GLOBAL ALLIANCE POWERFUELS

Powerfuels: A missing link to a successful global energy transition

Current state of technologies, markets, and politics –
and start of a global dialogue

powered by dena German Energy Agency

Imprint

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The Global Alliance Powerfuels Founding Members

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1 Executive summary

A Global Alliance to develop international markets for powerfuels

The Global Alliance Powerfuels was initiated by the German Energy Agency (dena) together with 16 renowned corporate partners as founding members. The strategic objective of the Alliance is to foster the development of a global market for powerfuels i.e. synthetic renewable gases and liquid fuels.

The Alliance has three main goals:

- raise awareness and acceptance of powerfuels as missing link to reach global climate targets,
- support the further enhancement of regulatory frameworks with an initial focus on Europe as region of demand,
- 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 acknowledged and 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 there will be common binding minimum standards for reporting by states 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. They ought to 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 gases and liquid fuels produced from Power-to-X processes by utilising renewable electricity. Powerfuels are game changers as they enable renewable energy to be stored and transported over long distances. Powerfuels will be a missing link for reaching climate targets due to four key reasons:

- Powerfuels are climate-friendly solutions to applications with no viable alternatives for fossil-fuel use,
- they utilize the worldwide potential for renewable energy systems as they can be transported and traded globally,
- they can reduce the cost of energy transition by utilising existing infrastructures and provide long-term renewable electricity storage options,
- they could accelerate the de-fossilisation of existing consumer end-use equipment since they are green drop-in alternatives to fossil fuels.

The technologies for powerfuel production are market-ready – and costs will fall further with economies of scale

The technologies for production of powerfuels are already demonstrated and tested, however the business models are not available yet, as costs are still high. Electricity costs are the largest portion of powerfuel costs, followed by carbon capture costs (for hydrocarbon) powerfuels and electrolysis of hydrogen. Through economies of scale the costs of powerfuel production technologies could significantly reduce. Sufficient demand for powerfuels could 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

Countries with abundant and low-cost renewable electricity generation conditions are particularly suited for powerfuel production. Depending on the country, powerfuels could be used for the own demand first to replace fossil fuel imports or could be exported to countries which 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

By sharing our vision through this paper, we want to raise awareness of powerfuels and initiate a global dialog with the following central questions.

- What role could powerfuels play for the energy transition in your country/industry?
- How do you compare the potential of importing/exporting powerfuels with respect to the import/export of fossil fuels to/from your country?
- What are the specific technologies, fuel types and usage possibilities you primarily see for powerfuels?
- What are the current political strategies, incentives or hurdles that are impacting the development of powerfuels in your country?
- What timeframe do you envision for the development of a market for powerfuels in your country?

We would like to call for your participation in the powerfuels discussion. 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.

2 The global challenge

Chapter Summary

1. The world community has acknowledged the human influence on the global climate system and that global action is needed to address climate change.
2. For the first time, from 2024 there will be common binding minimum standards for reporting by states on their greenhouse gas emissions and other climate protection measures.
3. Strategies to address climate change present challenges and opportunities for the private sector. Governments are called upon to promote policies that safeguard competitiveness, economic growth and jobs and enable companies to use their innovative power to protect the climate and make the transition to a sustainable global economy possible.
4. Synthetic renewable gaseous and liquid energy sources are game changers for the energy transition as they enable renewable energy potentials to be utilized worldwide since they can be stored and transported over long distances. This will make powerfuels the necessary missing building block for the energy transition along with increase in energy efficiency and the direct usage of renewable electricity.

2.1 Climate change and the need for global action

Greenhouse gases occur naturally and are essential to the survival of humans and millions of other living organisms, by keeping some of the sun's warmth from reflecting back into space and making the Earth liveable. But after more than a century and a half of industrialisation, deforestation, and large scale agriculture, quantities of greenhouse gases in the atmosphere have risen to record levels not seen in three million years. As populations, economies and standards of living grow, so does the cumulative level of greenhouse gases (GHGs) emissions.[1]

Human activities are changing the natural greenhouse on earth. Over the last century the burning of fossil fuels like coal, oil and gas has increased the concentration of atmospheric carbon dioxide (CO_2). This happens because the fossil fuel (coal/oil/gas) burning process combines carbon with oxygen in the air to make CO_2. To a lesser extent, the clearing of land for agriculture, industry, and other human activities has also increased concentrations of greenhouse gases.[2]

There are some basic well-established scientific links:[3]

- The concentration of GHGs in the earth's atmosphere is directly linked to the average global temperature on Earth;

[1] (United Nations, 2019)
[2] (National Aeronautics and Space Administration, 2019)
[3] (United Nations, 2019)

- The concentration has been rising steadily, and mean global temperatures along with it, since the time of the Industrial Revolution;
- The most abundant GHG, accounting for about two-thirds of GHGs, is carbon dioxide (CO_2) and is largely the product of burning fossil fuels.

A global perspective is needed to address climate change[4]. No country can fight it effectively on its own. Efforts must involve civil society, and existing stakeholders must be won over to effectively involve industries and sectors such as infrastructure, technical equipment, current applications as well as, financial resources. The focus should be on business opportunities on the one hand and on realistic transformation paths for existing applications on the other.

2.1.1 Climate targets for the reduction of GHG emissions

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC), a group of 1,300 independent scientific experts from countries all over the world under the auspices of the United Nations, concluded there's a more than a 95 percent probability that human activities over the past 50 years have warmed our planet. The industrial activities that our modern civilisation depends upon have raised atmospheric carbon dioxide levels from 280 parts per million to 400 parts per million in the last 150 years. The panel also concluded there's a better than 95 percent probability that human-produced greenhouse gases such as carbon dioxide, methane and nitrous oxide have caused much of the observed increase in the Earth's temperatures over the past 50 years.[5]

At the United Nations Framework Convention on Climate Change 21st Conference of the Parties (COP 21) 2015 in Paris, the international community set itself the common goal of limiting global warming to 2 degrees Celsius. After three years of negotiations, the international community agreed in December 2018 in Katowice at COP 24 on common rules for the implementation of the Paris Climate Convention.

For the first time, from 2024 there will be common binding minimum standards for reporting by states on their greenhouse gas emissions or other climate-protection measures. It is already foreseeable that the current climate targets of the states will not be sufficient to limit global warming to well below 2°C and, if possible, to 1.5°C. The climate change is also likely to be a major factor in the future. Without further efforts, the global temperature will rise by more than 3°C by 2030.

The Emissions Gap Report 2018 by the United Nations Environment Programme therefore calls for a tripling of global climate efforts to meet the 2°C target. In order to limit global warming to 1.5°C, a fivefold increase in efforts was even necessary[6]. National governments around the world have committed to highly ambitious goals to reduce greenhouse gases in the years to come. For instance, The Federal German Government has set the goal to reduce GHG emissions by 80% to 95% by 2050 compared to 1990s levels. Reaching this goal, entails a massive change in the supply and utilisation of energy as we know it today. It is important that countries coordinate with each other in order to achieve the common goal of effectively limiting global warming.

