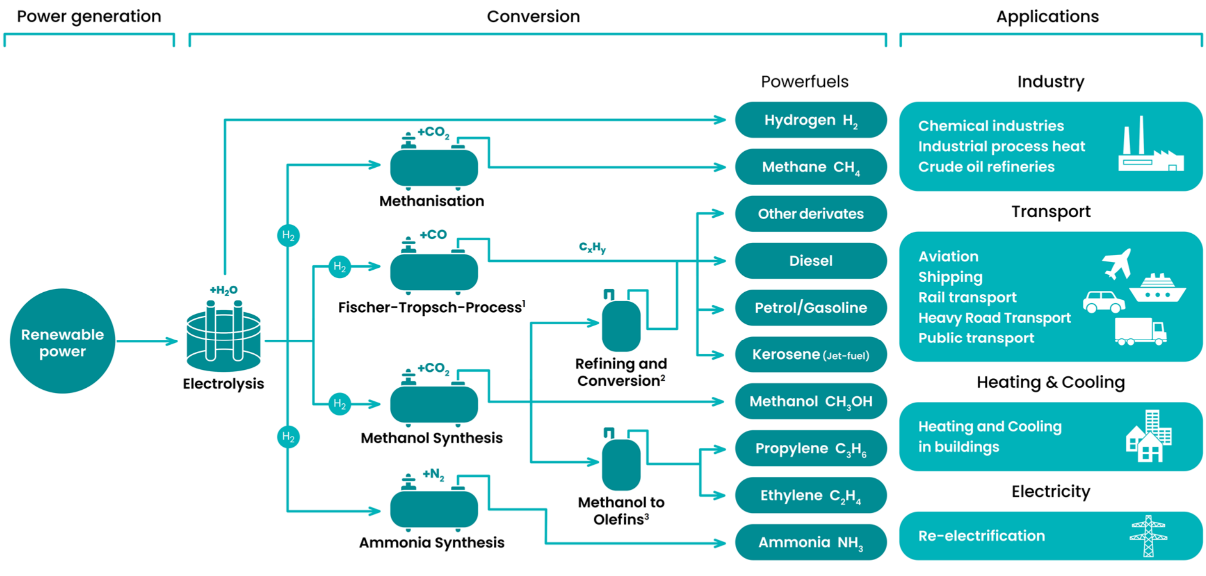
Chapter Summary

1. Powerfuels are **synthetic gaseous and liquid fuels and feedstock** based on renewable electricity.
2. Powerfuels will be the **missing link for reaching climate targets** due to following key reasons:
   a. Powerfuels are climate-friendly solutions to **applications with no viable alternatives**.
   b. Powerfuels can **reduce the cost of energy transition** by utilising existing infrastructures and they provide long-term storage options for renewable energies.
   c. Powerfuels can utilise the **worldwide renewable energy production potentials** as they can be transported and traded globally.
   d. Powerfuels could **defossilise existing consumer end-use equipment** as green drop-in alternative to fossils.
3. **Electricity costs are the largest portion of powerfuels costs** followed by carbon capture costs. There is considerable scope for future cost reductions through economies of scale.
4. Individual **technologies for production of powerfuels are already available**, however they are yet to be integrated in complete commercial value chains.

Definition of powerfuels

Powerfuels are synthetic gaseous or liquid fuels that draw their energy content from green electricity. Powerfuels are renewable and climate-friendly and can be used as energy carriers and as feedstock. This definition includes but is not limited to hydrogen, synthetic gas (e.g. methane, propane), synthetic liquid fuels and chemicals (e.g. methanol, diesel, gasoline, kerosene, ammonia, Fischer-Tropsch products), hence being technologically neutral. In line with the long-term goal of reducing GHG emissions, the carbon needed for the production of hydrocarbon powerfuels (methane, propane, methanol etc.) can originate from industrial point sources (Carbon Capture and Utilisation CCU), Direct Air Capture DAC and biogenic sources. Nitrogen that is required for ammonia synthesis can be captured by direct air separation units. Figure 1 shows the various processes and end products of powerfuels processes.

In line with the definition of powerfuels, "e-fuels", "synthetic fuels" and RFNBO (Renewable Fuels of Non-Biological Origin) are synonyms. However, the term powerfuels is preferred, as giving a more holistic perspective. The wording e-fuels has mainly been used in relation to the transport sector (LBST and dena, 2017), while "synthetic fuels" is much more generic and does not reveal the importance of electricity in producing these fuels. Additionally the term "synthetic fuels" is not necessarily related to renewable fuels. Therefore, powerfuels are proposed as coherent wording, to overcome the shortcomings of the other terminology.



1 Includes: Fischer-Tropsch synthesis, hydrocracking, isomerization and distillation.
2 Includes: DME/OME synthesis, olefin synthesis, oligomerisation and hydrotrating.
3 Methanol-to-olefins process.

Figure 1: Various possible powerfuels processes, products and applications

Reasons for powerfuels as missing link to reaching climate targets

Direct use of renewable energies (including electricity, but also biomass) and energy efficiency are important pillars of the energy transition. However, for some sectors and applications these pillars are insufficient to realise significant reduction of GHG emissions. Powerfuels have the potential to become the third pillar of the energy transition, not as substitute, but as complement to the other two pillars (Figure 2). Powerfuels will be the "missing link" (IRENA, 2018, p. 16) to achieve net-zero global greenhouse gas emissions through a cost-efficient transition .

Particularly, powerfuels can contribute significantly to the energy transition worldwide in the following ways:

1. Powerfuels allow to **reduce emissions of applications that cannot be directly electrified** and provide **additional options for other sectors** that are mainly supplied with fossil fuels.

2. **Reducing the cost of the energy transition** by capitalising on the given energy infrastructure. Powerfuels can be transported, distributed and stored within existing systems, thus limiting the need for new investment and providing options for long-term storage.

3. Opening new options for **defossilisation of consumers' existing applications** where alternative abatement measures are unfeasible (economically, technologically and socially) or where investment cycles are long. Powerfuels provide additional abatement option, which could enhance social acceptability of climate policy measures.

4. **Leveraging the global potential of renewable energies** and materialising economic gains of international trade. Powerfuels are fully tradeable on global scale at relatively low cost of transportation. This opens options for countries with large energy demands, but limited space and/or potential for renewable energy sources by additionally helping to diversify supply of energy importers. It

also provides new carbon-neutral export opportunities for countries with high renewable energy potential and fossil fuels production today.

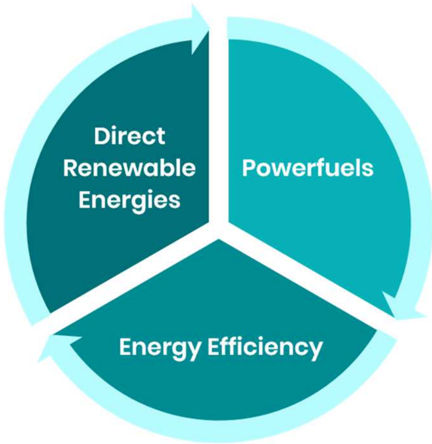


Figure 2: Three pillars of the successful energy transition

Powerfuels are climate-friendly solutions for applications where defossilisation was not feasible so far
Chemical energy carriers such as powerfuels and fossil fuels have a very high energy density. As shown in Figure 3, this is particularly true for liquid fuels, but also with regard to gaseous carriers. This characteristic translates into a major advantage of chemical energy carriers compared to electricity, particularly when very high amounts of energy are required (Perner *et al.*, 2018, p. 11). From today's perspective, direct electrification is technologically unfeasible for some applications. Therefore, it will be difficult to achieve significant fossil CO_2 emissions reduction in these energy applications. This holds particularly for:

1. **Aviation**
2. **Maritime shipping**
3. **Non-electrical rail transport**
4. **Heavy-duty long-distance road transport**
5. **Steel production**
6. **Heavy machinery** used in sectors such as agriculture, construction, mining etc.
7. **Dispatchable power generation** (power-to-gas-to-power)
8. **High-temperature industrial process heat**

As powerfuels are climate-friendly[1], the widespread substitution of fossil fuels with powerfuels in these sectors could strongly contribute to the defossilisation and to the reduction in GHG emissions. Furthermore, various industries rely on fossil resources as feedstock. In these sectors, powerfuels could furthermore contribute to the reduction of GHG emissions:

1. **Feedstock/precursors for chemical industry**
   Green Methanol as feedstock
2. **Fertilizer production**
   Green Ammonia as feedstock
3. **Steel production**
   Green Hydrogen as reducing agent
4. Various **other production methods** currently relying on grey hydrogen produced from natural gas, such as crude oil refining

Powerfuels reduce the cost of energy transition by making use of existing infrastructures and providing long-term storage options (J. Perner and Bothe, 2018, p. 20)
On a molecular level, powerfuels are equal to their "conventional counterparts". Therefore, powerfuels can capitalise on the existing and well-established infrastructure for transportation, distribution and storage of fossil fuels (e.g. oil and gas pipelines, storage facilities, refinery equipment and international shipment). By using the existing infrastructure, significant cost savings could be achieved. For example, recent studies focussing on Germany indicate that – with regard to 2050 – the reliance on a broader technology mix (including powerfuels) could lead to substantial cost savings compared to high electrification scenarios because of the continued use of gas and liquid fuel transport infrastructure (Bothe, D. and Janssen, 2018, p. 24; dena, 2018, p. 29 ff.).

[1] In case the carbon originates from DAC, powerfuels are carbon-neutral.