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[4] (Stocker et al., 2013, p. 15)
[5] (National Aeronautics and Space Administration, 2019)
[6] (United Nations Environment Programme (UNEP), 2018, p. 4)

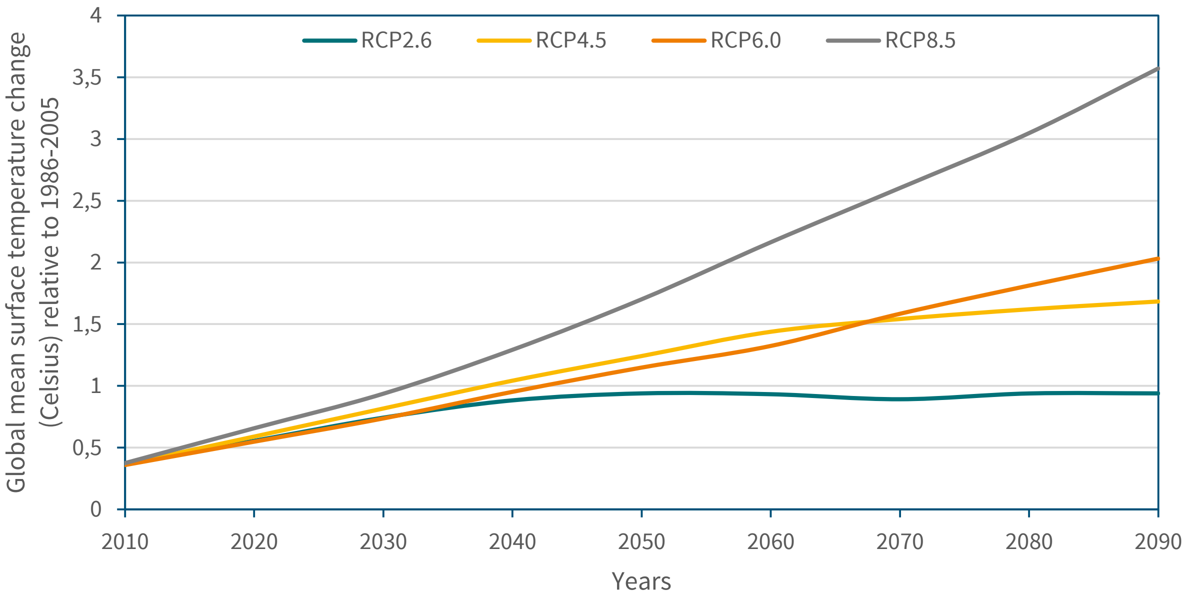

Figure 1: Estimated Global mean surface temperature change relative to 1986-2005 for different IPCC scenarios[7]

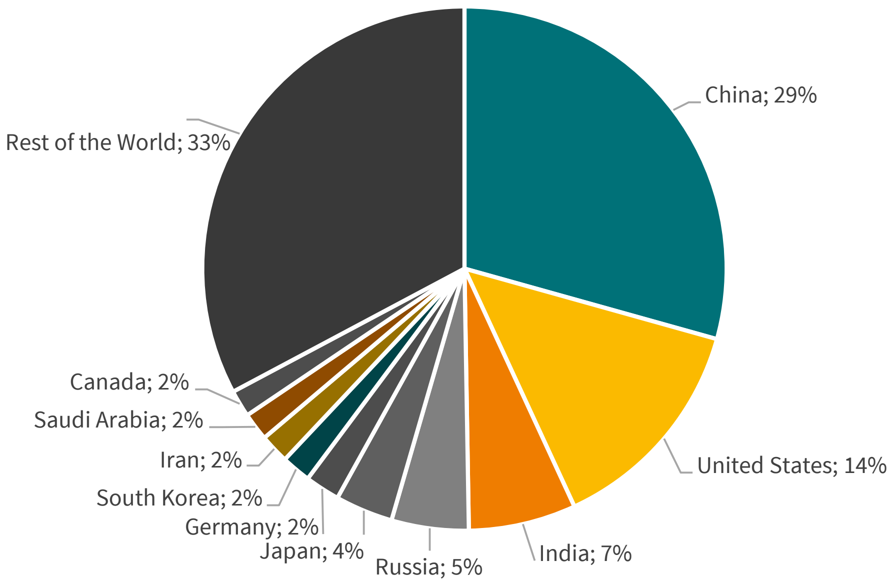

Figure 2: 2017 World's Largest-10 Carbon-Emitting Countries[8]

[7] Source: (Prather et al., 2013)

[8] Source: Based on EU EDGAR Database (Joint Research Centre (European Commission), 2018)

Through international climate protection agreements such as COP 24, the community of countries will work more closely together on climate protection in the future: Industrialised countries, which have contributed significantly to CO_2 emissions in recent decades, will cooperate closely with developing countries. This applies in particular to the development of reporting systems - but also to the transfer of know-how for effective climate protection.

2.1.2 Climate change mitigation as part of corporate risk management and strategy development

Climate change is one of the highest-impact risk to business and presents major implications both inside individual companies and across the full supply chain[9]. Impacts of climate change can both endanger key business functions in short term as well as endanger the complete business model in medium/long term. Effective measures are therefore needed by businesses in order to reduce GHG emissions from operations, products and services.

On the one hand, companies are emitters of greenhouse gases as part of their value chain. On the other hand, companies play a central role in combating climate change as a source of finance and driver of innovation and technological development. Without companies, climate targets will not be achieved. The challenge of climate change presents both wide-ranging threats and opportunities for the private sector. The immediate effects of climate change are already threatening the viability of existing business practices in agriculture, infrastructure, and construction. But climate change also opens up opportunities.[10]

But companies cannot do it alone. Governments are called upon to promote policies that safeguard competitiveness, economic growth and employment. They ought to enable companies to use their innovative capabilities to protect the climate and make the transition to a sustainable global economy possible.