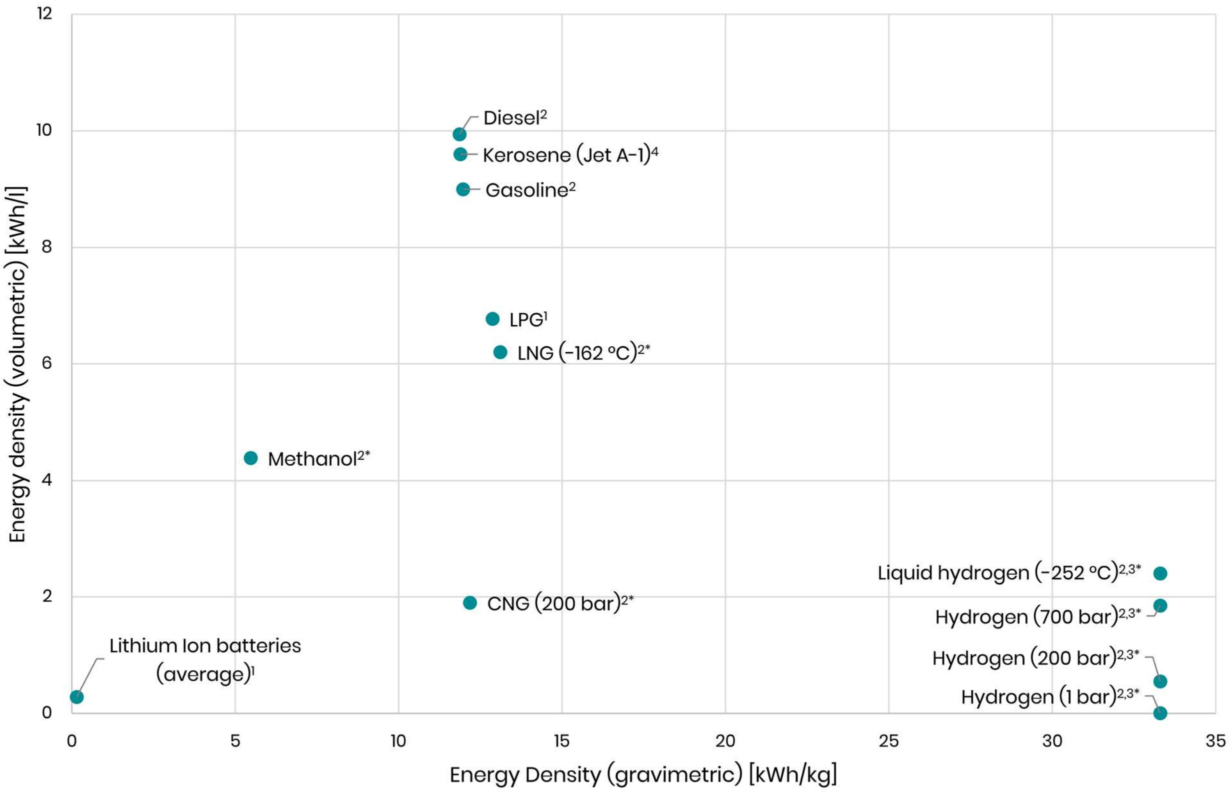


Figure 3: The gravimetric and volumetric energy density of various energy carriers (* based on LHV)[2]

By using the existing infrastructure for powerfuels, the social acceptance of the energy transition could be increased, comparing to a scenario with construction of new infrastructure like electricity grids. This could help to accelerate the rate of energy transition. Due to the same or similar molecular structure, powerfuels can be gradually integrated/mixed within the existing flows of fossil energy carriers (drop-in). This enables a quick introduction of powerfuels in the short and medium term, without the need for change of existing appliances/equipment. This could help guaranteeing smooth transition paths since end-user behaviour does not need to change (J. Perner and Bothe, 2018, p. 23). For example, synthetic methane can be injected without limitations within the existing gas grids even today. Synthetic propane can be utilised in the existing infrastructure, especially in rural areas that are not connected to the natural gas grid. Molecular hydrogen can also be injected up to a certain limit based on the end-use application. Similarly, synthetic liquid fuels produced through the Fischer-Tropsch process can be blended with conventional ones.

Another major advantage in this regard is that the existing long-term storage facilities for fossil fuels can also be used for powerfuels (e.g. gas caverns, oil deposits, storage tanks in households and commercial applications). This is important as with the increasing reliance on electricity produced from fluctuating RES, large-scale storage solutions will be needed in countries with intermittent weather conditions (daily and seasonal). Batteries and pumped storage hydro plants are efficient options for short and mid-term periods. However, long-term options to seasonally store RES production are still missing. Powerfuels are able to close this gap and could thus enhance the security of supply of countries (J. Perner and Bothe, 2018, pp. 19–20).

[2] References: 1 (Sterner and Stadler, 2014, pp. 649 & 650), 2 (Zweifel, Praktiknjo and Erdmann, 2017, pp. 169 & 201), 3 (Paschotta, 2021), 4 (ExxonMobil, 2020)

Powerfuels can utilise the worldwide renewable electricity production potential as they can be transported and traded globally
Like their fossil counterparts, powerfuels can easily be transported without major limitations. This also holds for long-distance transport (Transportation costs are relatively low and infrastructure is well established). Therefore, powerfuels are perfectly suitable for global commodity trade. There are various advantages linked to this characteristic:

As electricity costs are a major cost component of powerfuels, countries with favourable conditions for RES will have a cost advantage. Powerfuels could help these countries to materialise this advantage, as powerfuels allow to indirectly exporting large amounts of locally produced renewable electricity. This could promote economic development and increase the GDP of many developing countries, as explained in Chapter 2.

Analogously, powerfuels allow countries with limited potential/limited space for RES, but high-energy demand to import climate-friendly energy carriers. Depending on the cost-differences in the production of powerfuels for different countries, this may lead to enormous savings compared to self-production of powerfuels (Ram *et al.*, 2020, p. 6). In this regard, powerfuels additionally could increase social acceptance of the transformation of today's energy system, as they could limit local land usage associated with RES.

Alternatives for the import of RES are less promising than powerfuels (J. Perner and Bothe, 2018, p. 26). Direct import of renewable electricity requires an expansion of today's electricity networks, resulting in high costs. Furthermore, the technical possibility for long-distance transmission of electricity is limited. Import of biomass or biofuels, is limited due to sustainability issues such as deforestation for land use and competition with food production.

Currently, the global supply of fossil fuels is relatively concentrated and the energy import strategies of many countries rely on few suppliers. As the global potential for RES is by far more distributed, there are many more potential suppliers. This opens importers the opportunity to furtherly diversify their procurement strategies, reducing their dependency on single suppliers and increase stability.

Powerfuels accelerate the defossilisation of consumers' existing technical devices and applications
Powerfuels are practically identical to their fossil counterparts on molecular level and could thus be used in existing end-user applications without any restrictions. Powerfuels deliver additional benefits compared to their fossil counterparts, in showing a higher chemical purity. This could increase the efficiency and lifetime of existing end-use equipment such as:

- Synthetic methane and hydrogen could substitute natural gas in the residential heating sector.
- Synthetic propane can substitute its fossil counterpart without limitations, whether in domestic (cooking and heating), automotive or leisure applications.
- Synthetic FT-fuels (gasoline or diesel) could be used for cars with internal combustion engines.
- Synthetic fuel oil could replace fossil fuel oil in the residential heating sector.

Powerfuels could allow continuing the usage of the mentioned equipment in a climate-friendly way. There are and will be additional technology options like heat pumps or Battery Electric Vehicles. However, the adoption rates of these new technologies depend on the regulatory framework and economic affordability. In the medium-term, a mix of conventional and new technologies for these applications is expected, thus highlighting the need for technology openness.

With regard to the building sector, renovation rates are relatively low and existing heating systems are only exchanged at long intervals. Furthermore, heat pumps are mainly applicable in buildings with well-insulated envelopes (Strategieplattform Power-to-Gas, 2018a). Therefore, the use of powerfuels in existing assets does not contradict the advantages that might come with a modernisation of these devices (e.g. by increased energy efficiency of a more modern equipment). They rather provide additional options, where the range of alternative technical solutions is inhibited, thus accelerating the defossilisation of these applications. This could also lead to higher social acceptability with regard to the energy transition, as end-users are empowered to contribute to climate change mitigation without investments in new applications.

Power-to-X technologies are available, capacity increase allows cost degression

There are several technologies used in the production of powerfuels. These are further explained and their Technology Readiness Level (TRL) is briefly assessed (NASA, 2012). Figure 1 contains a summarised overview of the various powerfuels production pathways.

Technologies for powerfuels production are tried and tested:

Electrolysis

Irrespective of the end product, all powerfuels production processes start with electrolysis. Hydrogen electrolysis refers to the splitting of water into hydrogen and oxygen using electrical energy. There are four main electrolysis technologies, as briefly described in Figure 4. Various other electrolysis technologies exist but are currently not available as commercial products.

Methanisation

In the methanisation process, hydrogen is furtherly processed by the addition of carbon dioxide to produce methane. Catalytic methanisation (TRL 8, efficiency 77 to 83 %) requires a nickel-based catalyst and is already in commercial use. In addition, biological methanisation (TRL 7, efficiency 77 to 80 %) using microorganisms could be carried out (Strategieplattform Power-to-Gas, 2018b).

Fischer-Tropsch-Process

Synthetic liquid fuels in the form of hydrocarbons could be produced through the Fischer-Tropsch process (TRL 8, efficiency ~56 %) (Strategieplattform Power-to-Gas, 2018b). In this process, carbon dioxide is converted to carbon monoxide in a first step using the reverse water-gas shift reaction. In a second step, the carbon monoxide and hydrogen are used to produce hydrocarbons with different chain lengths. These hydrocarbons can be used as feedstock for producing various gaseous and liquid fuels such as propane, petrol, diesel or kerosene (jet fuel).

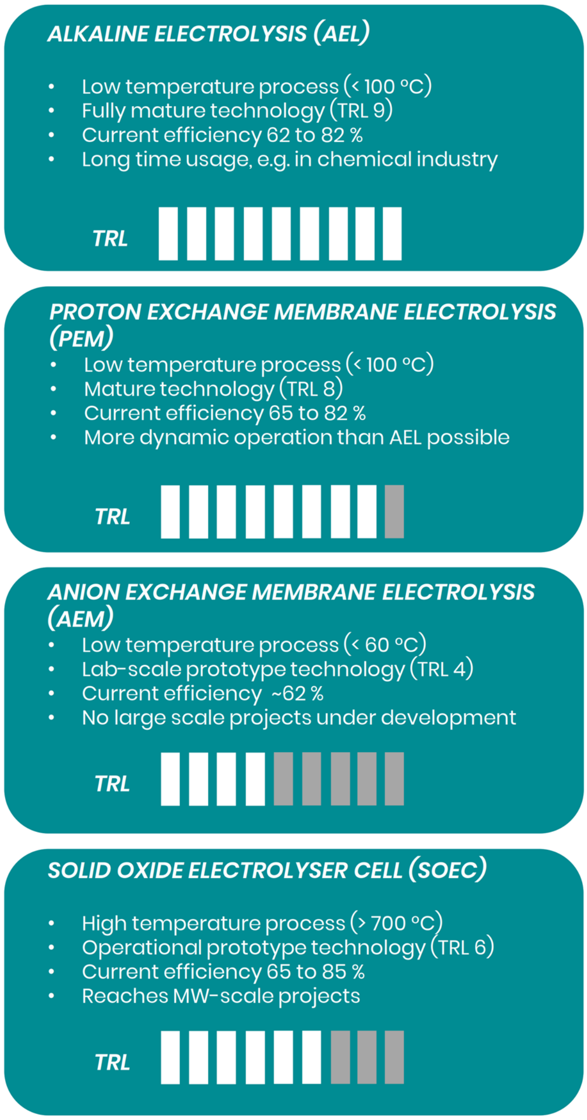


Figure 4: Main electrolysis technologies and their TRL (Technology Readiness Level)[3]

Methanol synthesis

Methanol can be produced from syngas, a mixture of hydrogen, carbon monoxide, and carbon dioxide. The methanol production process is already widely used in the chemical industry and well established for decades (TRL 9, efficiency 56 to 66 %) (Strategieplattform Power-to-Gas, 2018b)(Márquez and Hobson, 2018). Methanol has multiple uses as fuel as well as a chemical commodity. Methanol can be used as fuel directly, for example in internal combustion engines or fuel cells. Methanol also is a basic feedstock for the chemical industry and can be converted to various other transportation fuels such as Dimethylether DME, Oxymethylenether OME, gasoline and jet fuel. It can

[3] Based on (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018; IRENA, 2018, 2020a, p. 31ff; Strategieplattform Power-to-Gas, 2018b; Enapter, 2021; Sunfire, 2021)

also be converted to other chemical intermediaries such as olefins for plastic production (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018, p. 70).