Consumers are increasingly interested in products based on renewable raw materials that they perceive as healthier, more natural and having a positive environmental impact. Many brand owners and retailers are therefore seeking to position themselves accordingly by defining strategies and goals for using renewable raw materials. In Europe, for instance, the use of renewable resources is also being driven by the European Commission's measures to cut CO_2 emissions and to support the bio-economy; similar programs exist in other regions.[11]

[9] (Global Future Council on Energy, 2018)

[10] (Henderson, Reinert, Dekhtyar, & Migdal, 2017)

[11] (BASF United States, 2019)

2.2 Existing approaches to achieving energy transition targets

Most GHG emissions are based on use of fossil resources, mainly in energetic consumption. Due to strong growth in developing countries, global energy demand will rise by a third by 2040.[12]

The main challenge is to reduce greenhouse gas emissions in the energy system while maintaining and increasing security of supply and the availability and affordability of energy. Rising energy consumption must be decoupled from greenhouse gas emissions. This will only work if energy system transformation is consistently driven forward on the basis of two well-known principles:

- responsible, economical use of valuable resources (efficiency),
- sustainable, climate-friendly energy sources (renewable energies)

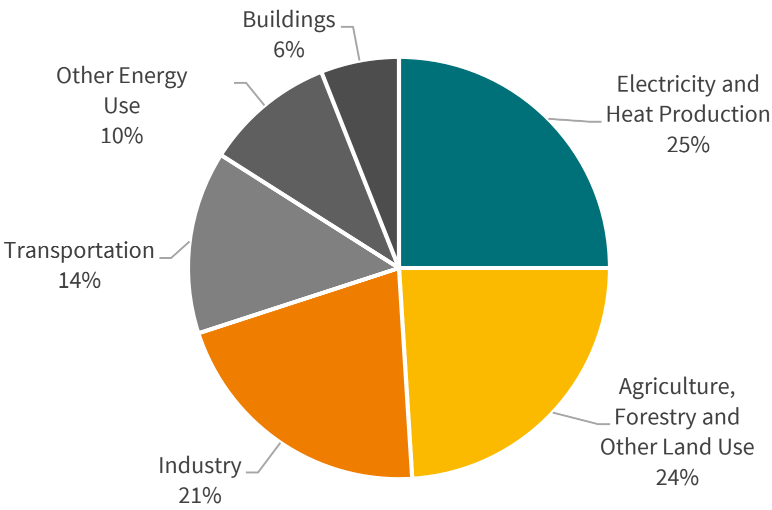

Figure 3: Global greenhouse gas emissions by sector for year 2010[13]

More than 40 percent of the total growth in energy demand will be met by alternative (renewable) energies. China will be the biggest driver, ahead of India, and will record more growth in alternative energies than all OECD countries combined. By 2040, the share of eco-energy in the total global energy supply will have quintupled to around 14 percent - driven in particular by wind and solar energy [14]. Electrification plays an important role in implementing the energy transition – first, because many applications with direct use of electricity have high efficiency (e.g. efficiency factor of electric engine up to 95% compared to up to 40% for combustion engines, depending on conditions); second, because electricity-based applications are emission-free at place of use and electricity generation can be based on emission-free renewable sources like sun and wind (generated both central or decentral).

[12] (BP energy economics, 2018)
[13] Source: based on IPCC Technical Summary (Edenhofer et al., 2014, p. 44)
[14] (BP energy economics, 2018)

Electric drives and applications are on the advance, from electric cars to heat pump heating. In the USA, electricity has grown from 3% of final energy in 1950 to approximately 21% today. Electricity's role continues to grow, ranging from 32% to 47% of final energy across different scenarios in 2050.[15] [16]

But, the direct use of electricity from renewable sources will not be able to cover energy requirements, so - the vision of “All Electric World” seems unlikely from today's technological perspective. Even if share of electricity in end energy demand would come completely from renewable sources, there will still be at least 53 to 68 percent, for which other renewable solutions have to be found!

Game Changers can be gaseous and liquid energy sources, which are produced climate neutrally with renewable energies. They make renewable energy storable and transportable over long distances. This makes powerfuels a missing link between energy efficiency, renewable energies and electrification.

2.3 Energy trilemma and the case for powerfuels

The energy trilemma of energy system transformation encompasses security of supply, public acceptance and economic affordability.

From the security of supply perspective, the fluctuating generation of electricity from renewable sources such as wind and sun poses new challenges:

- the short-term, current stability of electricity grids
- the "temporal" and "spatial" displacement of electricity.

Even with greater electrification in the future, powerfuels will ensure security of supply. Today, as in the year 2050, the annual peak load is covered in particular by secure, controllable power plant capacities and by demand-oriented control, storage and electricity imports. Gas-fired power plants as well as larger and smaller combined heat and power plants are mainly used today to secure power plant capacity. Powerfuels increase the range of possibilities for balancing energy systems of the future.

From the public acceptance perspective, powerfuels can be used as drop-in replacements for present-day fossil fuel use. This minimises the amount of change that end-users have to make in the energy transition process. Also public acceptance for new infrastructure investments (for example the construction of new electricity transmission lines) has been marred by not-in-my-backyard phenomenon. Since powerfuels can be transported with existing gas and liquid fuel transport infrastructure, the need for new infrastructure is minimised.

From the economic affordability perspective, energy transition approaches must be compared based on entire system-level costs (also referred to as cradle to grave costing). Evaluating energy transition approaches only based on the tank-to-wheel basis ignores the other critical cost components of the complete energy system. If system-level costs are considered, powerfuels offers a lower total cost pathway that is complementary in nature to the other energy transition approaches.

These points are further explained in the next Chapter.

[15] (Electric Power Research Institute, 2018)
[16] (Global Future Council on Energy, 2018)

3 What are powerfuels and why are they relevant?

Chapter Summary

1. Powerfuels are synthetic gases and liquid fuels produced from Power-to-X processes using renewable electricity.
2. Powerfuels will be a missing link for reaching climate targets due to following key reasons:
   - They are climate-friendly solutions to applications with no viable alternatives.
   - They can reduce the cost of energy transition by utilising existing infrastructures and provide long-term storage options.
   - They can utilise the worldwide renewable electricity production potential as they can be transported and traded globally.
   - They could accelerate the de-fossilization of existing consumer end-use equipment since they are green drop-in alternatives to fossil fuels.
3. Electricity costs are the largest portion of powerfuel 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.

3.1 Definition of powerfuels

The Alliance defines Powerfuels as synthetic gaseous or liquid fuels that draw their energy content from renewable electricity. Powerfuels are renewable and climate-friendly and can be used as energy carriers and as feedstocks. Our definition includes but is not limited to hydrogen, synthetic gas (e.g. methane, propane) or synthetic liquid fuels and chemicals (e.g. methanol, diesel, gasoline, kerosene, ammonia, Fischer-Tropsch products) and is hence 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 carbon capture of existing emission streams and biogenic sources, or from direct air capture technologies that draw carbon dioxide from the ambient air. Nitrogen (required for ammonia synthesis) can be captured by direct air separation units. Figure 4 shows the various processes and end products of powerfuels processes.

In line with our definition of powerfuels, “e-fuels” and “synthetic fuels” are synonyms. However, we prefer powerfuels, as the wording e-fuels has mainly been used in relation to the mobility sector[17] and “synthetic fuels” is much more generic and does not reveal the importance of electricity in producing these fuels and is not necessarily related to renewable fuels. Therefore, we propose powerfuels as coherent wording, to overcome the shortcomings of the other terminology.

[17] (Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017)

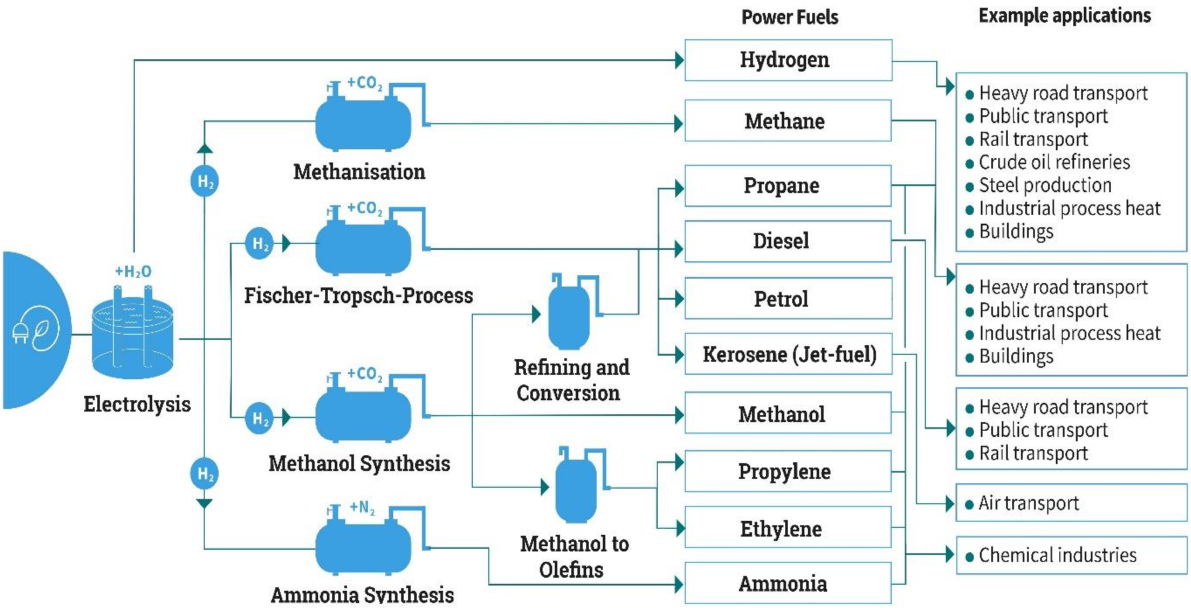

Figure 4: Various possible powerfuel processes, end products and example applications.

3.2 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. The Alliance strongly believes that powerfuels will be a "missing link" [18] 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 GHG emissions of applications that cannot be directly electrified and provide additional options for those sectors that are currently 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. **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 high energy needs, but limited space and/or potential for renewable energy sources and could help to diversify supply of energy importers. This also provides new carbon-neutral export opportunities for countries with high renewable energy potential and fossil business today.

[18] (IRENA, 2018a, p. 16)

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

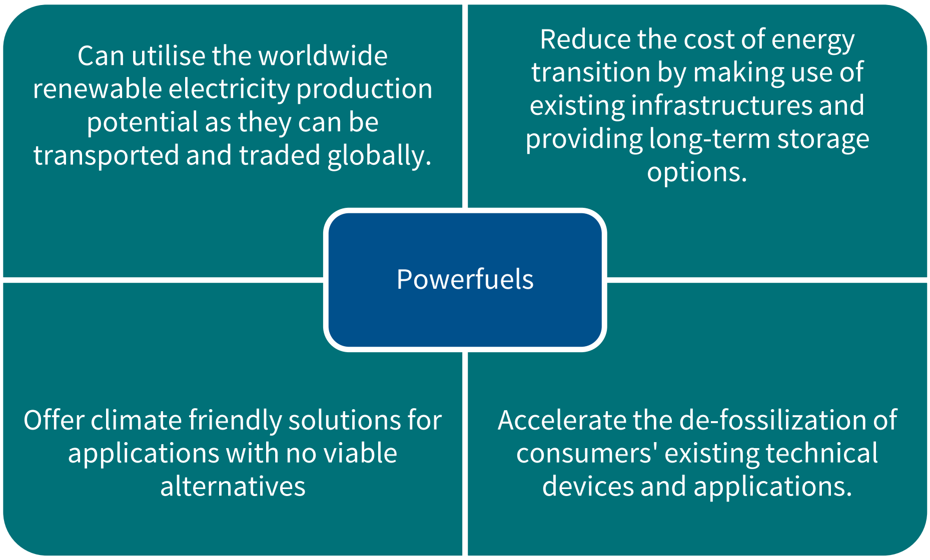

Figure 5: Reasons for powerfuels as missing link to reaching climate targets

3.2.1 Powerfuels are climate-friendly solutions for applications with no viable alternatives

Chemical energy carriers such as powerfuels and fossil fuels have a very high energy density. As shown in Figure 2, 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 energies are needed[19]. From today's technology perspective direct electrification is even unfeasible for some applications. Therefore, it will be difficult to achieve significant CO_2 reductions in these 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).

[19] (Perner, Bothe, Lövenich, Schaefer, & Fritsch, 2018, p. 11)

8. High-temperature industrial process heat

As powerfuels are climate-friendly[20], the widespread substitution of fossil fuels with powerfuels in these sectors could strongly contribute to the defossilization and to the reduction in GHG emissions.

Furthermore, there are many industries that rely on fossil fuels as raw or non-energy input materials. Here again powerfuels could contribute to the reduction of GHG emissions.

1. Replacing hydrogen from steam reforming of natural gas with green hydrogen
2. Feedstock/precursors for chemical industry
3. Fertilizer production (Ammonia synthesis uses natural gas feedstock)
4. Steel production (using hydrogen as reducing agent)

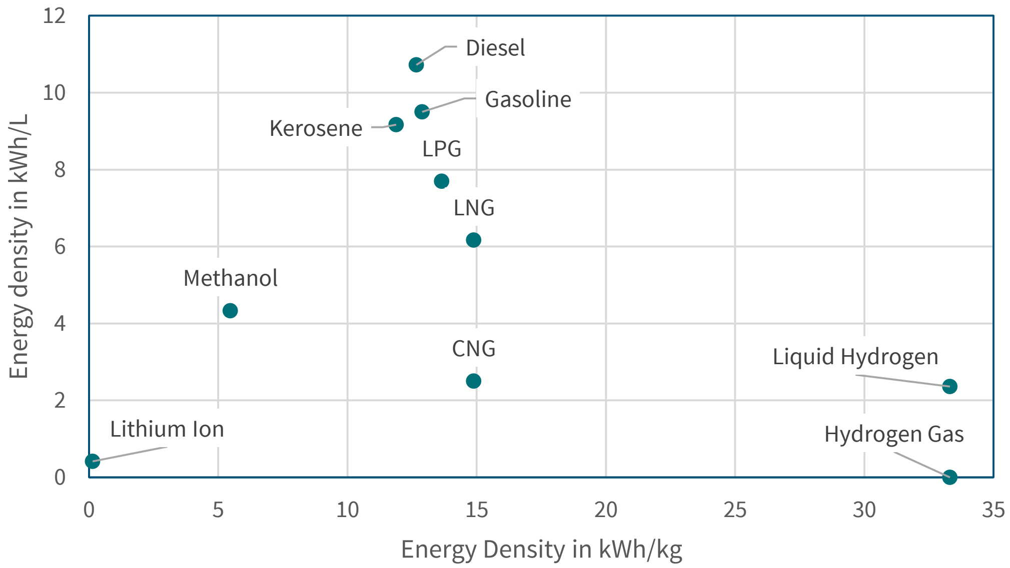

Figure 6: Graph showing the gravimetric (kWh/kg) and volumetric (kWh/L) energy density of various energy carriers[21]