Ammonia synthesis
Conventional production of Ammonia (TRL 9) for the fertiliser industry uses hydrogen produced by steam reforming of natural gas (ISPT, 2017). Green hydrogen produced from electrolysis can also be used instead. The conventional ammonia production via the Haber-Bosch-Process is a long established industrial process.

Carbon Capture
Carbon-containing powerfuels such as FT fuels or Methanol, require Carbon, especially in the form of CO_2 as feedstock. On the industrial scale required for powerfuels production, there are three primary ways for obtaining CO_2 as feedstock (UBA, 2016; LBST and dena, 2017; Global Alliance Powerfuels, 2020, p. 8):

- Industrial CO_2 point sources (TRL 6-9): CO_2 can be captured from already existing industrial point sources such as steel works or cement mills. Industrial emissions have to be purified and subsequently CO_2 is extracted. Based on the specific technology used, the TRL varies.
- Biogenic CO_2 sources (TRL 6-9): CO_2 can also be captured from biogenic sources. Biogenic CO_2 originates always from biomass and is produced in various processes such as combustion, fermentation or decomposition. For example, in biogas and ethanol production CO_2 is released.
- Direct Air Capture (DAC) (TRL 6): A location-independent source of CO_2 is presented by capturing it from ambient air. DAC technologies are currently under development and first prototype plants are in operation (Carbon Engineering, 2021; Climeworks, 2021).

It should be noted that in order to contribute to the reduction of GHG emissions, no CO_2 should be produced due to the sole purpose of providing input for powerfuels. Furthermore, powerfuels should not be the decisive factor to invest in or maintain fossil-based emitting technologies. For example, using CO_2 from fossil power generation should not prolong the life cycle of the plants (lock-in effect).

Technology Outlook
Various individual technologies that are part of powerfuels processes are already available. In order to reduce the costs of producing powerfuels, plants require constant operation throughout the year and further technical development. This needs to be aligned with a fluctuating supply of regenerative electricity, which requires storage further up the production chain (e.g. hydrogen or battery storage).

Since water electrolysis is the common base for all powerfuels processes, the scale of powerfuels projects could be better understood by considering the electrolyser capacities. In the past, with few exceptions like the Energiepark Mainz in Germany (6 MW, installed in 2015) and the Guangdong Synergy project in China (3 MW, installed in 2017), most electrolysers installed had less than 2 MW capacity. According to the IEA World Energy Investment Report, the annual worldwide electrolyser capacity addition from 2010 to 2017 has been below 20 MW per year (IEA, 2018c, p. 221). However, this is rapidly changing, as politics and industrial sector start to realise the importance of powerfuels, resulting in announcement of several planned projects with electrolyser capacities up to 100 MW (e.g. Energiepark Bad Lauchstädt (35 MW) and GET H2 Nukleus (100 MW)) (DBI, 2020; OGE, 2020). On the base of national hydrogen strategies, especially from European countries, the rate of installed electrolyser capacities are estimated to reach GW-scale by the second half of the 2020 decade.

Most important cost drivers
Electricity cost is the main driver behind for powerfuels costs followed by carbon capture costs (LBST and dena, 2017, p. 87). As green hydrogen is the base feedstock for all powerfuels, the investment costs for the electrolysers play another important role as main cost driver (IRENA, 2020b). The cost of producing synthetic liquid fuels and gases vary substantially between fuels and for the different assumptions drawn regarding underlying cost figures (J. Perner and Bothe, 2018, p. 70). Powerfuels plants located outside the EU can expect equivalent full-load period of up to 7,000 hours per year with renewable electricity from combination of wind and PV systems. Cost reductions require considerable, early and continuous investments in electrolysers and CO_2-absorbers.

Electricity generation costs

Due to high investment costs but low operating costs, the generation costs of renewable electricity is highly dependent on the amount of full-load hours (FLH) per year. The larger the number of FLH, the lower is the Levelised Cost of Electricity LCOE produced (Hank *et al.*, 2020). Hence, regions with favourable characteristics for the production of electricity from renewable energies (e.g. wind, solar, geothermal, hydropower) are particularly suitable for the production of powerfuels, as associated generation costs of electricity are relatively low. Especially for powerfuels plants, a higher amount of FLH can be obtained by optimally combining PV and wind potentials with battery or hydrogen storage to increase plant load factors. Due to the decreasing investment costs associated with renewable energies, electricity generation costs are expected to fall continuously within the next decades. Figure 5 illustrates this historical decline in LCOE of renewable energy sources. Nevertheless, in 2050 electricity costs will remain the key cost driver of powerfuels. Taxes and levies that augment the electricity price for electrolysers automatically translate into higher costs for the production of powerfuels. (LBST and dena, 2017, p. 87; Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018, p. 82)

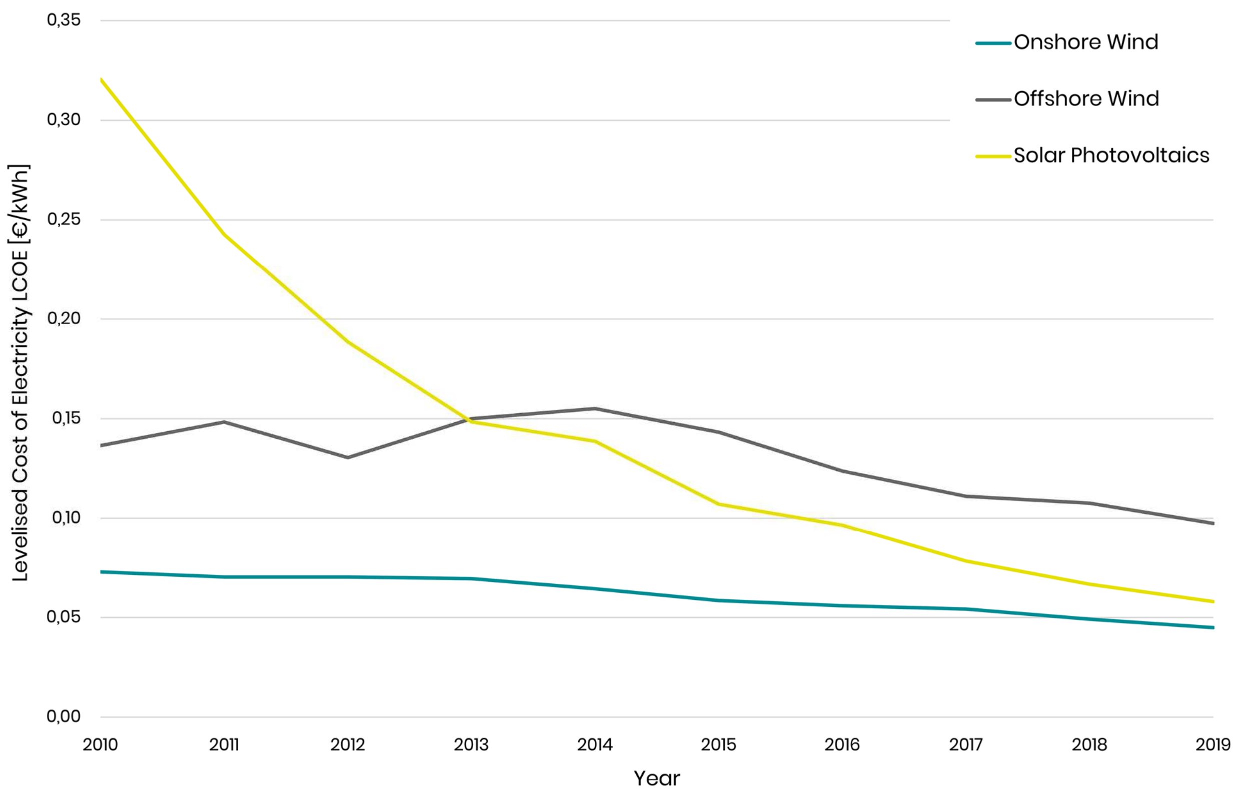


Figure 5: Development of the global weighted average Levelised Cost of Electricity LCOE from renewable energy sources (2010-2019)(IRENA, 2020c, p. 25, 2021a)

Investment costs

Plants for the production of powerfuels are capital-intensive, constituting high fixed and low marginal costs. Thus, the costs associated with the initial investment in synthetic fuel conversion plants are another important cost driver with regard to powerfuels. The investment costs for water electrolysis are expected to further fall within the next decades, continuing their historic trend. The degree of the estimated reduction varies between the different studies undertaken, as investment costs are related to plant size and plant technology (see Figure 6) (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018, p. 61).

Investments in electrolysers have been gradually increasing in the recent years and are estimated to grow in a fast pace (IEA, 2018c, p. 220). Electrolyser investment costs have been falling in the past years, indicating a scope for economies of scale. To further decrease investment costs in electrolyser technology, a significant scale-up of the plant size is required.

Investment costs relative to the total production costs of powerfuels decrease with the utilisation rate of conversion plants. In order to be operated economically, powerfuels plants should reach full load hours of at least 3,000 to 4,000 hours per year. Many regions in the EU and other parts of the world can expect an equivalent full-load period of more than 4,000 hours per year (Fasihi, Bogdanov and Breyer, 2016).

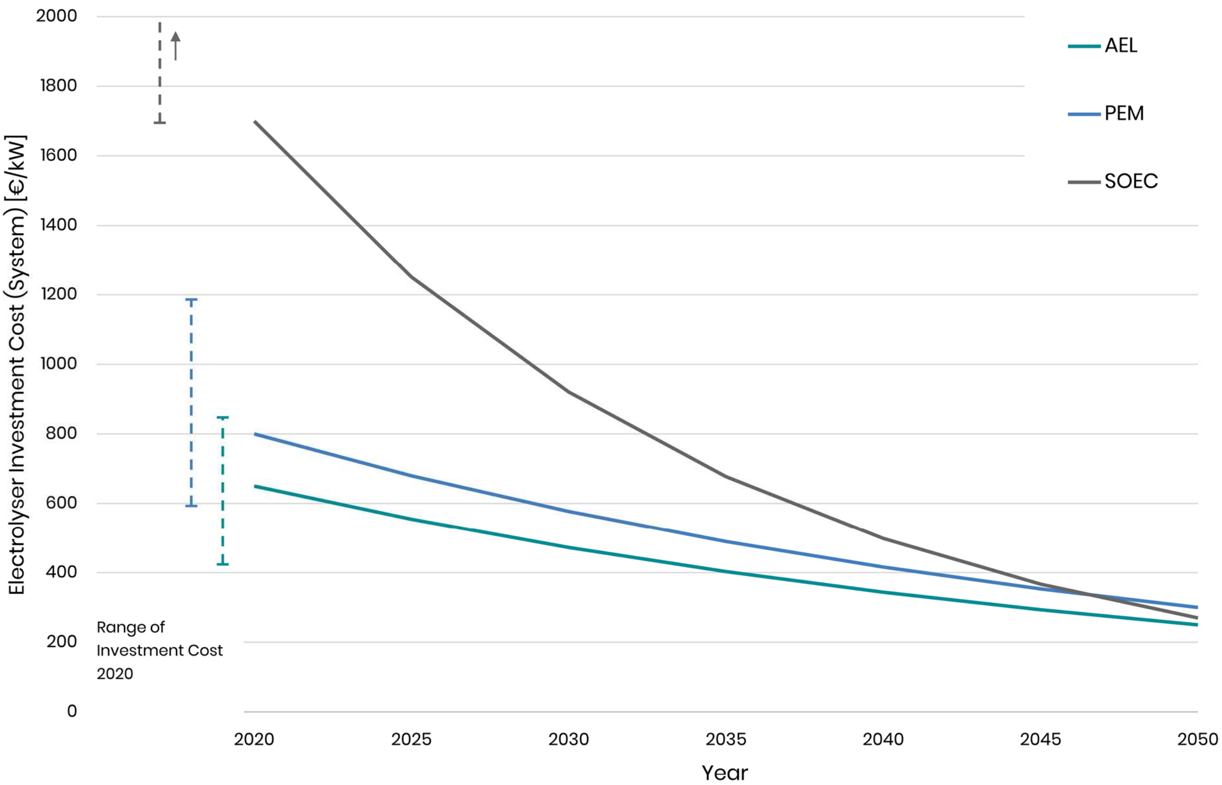


Figure 6: Estimated evolution of electrolyser investment costs, Based on data from (dena, 2018, pp. 380–382; IRENA, 2020a, pp. 65–66).

Carbon capture costs

Carbon capture from concentrated point sources (industrial and biogenic) is more technologically mature. Cost estimates for carbon capture from concentrated sources range from 30 to 70 €/tCO_2. Direct Air Capture is still technologically evolving and associated with costs of more than 150 €/tCO_2 , depending on the specific technology used (Keith *et al.*, 2018; Global Alliance Powerfuels, 2020, p. 8).

Other costs

Some parts of the world have excellent renewable electricity generation potential, but lack clean water sources. In these cases seawater could be desalinated and used for electrolysis, so costs related to that have to be considered (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018, p. 84). However, water requirements are limited for example, a demand of 1.3 to 1.4 litres water per litre of jet fuel is estimated (UBA, 2016, p. 18).

Transportation and storage of raw materials, intermediate products and completed products of powerfuels production should also be taken into consideration especially in cases where the production facility and end consumption are far apart.

Estimation of powerfuels demand

Several studies have estimated the expected global powerfuels demand for different scenarios. Depending on the share of powerfuels usage in each sector, the global total powerfuels demand in 2040 varies from 10,000 to 40,000 TWh (J. Perner and Bothe, 2018; Ram *et al.*, 2020). As a reference, the global total oil and gas consumption for 2017 was 90,500 TWh (BP, 2018). Figure 7 shows the estimated demand of different powerfuels for the years 2030, 2040 and 2050 for the scenario of a completely renewable energy system in 2050. With a total amount of 43,200 TWh in this (high-electrification) scenario for 2050, powerfuels are expected to account for 28 % of global energy demand in 2050 (Ram *et al.*, 2020, p. 6).

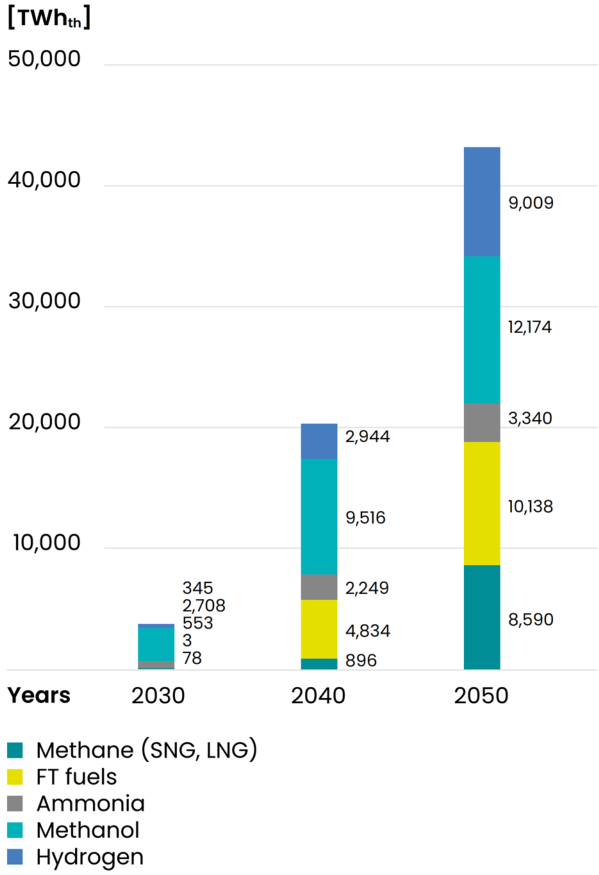


Figure 7: Development of powerfuels demand from 2030 to 2050 for the scenario of a completely renewable energy system in 2050 (Ram *et al.*, 2020, p. 23)

2 Future role of powerfuels in different countries

Powerfuels provide value for different countries in different ways: as powerfuels suppliers, technology providers, demand countries – or all of the above.

1. Powerfuels are an **opportunity for countries with high renewable potential**. They can create value locally, contribute to the local energy transition and be exported globally.
2. Powerfuels are an **opportunity for countries that use them**: They help reach climate goals, diversify energy sources, and enable energy transition.
3. Countries and industries with **technologies for powerfuels and global energy trading expertise** will also benefit.
4. Countries that **combine several such motives** may be the forerunners of the future global market for powerfuels.

As outlined in the previous chapters, powerfuels provide value in many areas and industries. Similar to the current global energy system based on fossil fuels, they enable global trade of energy – and contribute to the local economy at all steps of the value chain. Looking at individual countries shows that there are considerable differences in their current situation and future trajectory. Nonetheless, powerfuels will be needed – and produced – around the world.

Countries as suppliers

Countries may become powerfuels producers for a variety of reasons. Many economies, especially in developing and emerging incomes, are currently based on the export of (fossil) energy. For those countries, powerfuels can be an opportunity to hedge against the risk of not being able to sell their reserves, as importing countries increasingly strive to become climate-neutral. Moreover, powerfuels constitute a business opportunity for countries that possess abundant space and good conditions for renewable power, to become exporters themselves. Powerfuels may then become a source of economic growth and employment.

Various previous studies have contributed to the analysis of possible suppliers, however most of them focus on analysing only selected countries (such as Europe as a supply region) or aggregate data regionally (LBST and dena, 2017; Fasihi and Breyer, 2017; Fasihi, Bogdanov and Breyer, 2016; Pfenning and Gerhardt, 2017; Singh, Moore and Shadis, 2005). The most comprehensive study on this matter was published by World Energy Council - Germany (Perner and Bothe, 2018), which bases its analysis by first examining the technical potentials for generating renewable electricity, followed by secondary factors such as economic and political framework conditions. With regards to these technical factors, the most widely quoted data is from Fasihi et al. (Fasihi and Breyer, 2017), which demonstrates that the high load factors of powerfuels plants necessary for competitive powerfuels are attainable through an optimal combination of wind and solar resources around the world, which many countries exhibit. Figure 8 shows these technical potentials for selected countries. Evidently, most large and economical powerfuels potentials are situated outside of densely populated industrialised countries such as many European countries, Korea and Japan.

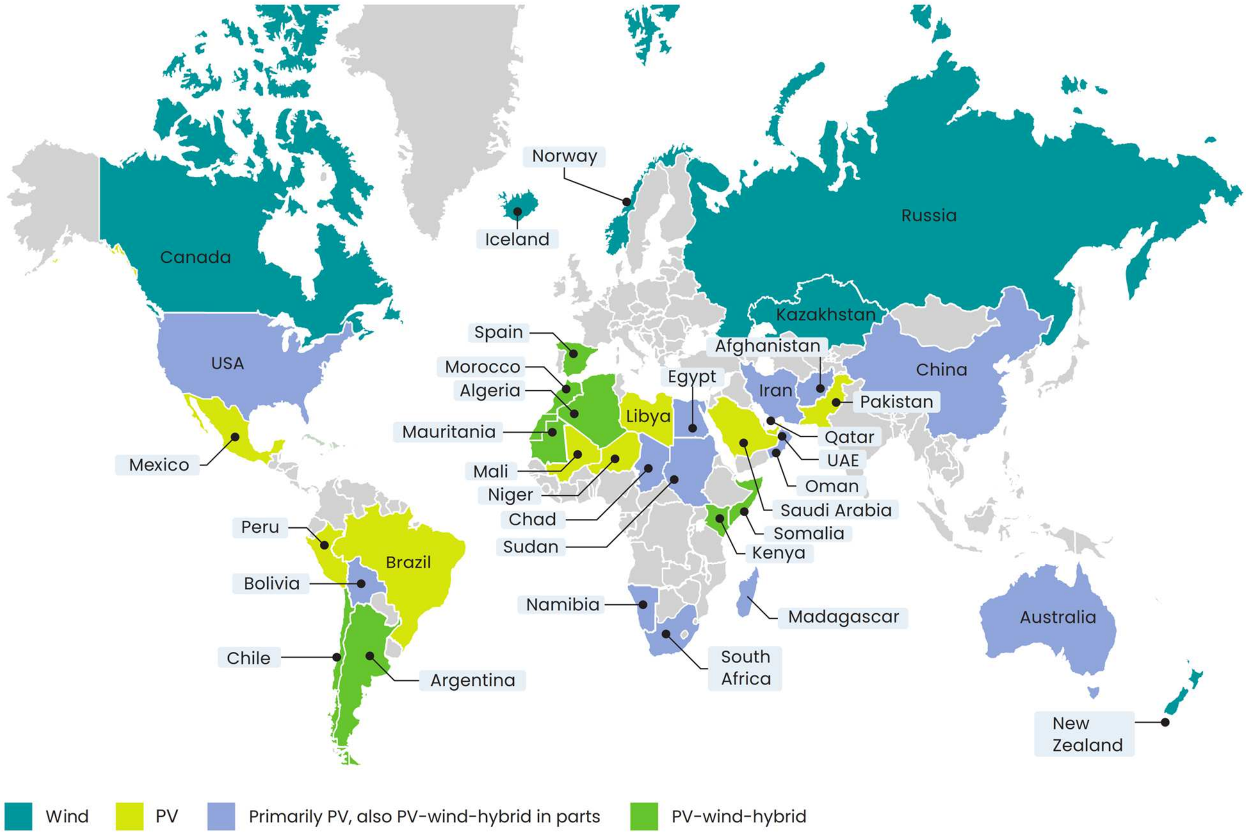


Figure 8: Snapshot of the World's strongest renewable electricity potentials[4]

Countries as powerfuels consumers

Powerfuels find their applications in almost all sectors and industries. Therefore, their theoretical potential corresponds with the current use of fossil fuels as energy carriers. Previous studies have attempted to estimate global demand in a similar way. For a completely renewable energy system, the demand for powerfuels is estimated to grow to 43,200 TWh per year, due to a recent study of LUT University (Ram *et al.*, 2020, p. 6). In this study a high electrification scenario is chosen, where powerfuels only account for 28 % of the final energy demand. However, they may constitute the majority of energy supply in sectors where no other defossilisation option is available.