3.2.2 Powerfuels reduce the cost of energy transition by making use of existing infrastructures and providing long-term storage options[22]

On a molecular level, powerfuels are equal to their "conventional counterparts". Therefore, powerfuels can capitalize 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). Because of utilising 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

[20] In case the carbon originates from DAC, powerfuels are carbon-neutral.
[21] Own graphical representation based on (Perner et al., 2018, p. 11) and (Sterner & Stadler, 2017)
[22] (World Energy Council - Germany, 2018, p. 20)

(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.[23]

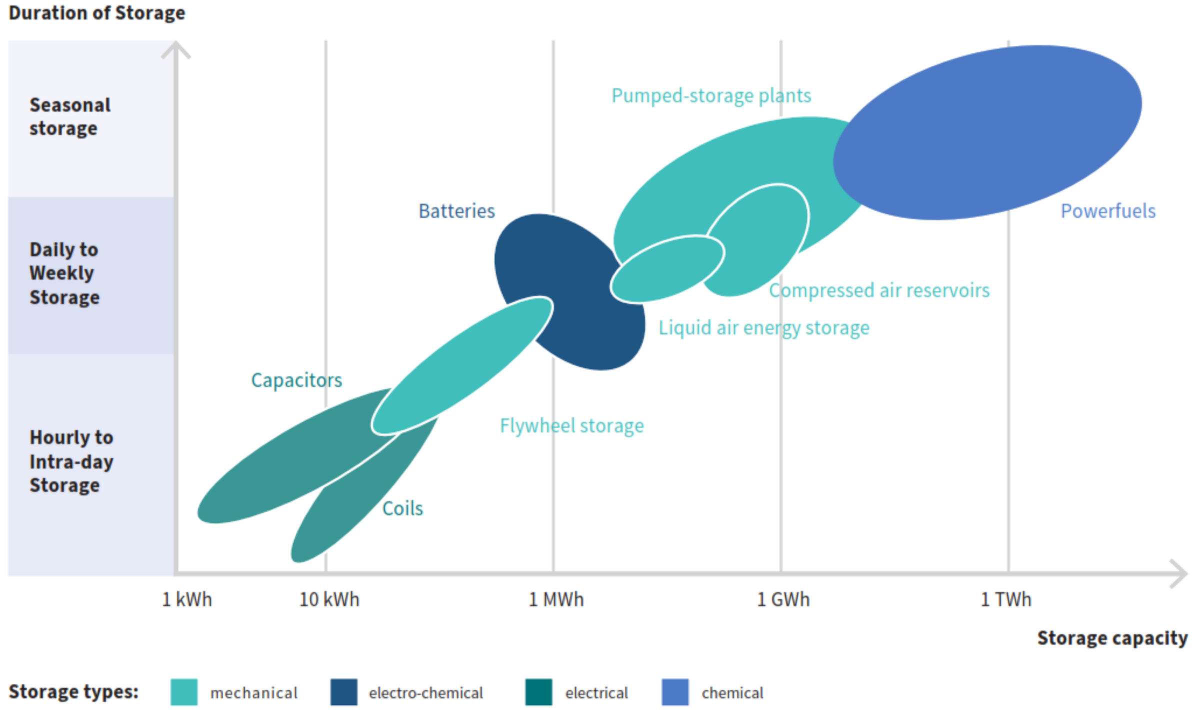

Figure 7: Common energy storage options compared with respect to storage capacity and the duration of storage[24]

Using the existing infrastructure also for powerfuels, instead of constructing new infrastructure (power grids for example) could increase social acceptance. Furthermore, powerfuels could accelerate the speed 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 already today (drop-in). This enables a quick partial introduction of powerfuels in the short and medium term, without the need for change of existing appliances/equipment and therefore guarantees smooth transition paths since end-user behaviour does not need to change.[25]. 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. Hydrogen can be injected up to a certain limit today 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 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

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[23](Deutsche Energie Agentur, 2018), (Bothe, Janssen, van der Poel, & Eich, 2018)
[24]Source: based on (Sterner & Stadler, 2017; World Energy Council - Germany, 2018).
[25] (World Energy Council - Germany, 2018, p. 23)

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.[26]

3.2.3 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 a lot advantages linked to this characteristic:

As electricity costs are a major cost component of powerfuels (see section 2.3.2), 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 export large amounts of locally produced renewable electricity. This could promote economic development and increase the GDP of many countries, as explained in Chapter 3 (Morocco case study).

Analogously, powerfuels allow countries with limited potential/limited space for RES, but high energy needs 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. Also in this regard, powerfuels could increase social acceptance of the transformation of today’s energy system, as they could limit the land usage associated with RES.

Alternatives for the import of RES are less promising than powerfuels[27]. Direct import of renewable electricity requires an expansion of today’s electricity networks, which comes at high cost. Furthermore, the possibility for long-distance transmission of electricity is limited. Import of biomass or biofuels, might be limited due to the competition with food production).

Today, the global supply of fossil fuels is relatively concentrated and the energy import strategies of many countries rely on few suppliers (please see Chapter 4 country analysis). As the global potential for RES is by far more distributed, there are many more potential suppliers. This opens importers the opportunity to further diversify their procurement strategies, reducing their dependency on single suppliers and increase stability.

3.2.4 Powerfuels accelerate the de-fossilization of consumers’ existing technical devices and applications

Powerfuels are completely comparable to their fossil counterparts on molecular level and could thus be used in existing end-user applications without any restrictions. Powerfuels are arguably better than fossil counterparts because of their carbon-neutral nature and are also purer since they do contain impurities, thereby increasing the efficiency and lifetime of end-use equipment. For example:

- Synthetic methane and hydrogen could substitute natural gas in the residential heating sector

[26] (World Energy Council - Germany, 2018, pp. 19–20)
[27] (World Energy Council - Germany, 2018, p. 26)

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

For these applications, powerfuels allow to continue their usage in a climate-friendly way. Naturally, there are and will be additional technology options for the above mentioned applications (e.g. heat pumps, BEV). However, the adoption rate of these new technologies depends on the regulatory framework and economic affordability. Hence, in the medium-term a mix of conventional and new technologies for these applications are 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[28]. 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 de-fossilization of these applications. This could also lead to higher social acceptability with regard to the energy transition because end-users are empowered to contribute to climate change mitigation without investments in new applications.

3.3 Individual technologies for powerfuel production are market-ready – and costs can fall further with economies of scale.

There are several technologies used in the production of powerfuels. These are further explained in the following section. Figure 4, contains an overview of the various powerfuel production pathways.

3.3.1 Technologies for powerfuels production are tried and tested

Electrolysis[29]

Irrespective of the end product, all powerfuel production processes start with Electrolysis. Hydrogen electrolysis refers to the splitting of water into hydrogen and oxygen through the use of electrical energy. There are three main electrolysis methods, described below.

- **Alkaline** electrolysis (TRL 9, efficiency 62% - 82%)
    - Low temperature conversion process ranging between 50-80 degrees Celsius. The separation of product gases and hydroxide ions through two electrodes which operate in liquid alkaline.
    - ALK electrolyser technology is fully mature. It has been used by industry since the 1920s for non-energy purposes, particularly in the chemicals industry (e. g. chlorine manufacture).
- **PEM** proton exchange membrane (TRL 8, efficiency 65% - 82%)
    - Low temperature conversion process ranging between 50-80 degrees Celsius

[28] (Strategieplattform Power-to-Gas, 2018a)
[29] (Strategieplattform Power-to-Gas, 2018b)and (IRENA, 2018a)

- PEM is electrolysis which is equipped in a cell with a solid polymer electrolyte (SPE). As a result, the conduction of protons, electrical insulation of electrodes and divergence of product gases occurs. Compared to alkaline electrolysis, PEM was created to overcome issues regarding low current, partial load, hydrogen density and power pressure issues surrounding alkaline electrolysis operations.[30]
- PEM electrolyser technology is rapidly emerging and entering commercial deployment. State-of-the-art PEM electrolysers can operate more flexibly and reactively than current ALK technology. This offers a significant advantage in allowing flexible operation to capture revenues from multiple electricity markets, as PEM technology offers a wider operating range and has a shorter response time.

- **SOEC** solid oxide electrolyser cell (TRL 6, efficiency 65%- 85%)
    - High temperature conversion process which continues to have small scale pilot projects running on the ground. [31]
    - By using solid oxide or electrolytes or particular ceramics, it runs on regenerative mode to produce hydrogen.
    - SOEC technology holds the promise of greater efficiencies compared to ALK and PEM. However, SOEC is a less mature technology, only demonstrated at laboratory and small demonstration scale.

Methanization

In the methanization process, hydrogen is further processed by the addition of carbon dioxide to produce methane. Catalytic methanization (TRL 8, efficiency 77% - 83%) requires a catalyst based on nickel and is already being used in the commercially used. In addition, a biological methanization (TRL 7, efficiency 77% - 80%) using microorganisms is carried out.

Propane and Liquid Synthesis

Synthetic liquid fuels could be produced either through the Methanol synthesis or the Fischer-Tropsch process.

- **Methanol synthesis** (TRL 8, efficiency 56% up to 66%)
    - In this method, Methanol is produced from chemical reaction between Hydrogen and carbon monoxide or carbon dioxide.
    - Methanol has multiple uses as it can be burned as a synthetic fuel, converted to other chemical intermediaries which are further processed to obtain plastics etc.[32]
- **Fischer-Tropsch synthesis** (TRL 8, efficiency $56\%_{2017}$ up to $66\%_{2050e}$)
    - In this process the carbon dioxide is first converted to carbon monoxide using Reverse Water-Gas shift reaction. Carbon monoxide and hydrogen are then used to produce the required liquid fuel.[33]

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[30] (Areva H2Gen, 2019)
[31] (Agora Verkherswende, Agora Energiewende, & Frontier Economics, 2018, p. 61)
[32] (Agora Verkherswende et al., 2018, p. 70)
[33] (Agora Verkherswende et al., 2018, p. 70)

- **Hydroformulation** (TRL 8, efficiency 62%$_{2019}$ up to 70%$_{2050e}$)[34]
    - The synthesis gas is created as a combination of hydrogen and carbon monoxide. This synthesis gas is then converted to C2 to C5 alcohols, which are subsequently subjected to hydroformulation and isomerization and are thus converted into fuel products.

Chemicals

- **Ammonia synthesis** (TRL 7-9)[35]
    - Conventional production of Ammonia uses Hydrogen produced by steam reforming of Natural Gas. Green Hydrogen produced from electrolysis could be used instead. Since there are no commercial applications of Power-to-Ammonia process, its TRL is considered as 7. But conventional ammonia production is an established process (Haber-Bosch) and since there is only a change in the Hydrogen feedstock source, technology maturity is high.

Carbon Capture[36]

There are two primary ways for obtaining CO_2 . They are

- **Capture from concentrated sources** (TRL 6-9)
    - Industrial emissions have to be purified and subsequently CO_2 is extracted. Based on the specific technology used, the TRL varies.
    - Biogenic sources like for example biogas, ethanol production also produces CO_2 , here the need for purification is much lesser compared to industrial sources.
- **Direct Air Capture** (TRL 6)
    - Companies like Carbon Engineering and Climeworks have showcased in pilot studies the ability to capture CO_2 from ambient air.

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 (e.g. using CO_2 from fossil power generation should not prolong the life-cycle of the plants).

3.3.2 Outlook on technologies for powerfuels

Various individual technologies that are part of Powerfuel processes are already available.

In order to reduce the costs of producing powerfuels, plants require constant operation throughout the year. 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). These processes are in the current development through earlier mentioned pilot studies.

Since the electrolysis step is common for all of these processes, the scale of these 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

[34] (Swedish Biofuels, 2019)
[35] (Institute for Sustainable Process Technology (ISPT), 2017)
[36](Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017); (Schmidt, Weindorf, Roth, Batteiger, & Riegel, 2016)

2017), most electrolysers installed had less than 2 MW capacity. According to the IEA World Energy Investment Report[37], the annual worldwide electrolyser capacity addition from 2010 to 2017 has been below 20MW per year. However this is rapidly changing, as industries start to realise the importance of powerfuels, resulting in announcement of several planned projects with electrolyser capacities up to 100 MW. The yearly planned electrolyser investment for the upcoming years exceeds 40 MW, thus indicating the growth of the electrolyser investments.

3.3.3 Most important cost drivers

Electricity costs is the main driver behind for powerfuel costs followed by carbon capture costs[38]. The cost of producing synthetic liquid fuels and gases vary substantially between fuels and for the different assumptions drawn regarding underlying cost figures[39].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 [40, 41]

Naturally, generation costs of electricity from renewable energies highly depend on the amount of full-load hours. The larger the number of full-load hours, the lower is the levelised cost of electricity produced. 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. Higher yearly full-load hours can then be reached by optimally combining PV and wind potentials with battery storage to increase electrolyser load factors. For example, Figure 8 illustrates the differences of the electricity generation costs for various plant types in different countries. Due to the decreasing investment costs associated with renewable energies, electricity generation costs are expected to fall continuously within next decades. Nevertheless, in 2050 electricity costs will still 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.