Notwithstanding these theoretical potentials, with fossil fuels available and cheaper for the foreseeable future, demand markets depend on two factors: climate ambition and ability to pay. These factors differ strongly between countries. Further, in the absence of consumers voluntarily switching to climate-friendly fuels as long as these come with higher costs than their fossil counterparts, market development will rely on governments to be ambitious in making powerfuels attractive and in economies to be able to pay for the sustainability mark-up.

Even high-income countries vary in their ambition to reduce GHG emissions. Nonetheless, almost all strive to significantly reduce them until 2030, and beyond. Especially the European Union now marks a front runner with an GHC emissions reduction goal of 55 % in

[4] Illustrative presentation of the RES potential, not an exhaustive list. Source: based on Perner and Bothe, 2018, p. 39

2030 comparing to 1990s values (European Comission, 2020). For the most ambitious countries and regions, such as the EU, powerfuels may constitute a necessary technology to reach those climate targets. Emerging countries such as China, Turkey and Indonesia are still planning to increase emissions up until 2030, due to anticipated strong economic growth. As future demand markets however, high-income countries may be the first adopters as they are able to afford the higher costs associated with infrastructure investment and powerfuels production. Between those high-income countries, the most ambitious emissions targets are currently in Canada and the EU. It should be noted however, that several regions are even more ambitious, as evident by efforts in California to achieve carbon neutrality in 2045 (Executive Department State of California, 2018).

3 Powerfuels create value in major industry sectors

Chapter summary

1. Powerfuels can be **applied to all industry sectors** as they can have the same molecular structure as fossil fuels, allowing for using existing infrastructure with long investment cycles.
2. Powerfuels can **replace both energy-based and feedstock use** of fossil fuels in the industry.
3. Defossilisation of **specific industries will need specific types of powerfuels**. As today, there is no common fuel type that fits all needs.

Transport sector

The transport sector accounts for 25 % of fossil energy demand globally (Rodrigue, 2017). In most countries, transport constitutes high shares of GHG emissions. In transport, there has been tremendous growth in the capabilities of battery-electric and alternative fuel vehicles in recent years however, they still make up only a small share of the overall number of vehicles available.

Due to the nature of the transport sector accounting for a large proportion of CO_2 emissions globally, the tightening of emission standards has increased the total costs of ownership of internal combustion engines with conventional fossil fuels. At the same time, the cost degression witnessed with BEV and hybrid vehicles is likely to continue. To add to this, we have seen a demand for hybridisation over the previous years, especially for road and train transport. This development is likely to continue, combining the advantages of chemical energy carriers with electric traction. However, there will be a shifting focus on renewable energy carriers in the future.

From a technical standpoint, there are still many mobility applications that require large volumetric or specific energy densities. Considering the whole transport sector, this holds mainly for vehicles that require a long range without refuelling/recharging, move heavy loads or have weight limitations. In the following sections, these particular areas of the transport sector are addressed and be presented how the need for powerfuels and regulation supporting the technology is unique for all applications. In summary, it is indicated that powerfuels constitute a large opportunity for defossilisation. In some applications, there is no known alternative, hence powerfuels can help mitigate risks for market stakeholders in the wake of upcoming regulation.

Civil aviation

Green hydrogen-based kerosene and green hydrogen will constitute the bulk aviation fuels of the future next to biogenic kerosene.

In 2018, the civil aviation sector produced 1.04 billion tons of CO_2 from fuel combustion alone, accounting for 2.5 % of total global anthropogenic CO_2 emissions (Lee *et al.*, 2021; Global Carbon Project, 2019; Sausen and Schumann, 2000). This corresponds to 329 million tons of fuel at a conversion rate or 3.16 tons of CO_2 per ton fuel burned. Despite the temporary drop in civil aviation emissions due to the COVID-19 Pandemic, fuel demand is expected to grow significantly by

2050, with a possible doubling of CO_2 emissions in a business-as-usual scenario (Hader, 2020; EUROCONTROL, 2021; NLR and SEO, 2021).

As for Europe, in 2016 the CO_2 emissions of all flights departing from the EU28 and the European Free Trade Association (EFTA) area amounted to 171 million tons of CO_2 resulting from the combustion of 54 million tons of jet fuel (European Aviation Safety Agency and EAA., 2019). In the EU28, civil aviation was accountable for 3.6 % of the area's total greenhouse gas emissions and for 13.4 % of the emissions from transport, making aviation the second most important source of transport GHG emissions after road traffic (EEA, 2019). In Germany the share of CO_2 emissions from domestic flights was 0.3 % of total German emissions (IEA, 2019b).

Most of aviation emissions result from the in-flight combustion of aviation kerosene, with Jet A and Jet A-1 comprising over 99 % of commercial aviation fuel consumption to date (Own analysis based on Masiol and Harrison, 2014; IEA, 2019a). It is important to recognise the ground emissions from aviation, but these are only responsible for 1 % to 2 % of CO_2 emissions from fuel combustion (Seißler, 2018). It is further crucial to consider so-called "non-CO_2" effects, i.e. atmospheric warming effects from fuel combustion not caused by CO_2. Those add significantly to the climate impact of aviation and strongly depend on the ambient conditions at the location of these emissions. The main warming effects follow from persistent contrails and contrail induced cirrus, as well as NO_x emissions, which form ozone (O_3) in the troposphere.

The technological options for decarbonising aviation and further reducing non-CO_2 effects, are limited. Civil aviation aircrafts have a lifespan of about 30 years (Jiang, 2013, p. 6) and cannot be electrified with today´s technologies (Singh *et al.*, 2019, p. 7). Hybrid-battery-powered, short-haul aviation could possibly reduce 5 % of 2050 aviation emissions. Furthermore, efficiency gains in fuel consumption are and will reportedly remain smaller than fuel consumption growth due to increased passenger demand despite the effects of COVID-19 on the aviation sector (based on (ATAG, 2011, p. 3; IATA, 2021) and own analysis based on (EUROCONTROL, 2021)). As such, aircrafts can only be marginally decarbonized by electrification combined with the use of renewable electricity. Conventional aircrafts, however, are limited in their efficiency gains and will require liquid fuels for propulsion at least until mid-century.

Drop-in-ready alternative aviation fuels with a lower carbon footprint relative to existing fossil variants represent a technologically viable solution to defossilise civil aviation. Other alternatives such as battery-electric aviation and hydrogen-powered aircrafts are additionally potential technological options to decarbonise aviation.

The "Destination 2050" report developed by the aviation industry, research institutions and policy-makers, presents a scenario exploring how all departing flights from the EU28 and the EFTA region can reach net-zero emissions by 2050. It concludes that in 2050 and compared to a business-as-usual scenario, 20 % of CO_2 emissions reduction can result from employing hydrogen-powered aircraft on intra-European routes and 17 % from improvements to fossil kerosene-powered aircraft or the employment of (hybrid-)electric aircraft (NLR and SEO, 2021). The report further concludes that 38 % of CO_2 emission reductions result from employing biological and electricity-based sustainable aviation fuels (SAF) (NLR and SEO, 2021).

Considering the above, the two powerfuels of interest in the context of civil aviation are hydrogen and e-kerosene. E-kerosene is a drop in ready fuel which, if produced with green hydrogen and CO_2 from Direct Air Capture (DAC), can have life-cycle GHG emissions up to 90% lower than fossil Jet A/A-1 (based on own analysis). The use of e-kerosene can further contribute to the mitigation of non-CO_2 effects, as in contrast to fossil aviation fuels, it is free of sulphur and its combustion generates lower NO_x emissions compared to fossil jet fuel (Timko *et al.*, 2010; Masiol and Harrison, 2014, p. 414). It should be noted, however, that if non-CO_2 effects are considered, the reduction of the warming effects from fuel achievable through the employment of e-kerosene amounts to about 50 % compared to fossil Jet A/A-1 (own analysis based on (Jungbluth and Meili, 2019; Lee *et al.*, 2021))

If green hydrogen is employed directly as final energy carrier, the CO_2 emissions from fuel burn are reduced by 100 %. When considering non-CO_2 effects, too, hydrogen can further outperform e-kerosene significantly. If green hydrogen is used in combustion, the warming effect from the fuel can be reduced by 50 % to 75 %. If green hydrogen is used in fuel cells, then the reduction increases to up to 90 % (Fuel Cells and Hydrogen 2 Joint Undertaking., 2020).

When comparing different options for production of sustainable aviation fuels, e-kerosene (also; Power to Liquid, PtL-Kerosene) shows significantly higher yields per hectare than biogenic SAF, whilst having a negligible specific water consumption (PtL water demand ~1.4 $l_{H_2O}/l_{jetfuel}$) (Figure 9).

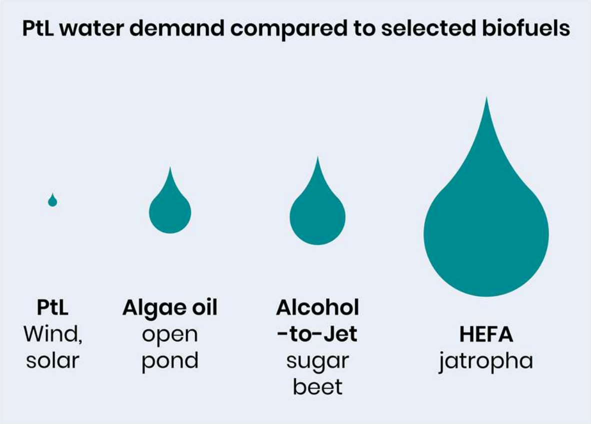


Figure 9: PtL-fuels water demand compared to selected biofuels (Volume representation, Based on UBA, 2016)

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 e-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.