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[37] (IEA, 2018c, p. 221)
[38] (Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017, p. 87)
[39] (World Energy Council - Germany, 2018, p. 70)
[40] (Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017, p. 87)
[41] (Agora Verkherswende et al., 2018, p. 82)

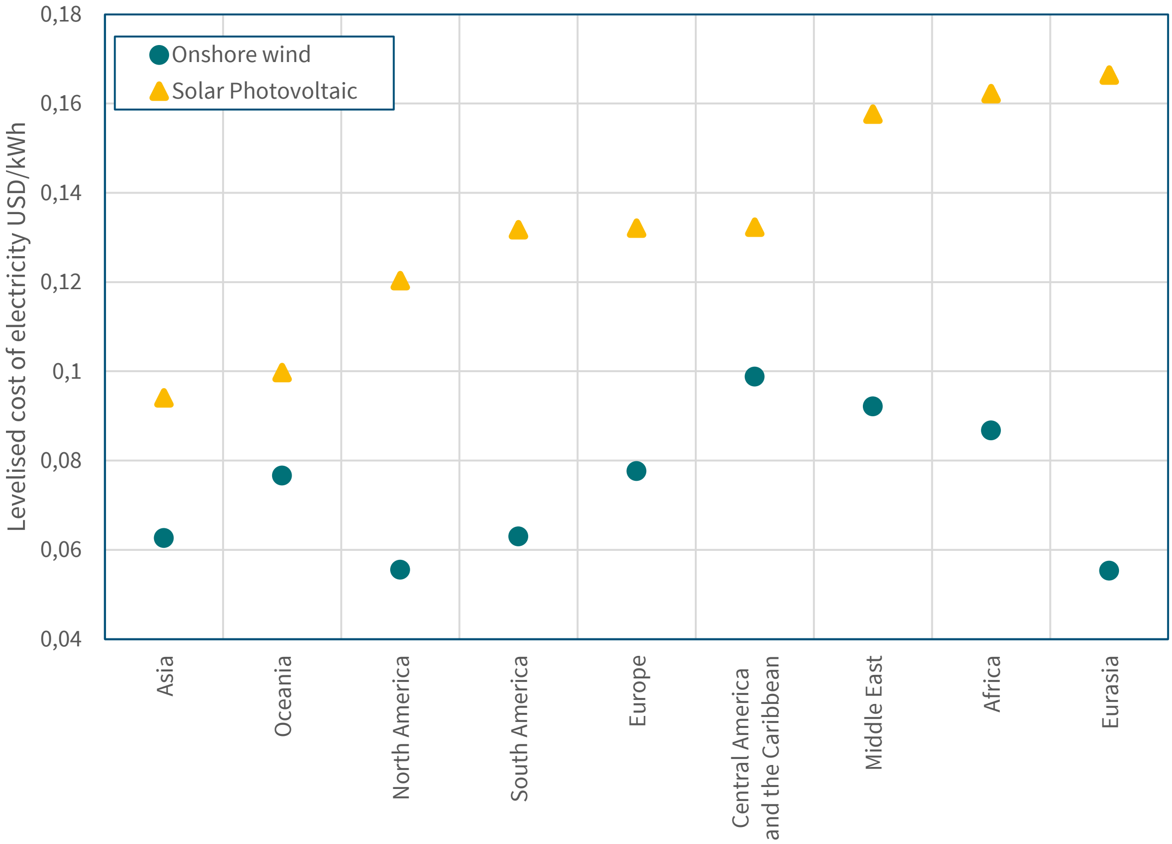

Figure 8: Regional weighted average levelised cost of electricity by renewable power generation technology for 2016 and 2017[42].

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. Investment costs for water electrolysis are expected to further fall within the next decades and continue 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 9).[43]

Investments in electrolysers have been gradually increasing in the recent years and are estimated to reach 40 million USD per year between 2018 and 2020[44]. Electrolyser investment costs have been falling in the past years, indicating a scope for economies of scale. In order to further decrease investment costs in electrolysers technology a significant scale-up of 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

[42] Source: based on (IRENA, 2018b, p. 40)
[43] (Agora Verkherswende et al., 2018, p. 61)
[44] (IEA, 2018c, p. 220)

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.[45]

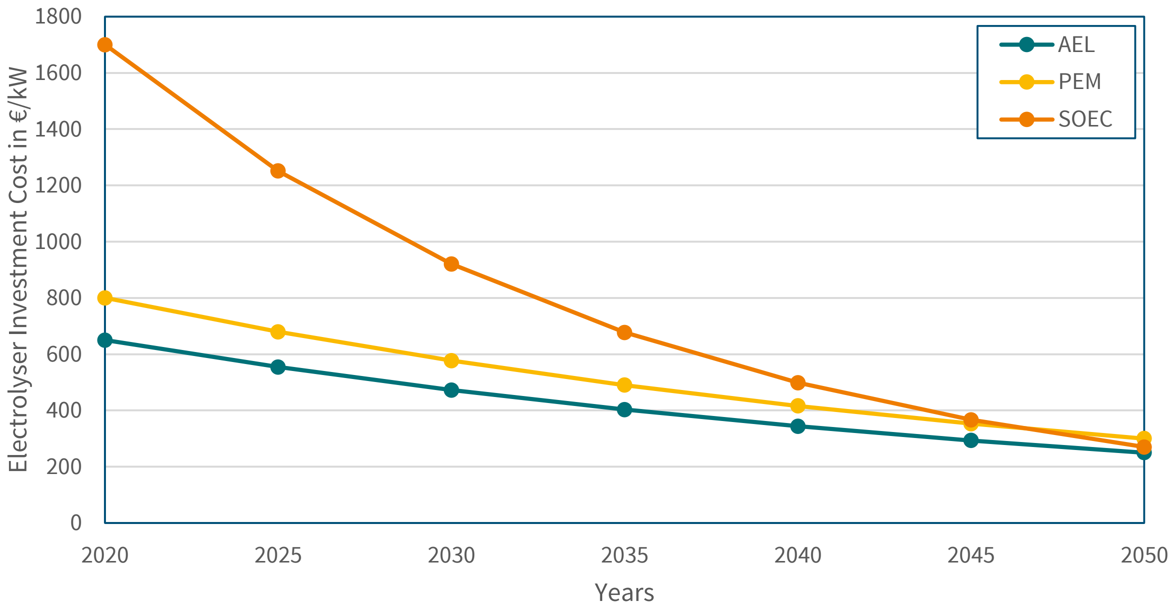

Figure 9: Estimated evolution of electrolyser investment costs[46].

Carbon capture costs

Carbon capture from concentrated sources is more technologically mature. Cost estimates range from 30-70€/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.

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.[47] However, water requirements are limited to e.g. 1.3-1.4 litres per litre of jet fuel[48].