Powerfuels will need to be REACH registered and ASTM certified. Fuels produced via Fischer-Tropsch Synthesis have already been approved for blending with Jet A/A-1 in the ASTM D7566 norm for up to 50 % (IATA, 2020). Other production routes, such as the methanol-route for e-kerosene production, still need ASTM approval. One particular mean in tacking this potential barrier is to build up a global standard and database for alternative sustainable fuels like NABISY (BLE, 2021) to allow globally produced kerosene to be counted towards a potential global emissions trading scheme.

Another factor to take into account regarding powerfuels in aviation is their current price, which is significantly higher than for Jet A/A-1. This may to some extent be industry specific, as aviation is facing rather high demand elasticity, particularly if such price increases are not global.

Maritime shipping

Powerfuels will be the game changer in defossilising the global maritime shipping sector, where other approaches such as direct electrification have limitations

To meet the 2 °C climate target, a strong defossilisation of all sectors, including shipping is required. As the reduction potential of the measures descripted above is limited, it is obvious that alternative fuels will play an important role for the reduction of GHG emissions in the maritime sector (Lloyds's Register Marine and UCL Energy Institute, 2014). In this regard, the most promising fuels within the shipping sector are:

- Electricity
- Advanced biofuels
- Hydrogen
- E-Ammonia
- E-Methanol
- E-LNG
- E-Marine very low sulphur fuel oil (VLSFO)/Marine Gas Oil (MGO)

Batteries are tested in ferries (Siemens, ABB), but for long-distance shipping there is the need for higher energy density in both weight and volume. This is further exacerbated by the high power rating of marine motors up to 80 MW. Therefore, from today's perspective there are large improvements in terms of battery capacity needed, in order to represent a broad option for the maritime transport industry.

In contrast, biofuels are sometimes seen as the most profitable zero-emission solution (Lloyds's Register Marine and UCL Energy Institute, 2014). Already today, they can be produced in such quality, that they are compatible with existing marine engines. Nevertheless, studies highly question whether the supply potential for biofuels will be sufficient to cover the needs of the global shipping fleet (ITF, 2018). Additionally the usage of biofuels is limited due to sustainability concerns regarding land use, deforestation and competition with food production.

Hydrogen can be used in fuel cells or as substitute (either completely or partly as blends) for heavy fuel oil (HFO) or Very Low Sulphur Fuel Oil (VLSFO) in combustion processes. For example, an equivalent mixture of HFO and hydrogen can reduce CO_2 emissions by up to 43 % per tonne-kilometre (Bicer and Dincer, 2018).

When addressing ammonia, the emissions reduction potential is of similar size (Bicer and Dincer, 2018). Ammonia is a hydrogen carrier, which has the advantage of higher energy density compared to hydrogen. It can be used in fuel cells or directly in combustion engines. New engines are being developed for the use of ammonia as fuel, however, within the shipping industry it has not been tested yet and there exists no operational ship powered by ammonia today (ITF, 2018, p. 35). MAN Energy Solutions announced an engine in early 2019 and is proceeding with an increased circle of stakeholders. The delivery of the first engines is planned for 2024 (Brown, 2019).

Finally, methanol also represents an alternative fuel option that has already been applied within the maritime transport sector. For example, there is a large methanol-powered passenger and car ferry that is operating between Germany and Sweden. However, the methanol supplied is produced from natural gas (ITF, 2018, p. 36). Further, MOL operates a methanol-powered methanol carrier since 2016 (MOL, 2020).

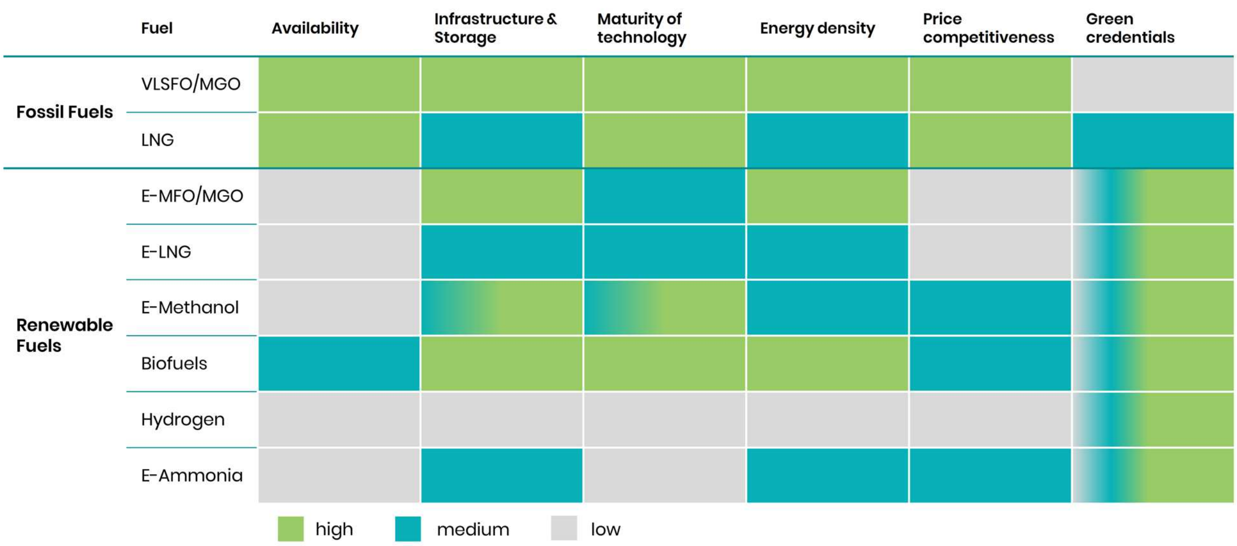


Figure 10: Comparison of alternative shipping fuels. LPG is excluded as it is expected to play only a minor role (Own illustration)

Figure 10 gives an overview of the various powerfuels options for maritime shipping and characterises different fuel and technology properties. Given the variety and diversity of the shipping industry, there will be no one-size-fits-all solution.

For international maritime trade on large ships, synthetic methanol and ammonia currently appear to be very promising fuel candidates.

For smaller ships, shorter transport distances and domestic shipping the use of hydrogen or direct electrification could also be viable options.

Passenger cars

Powerfuels can complement direct electrification of passenger cars to defossilise global road transport.

Road transport constitutes a significant source of CO_2 emissions as well as local air pollutants: Globally, road transport is responsible for 11.9 % of GHG emissions, with 60 % of these emissions coming from passenger travel (cars, motorcycles, and buses) (Ritchie and Roser, 2020). Within the European Union, passenger cars alone account for approximately 61 % of GHG emissions from road transport and 12 % of total EU GHG emissions (EEA, 2019).

The introduction of alternative propulsion systems and fuels for passenger cars constitutes an important measure to reduce GHG emissions, and can also improve local air quality. Propulsion systems and renewable fuels that could contribute to mitigating GHG emissions for cars include, e.g., battery and plug-in hybrid electric vehicles, as well as gaseous and liquid biofuels and powerfuels.

Powerfuels could either be used in fuel cell vehicles (FCEV), which power an on-board electric motor using oxygen from the air and compressed hydrogen, or as drop-in gaseous or liquid replacement fuels for internal combustion engine (ICE) cars.

Advantages of using powerfuels compared to battery electric vehicles (BEV) include the higher range and the lower time for refuelling. In addition and similarly to battery electric vehicles, FCEV can contribute to improved air quality in urban areas, as they are locally emission-free.

Liquid and gaseous drop-in powerfuels offer the advantage of being fully compatible with the existing distribution and storage infrastructure as well as the vehicle technology of ICE. They can be produced to closely resemble crude oil-based diesel/ gasoline/ Liquefied Petroleum Gas (LPG) or natural gas in their basic properties, or even improve on them in terms of lower local emissions. Liquid and gaseous powerfuels could thus gradually be blended into conventional fuels and hereby contribute to defossilising the existing fleet of ICE passenger cars – as well as creating a large offtake market for powerfuels.

Heavy road 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 % since 1990. In 2016, heavy duty vehicles were responsible for 27 % of road transport CO_2 emissions and almost 5 % of total EU GHG emissions (EEA, 2018). Additionally, EU freight transport is greatly dependent on road transport: 70 % of European freight is being transported by trucks, most of them being driven by diesel engines.

While further increases in the efficiency of conventional power trains may be achieved, they will not be sufficient to address the requirements in reducing GHG emissions. This makes alternative propulsion systems and substitution of fuels the only viable options to reduce emissions. Available options include biogenic methane and LNG, hybrid-systems, battery electric vehicles, electric trolley-trucks using overhead lines and the deployment of hydrogen and its derivatives.

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.

Table 1 shows a comparison of different technologies and required infrastructure of different propulsion systems in heavy road transport. For electric heavy-duty vehicles with overhead lines, a widespread grid of roads equipped with this technology across the whole EU would be required (dena and LBST, 2017, p. 34). Only a few member states, among them Germany and Sweden, are discussing overhead lines as a source of electricity for heavy-duty vehicles. In addition to natural gas/LPG and hybrid drive systems as well as direct electrification, the use of powerfuels will make an important contribution to reducing traffic-related emissions in the future. The use of powerfuels is a sensible supplement to direct electrification, especially on routes with high vehicle utilization. Powerfuels-based drivetrain currently have longer ranges and significantly shorter refuelling times than electric vehicles.

Table 1: Comparison of technology and infrastructure for different propulsion types

	Technology readiness	**Infrastructure**
FCEV 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 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 Synth. Diesel	Further use of existing and disseminated technology	Further use of existing and disseminated infrastructure
BEV Renewable electricity	BEV trucks are yet in early production stage; not yet suitable for long distances; high weight of the battery	Recharging infrastructure in under construction
Trolley Renewable electricity	Overhead line hybrid trucks are yet in prototype stage	Capital-intensive construction of infrastructure needed; disseminated usage and border-crossing traffic problematic

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 GHG emissions 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, trolley buses and the usage of powerfuels.

The use of powerfuels is necessary for routes with high capacity utilisation and compliment the transport 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. However, still 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. NO_x).

Rail transport

Despite being already the most electrified transport sector, powerfuels can help reducing residual fossil energy consumption especially on local tracks and in emerging countries.

On the global level, the majority of railway tracks is not electrified. This holds particularly for emerging economies (as of 2016, 62 % of tracks are electrified in China, 45 % in India, 24 % in Africa and less than 10 % in South and North America) (IEA and UIC, 2017, p. 23). However, even in industrialized countries, a large part of rail traffic is not electrified, but runs on diesel. For example, in Germany, about 40 % of the rail network is not electrified and requires the operation of diesel locomotives. This holds particularly for local passenger and freight transport routes where electrification – from an economic point of view - is not worthwhile.

Theoretically, the full electrification of train traffic combined with the use of electricity of renewable energies is an option for the rail transport sector. However, building overhead lines is very expensive and requires substantial infrastructure investments. Depending on the utilisation rates of the respective tracks, these high infrastructure costs could make an electrification economically unfeasible. This is often the case for local network sections with limited utilisation. As a reference, the share of diesel locomotives on total rail transport service is only 8 % in Germany (BMVI, 2018, p. 44).

The use of alternative propulsion technologies such as hydrogen fuel cells represent a promising abatement option for rail transport, if electrification is (economically) not feasible. First pilot projects have already proven the suitability of this technology in the rail sector. The Coradia iLint hydrogen fuel cell train developed by Alstom can serve as example, as it is the first regular operating train that is powered with hydrogen. In 2018, two fuel cell-powered pilot trains took up commercial service and have been operating on a regional connection in Lower Saxony (Germany) since then (Alstom, 2018). Synthetic diesel could be another powerfuel used in rail transport, allowing the continued usage of proven equipment while reducing GHC emissions. However, due to the possibility of direct electrification and less weight/volume restrictions, hydrogen seems to be the most promising powerfuels option for rail transport.

Basic industries

Steel production

Hydrogen, used in the direct reduction route, can fully defossilise the steel industry, making powerfuels a game changer for the sustainable growth of this essential industry.

Steel is critical for modern life. Its strength and versatility has led to applications in many sectors, including construction, transportation, packaging, shipping etc. As a result, crude steel production saw an average growth of 3.6 % per year, from 2015-2019 (worldsteel, 2020). However, steel production accounts for around 7 to 9 % of global CO_2 emissions (Bhaskar, Assadi and Somehsaraei, 2020; worldsteel, 2021b). Its production follows two main routes: the blast furnace-basic oxygen furnace (BF-BOF) route and electric arc furnace (EAF) route. The key difference is in the type of raw materials they consume. The BF-BOF route is based on the use of iron ore, coal and recycled steel. It accounts for more than 70 % of the total steel produced. The EAF route is mainly using recycled steel and electricity (worldsteel, 2021a).

Carbon emissions are directly related to iron ore reduction with coked coal, a process that produces hot metal (near pure iron) and CO_2, utilising a chemical reaction between iron oxide and carbon monoxide (worldsteel, 2019). Coke acts as both, a fuel and reducing agent in the blast furnace, forming carbon dioxide when burned. In 2020, on average, for every tonne of steel produced, 1.85 tonnes of CO_2 were emitted (worldsteel, 2021b).

Alternative low carbon processes to the traditional (BF-BOF) route as described above are BF-BOF with CCS, direct reduction of iron ore with CCS (DRI) and green hydrogen based DRI (Bhaskar, Assadi and Somehsaraei, 2020). Since concerns over the safe transport and storage of captured carbon makes CCS less attractive, hydrogen direct reduction of iron ore (HDRI)-EAF based steel production is the most viable alternative to BF-BOF based steel production (Bhaskar, Assadi and Somehsaraei, 2020; McKinsey, 2020). It represents a technically proven production process that enables nearly emission-free steel production.

The majority of direct reduced iron is produced by iron oxide reacting with hydrocarbon based reducing gases, produced from reforming natural or coal gasification. In the HDRI-EAF system, hydrogen is used as the reducing gas (Bhaskar, Assadi and Somehsaraei, 2020). According to IEA estimates, the use of green hydrogen in the iron and steel sector has the potential to reduce GHG emissions by 2.3 Gt CO_2 per year globally (Philibert, 2017, p. 5). The DRI route is also in favour of lower capital investment, space requirements and simpler design and operation.

The first HDRI based steel production unit was commissioned in the year 1999 in Trinidad (Elmquist, Weber and Eichberger, 2002). Currently, all major European steel industry stakeholders are building or already testing hydrogen based production with numerous projects (McKinsey, 2020). In the joint venture HYBRIT by SSAB, LKAB and Vattenfall, construction work for the first pilot plant for hydrogen based steel production started in 2018 in Luleå, Sweden. In Germany, the SALCOS consortium is investigating the feasibility of integrating solid oxide electrolysers for hydrogen production at a Salzgitter steel production facility powered by 30 MW of wind turbines (Salzgitter, 2020). With the ambition to become carbon neutral, Tata Steel Europe has partnered up with leading chemicals company Nouryon and the Port of Amsterdam to develop the largest green hydrogen cluster in Europe (Tata Steel, 2018).

Studies reveal that electrolyser efficiency and renewable electricity prices are the most important factors for techno-economic performance of HDRI-EAF processes (Bhaskar, Assadi and Somehsaraei, 2020; McKinsey, 2020). However, using electrolysers, additional business cases can be developed for steel producers, e.g. by participating in the power reserve markets to help grid balancing.

Chemical industry

Petrochemicals, which turn crude oil and natural gas into all sorts of daily products, are integral to modern societies. Powerfuels have the ability to take over this key role as feedstock, while defossilising a whole industry.

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 % of the total primary demand for crude oil and 8 % 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 (IEA, 2018b). 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 % of feedstock 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 (IEA, 2018b, pp. 55–70). 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.

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 refining. 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 % of global fertilisers are ammonia-based. As over 90 % of worldwide ammonia production is used for fertilisers and ammonia significantly consists of hydrogen, the world's agricultural industry depends heavily on hydrogen: 55 % of worldwide hydrogen demand is currently used for ammonia production. Another 10 % of worldwide hydrogen demand is currently used in methanol production, which has broad application areas. Around 25 % of feedstock methanol is further processed into formaldehyde, which is mainly used to produce synthetic resins (IRENA, 2021b, p. 23).

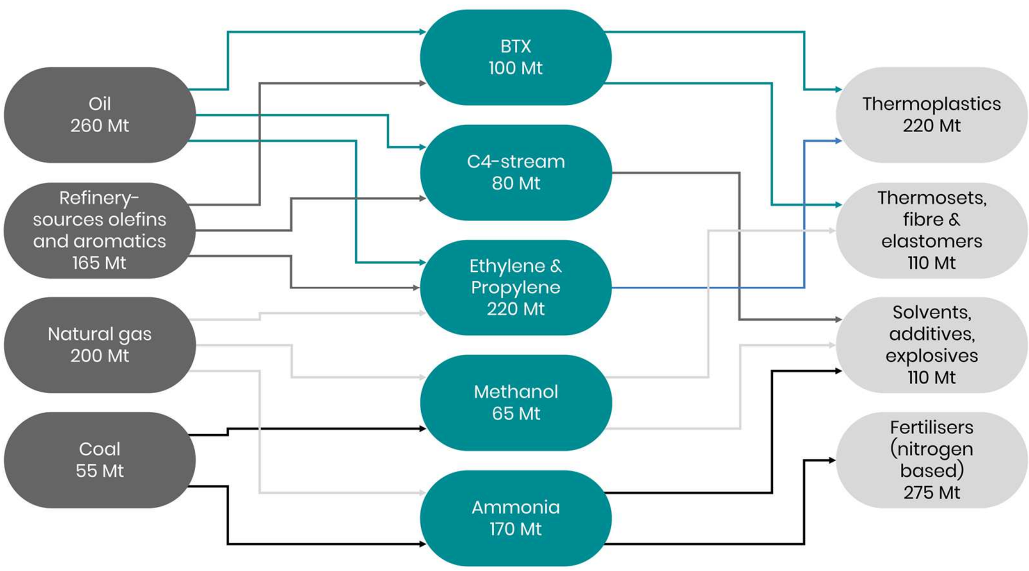


Figure 11 Simplified scheme of fossil resources and product flows in the chemical industry in 2013 (BTX: benzene, toluene, xylene) (Based on data from (IEA, 2018b; Levi and Cullen, 2018))

As displayed in Figure 11, the four most-important basic chemicals **Ethylene**, **Propylene**, **Methanol** and **Ammonia**, together with the aromatic intermediates summarised as **BTX** and butane-based chemicals summarised as **C4-stream** 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 defossilisation of the chemical industry.

Energy sector

Electricity

On the way to climate-neutral power systems, powerfuels are essential for electricity storage, peak load generation and grid balancing.

While modern economies rely on a secure and affordable supply of electricity, the need to address climate change drives a dramatic transformation of power systems around the world. Electricity is the fastest growing source of final energy demand. The sector is now attracting more investment than oil and gas combined (IEA, 2020a). At the same time, electricity generation accounts for more than 40 % of total energy related GHG emissions and is still heavily dependent on fossil fuels (IEA, 2020c, p. 249).

The necessary phase-out of conventional power generation gives rise to increasing shares of fluctuating renewables in the energy mix. As a result, flexibility is becoming a cornerstone in power systems around the world. Hence, grid balancing options and storing excess electricity are gaining in significance. Curtailment in peak generation times of wind and PV can be bridged by converting electricity to hydrogen. This creates a business case for renewable energy producers as they can offer Primary Control Reserve to transmission system operators on control power markets. In addition, it provides a solution to interconnect electricity and gas grids.

Storing renewable electricity poses a challenge, compared to easily stored fossil fuels. With renewable hydrogen and its derivatives, storage capabilities are achieved that are comparable to fossil energy in the form of coal and natural gas. As depicted in Figure 12, powerfuels allow for long-term storage of large quantities in cavern reservoirs and pore storages (Sterner and Stadler, 2014, p. 654).

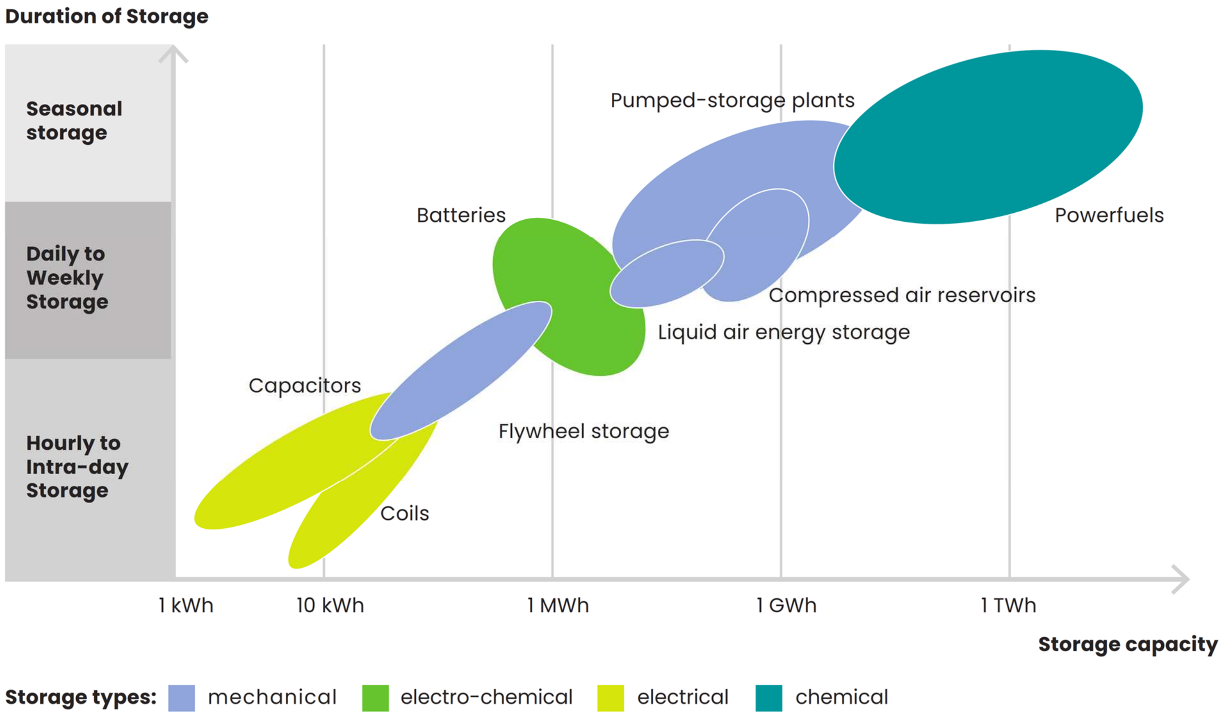


Figure 12: Common energy storage options compared with respect to storage capacity and the duration of storage (Based on Sterner and Stadler, 2014; Perner and Bothe, 2018)

In a 100 % renewable energy system, storing electricity in the form of powerfuels is the only viable option to ensure security of supply for peak-load electricity demand. Reconversion to electricity can follow various routes. On a small scale, fuel cells can provide backup power generation with high efficiency up to 80 % when applied in a combined heat and power (CHP) setup (Haseli, 2018). On a larger scale, hydrogen ready gas turbines will be able to provide peak-load electricity in the years to come. Currently, all major gas turbine manufacturers are exploring to increase amount of hydrogen in the fuel mix, while ultimately aiming to run on 100 % green hydrogen (Siemens, 2019; GE, 2021). Today, methanised hydrogen can immediately serve as a fuel for natural gas turbines, as well as small amounts of hydrogen from 5 – 8 % can be directly added to the fuel mix to lower carbon emissions (Langston, 2019).

Oil and gas industry

Oil and gas are the main fossil raw material sources for many industries (transport, heating and cooling, chemicals etc.). Moving from these fossil-based sources to powerfuels is also beneficial for several reasons apart from achieving the GHG goals.

The general value chain of the oil and gas industry is shown in Figure 13. Of these various steps, some are also relevant for powerfuels (highlighted in the black box). Exploration and production are specific to oil and gas deposits and hence the infrastructure and technologies here cannot be utilised for powerfuels. Refining, transport, storage and distribution infrastructures on the other hand can be directly used for powerfuels with no or minimal modifications. Oil and gas are internationally widely transported commodities. Core competencies of companies in these areas of the value chain could be directly used for powerfuels transportation. This utilisation of existing infrastructure built for fossil-based systems by powerfuels systems would be economically beneficial.

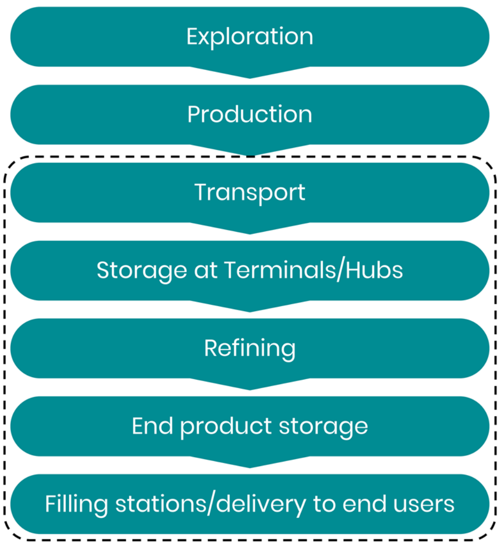


Figure 13: Simplified representation of the oil and gas-industry value chain. Relevant steps for powerfuels are highlighted in the black box.

For oil and gas companies, the most important source of revenue today is, of course, the sale of oil and gas. The availability of oil reserves that are easy to extract (typically onshore) is diminishing. Extracting oil and gas from offshore fields is costlier than onshore fields, thus resulting in increasing costs for oil and gas production. In addition, oil and gas companies react on societal and economic pressures by adopting sustainable strategies, which imply a gradual decline of upstream investments (about 1 – 2 % per year (Shell, 2021)) and build on differentiation (BP, 2020; Shell, 2021).

In the future, powerfuels could replace fossil fuels in several applications as discussed above. Powerfuels could be a natural next step for these oil majors, as they already have the expertise in various aspects of the conventional value chain. Involvement of multiple oil majors in pilot power-to-hydrogen projects could be seen as a step in this direction.

Process heat

Powerfuels will play an important role for defossilising industrial heat. This particularly holds true for processes where no efficient electro-thermal 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 % of the industrial and 12 % of the total global CO_2 emissions (IEA, 2018a).

Improving energy efficiency is crucial to reduce the overall energy demand for industrial heat, therewith directly avoiding GHG emissions. For the production of low and medium temperature heat, direct use of renewable energies like solar or geothermal, as well as the use of 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 (UBA, 2015), powerfuels are essential to reach climate goals while fulfilling energy demands in application areas like high temperature process heat.

Powerfuels like hydrogen, synthetic methane or synthetic methanol can offer a sustainable alternative. 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.

Heating in buildings

Powerfuels can provide suitable solutions for defossilising existing building heating systems and could deliver a reliable and steady energy source for heating.

From region to region, heating in buildings has different energy requirements, depending on local weather conditions that have been changing since the last decades. Globally, the building sector represents around 30 % of global final energy use. Out of this, around three quarters are used for space heating, water heating and cooking. This consumption is equivalent to 21 % of global energy-related CO_2 emissions (IEA, 2019b). In the European Union, 75 % of the energy requirements for heating in 2018 were originating from fossil fuels (around 50 % from natural gas), while 19 % were supplied using low carbon sources (European Commission, 2021).

To reduce the overall energy demand in the building sector, better thermal insulation is the priority, but it alone is not sufficient to reach the ambitious emissions reduction targets of the Paris agreement. Hence, some countries have included the integration of alternatives from low carbon sources into their agenda, both in new and existing buildings. Nevertheless, some of these alternatives bear different challenges, particularly related to existing infrastructure and the end-use equipment. Currently, bioenergy is the main low carbon alternative, however technologies such as solar and geothermal are expanding. Alternatives from low carbon sources that are expected to see considerable growth are solar, renewable district cooling and heating and geothermal. The share of electricity will have an important impact in emission reduction, if it is coming from renewable sources.

In newly built houses, electric heat pumps have become the most common technology to provide heating. In the EU, the market is growing quickly, with an annual average growth rate of 12 % since 2015 (IEA, 2020b). This growth is expected to continue in the coming years. Heat pumps can extract thermal energy from the air, water or ground, multiplying the electricity input, which makes them more efficient than systems based directly on electricity or fossil fuels (Lun and Tung, 2020). Nevertheless, as electric heat pumps typically provide lower heating temperatures than traditional boilers, they may not always be integrated into existing buildings. The need for retrofitting radiators and increasing building efficiency beforehand translates into higher cost and limits the technical and economic feasibility.

Power-to-gas processes can supply synthetic methane that can be fed at a share of 100 % into the current infrastructure, without the need for further modifications. Synthetic methane represents a viable short-term solution for the building sector, as it has the properties of natural gas, while offering the advantage of lower CO_2 intensity. Nevertheless, current regulations present a barrier for the installation of large-scale plants.

A short to medium term alternative is the blending of hydrogen into the existing natural gas grid. According to IEA, in 2030 around 4 Mt of hydrogen could potentially be used for space heating (IEA, 2019c, p. 123). In the long term, higher integration will require an upgrade of the current infrastructure. Additionally, new equipment such as hydrogen boilers or fuel cells will need to be incorporated at the end-use point and measures to address safety concerns and customer acceptance will need to be developed.

4 Call for Discussion

The Global Alliance Powerfuels strongly believes that powerfuels complement energy efficiency, renewable energy deployment and electrification in achieving climate goals. From the energy trilemma perspective, powerfuels offer a lower total system cost pathway for energy transition, require less change in public behaviour and act as a complement to the intermittent nature of renewable energy sources like wind and solar.

The Global Alliance Powerfuels considers powerfuels to provide value for different countries in different ways, either as powerfuels suppliers, technology providers or as green alternative for fossil-fuel import dependent countries. The Global Alliance Powerfuels emphasises the need for an international powerfuels market where all countries can benefit and move towards reaching climate change mitigation goals at the same time.

The development has already started

In the last few years, increased efforts of governments, researchers and companies can be observed around the world in building a global powerfuels economy. Countries and industries in the fossil energy business today are looking for ways to lower the emissions of their products and sustainable future prospective. More and more discussions are taking place in different countries and regions, while many different powerfuels technologies and possibilities are being emphasized. At the same time, first international cooperation is taking place.

Get in touch

By sharing the vision of the Global Alliance Powerfuels through this paper, an international discussion on the different ideas, strategies and possibilities of global markets for powerfuels should be enabled. The Global Alliance Powerfuels calls for your participation in this discussion. There are several opportunities to get in touch:

- Visit the Global Alliance Powerfuels website at www.powerfuels.org
- Attend one of our upcoming events
- If you are interested in becoming a member or partner of the Alliance, contact us at powerfuels@dena.de

We are eagerly looking forward to your opinions, insights and opportunities to work towards a sustainable global energy future.

Abbreviations

AEL	alkaline electrolysis
AEM	anion exchange membrane
BEV	battery electric vehicle
BF-BOF	blast furnace – basic oxygen furnace
BTX	benzene, toluene, xylene
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CHP	combined heat and power
CNG	compressed natural gas
DAC	direct air capture
DME	dimethyl ether
DRI	direct reduction of iron
EAF	electric arc furnace
FCEV	fuel cell electric vehicle
FLH	full load hours
FT	Fischer-Tropsch
GDP	gross domestic product
HDRI	hydrogen direct reduction of iron
ICE	internal combustion engine
LCOE	levelised cost of electricity
LHV	lower heating value
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MGO	marine gas oil
MTO	methanol-to-olefins
OME	oxymethlyene ether
PEM	proton exchange membrane
PV	photovoltaics
PtL	power to liquid
RES	renewable energy source
RFNBO	renewable fuel of non-biological origin
SAF	sustainable aviation fuel
SNG	synthetic natural gas
SOEC	solid oxide electrolysis cell
TRL	technology readiness level
VLSFO	very low sulphur fuel oil

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