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

[45] (Fasihi, Bogdanov, & Breyer, 2016)
[46] Source: based on (Deutsche Energie Agentur, 2018, pp. 435–437)
[47] (Agora Verkherswende et al., 2018, p. 84)
[48] (Schmidt et al., 2016, p. 18)

3.4 Preliminary estimation of powerfuel demand

Several studies[49,50] have estimated the expected global powerfuel demand for different scenarios. Depending on the share of powerfuel usage in each sector, the global total powerfuel demand in 2040 varies from 10300 TWh in the low case to 41175 TWh in the high case. As a reference, the global total oil and gas consumption for 2017 was 90500 TWh[51]. The powerfuel production capacity to cover this demand is estimated to range from 4000 GW to 16000 GW.

These statistics are only meant to provide an indication of the order of magnitude for powerfuel demand. The key message to note is, irrespective of the scenarios considered, powerfuels play a crucial role in the future energy system. In order to build up the necessary production capacity to meet future powerfuels demand, action is needed now!

[49] (Perner et al., 2018)
[50] (World Energy Council - Germany, 2018)
[51] (BP energy economics, 2018)

4 Future role of powerfuels in different countries

Chapter Summary

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 renewable potential. They can create value locally, contribute to the local energy transition and be exported globally.
2. Powerfuels are an opportunity for countries which 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 green 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 countries' current situation and future trajectory. Nonetheless, powerfuels will likely be needed – and produced – around the world.

4.1 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 which possess abundant space and good conditions for renewable power to become exporters themselves. Powerfuels may then become sources of economic growth and employment.

Various previous studies have contributed to the analysis of possible suppliers[52], however most of them focus on analysing only selected countries (such as Europe as a supply region) or aggregate data regionally. The most comprehensive study on this matter was published by World Energy Council - Germany[53], which bases its analysis by first examining the technical renewable potentials, followed by secondary factors such as economic and political framework conditions. With regards to these technical factors, the most widely quoted data originates from Fasihi et al[54], which demonstrates that the high load factors of powerfuels plants

[52] (Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017); (Fasihi & Breyer, 2017); (Pfenning & Gerhardt, 2017); (Singh, Moore, & Shadis, 2005); (Drennen & Schoenung, 2014); (Fasihi et al., 2016)
[53] (World Energy Council - Germany, 2018)
[54] (Fasihi & Breyer, 2017)

necessary for competitive powerfuels are attainable through an optimal combination of wind and solar resources around the world, which many countries exhibit. Figure 11 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.

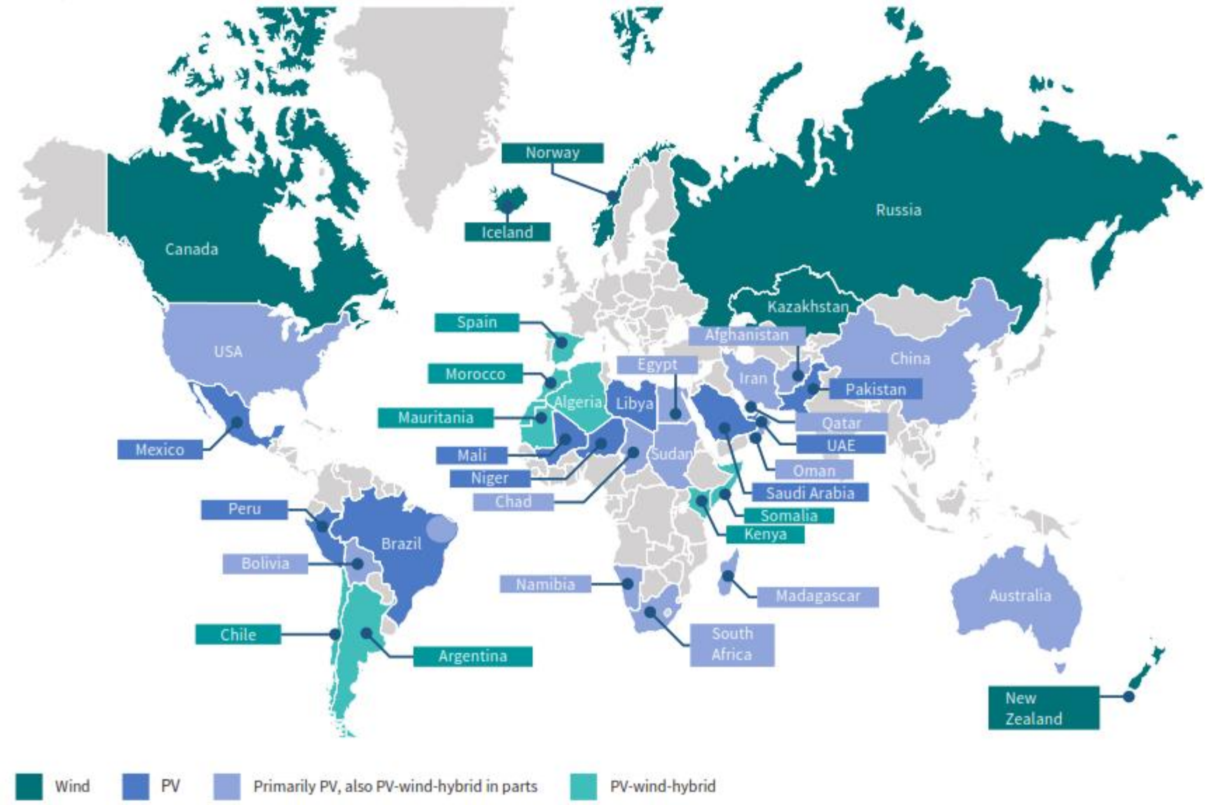

Figure 10: Snapshot of the World's strongest renewable electricity potential[55]

From the current discussion around powerfuels supply countries, a number of narratives emerges that describe reasons which may lead countries to become powerfuels suppliers. Figure 11 shows the typology proposed by World Energy Council - Germany[56].

[55] Illustrative presentation of the RES potential, not an exhaustive list. Source: based on (World Energy Council - Germany, 2018, p. 39)
[56] (World Energy Council - Germany, 2018, p. 45)

TYPE	CHARACTERISTICS	EXAMPLE
FRONTRUNNERS	• Powerfuels already on countries' (energy) political radar • Export potential and Powerfuels readiness evident • Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration	Norway
HIDDEN CHAMPIONS	• Fundamentally unexplored RES potential • Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ Powerfuels could readily become a serious topic if facilitated appropriately	Chile
GIANTS	• Abundant resource availability: massive land areas paired with often extensive RES power • Powerfuels readiness not necessarily precondition, may require facilitation ➢ Provide order of powerfuels magnitudes demanded in mature market	Australia
HYPED POTENTIALS	• At centre of powerfuels debate in Europe with strong powerfuels potential • Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation	Morocco
CONVERTERS	• Global long term conversion from fossil to green energy sources • Powerfuels to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for powerfuels export technology development; may requires political facilitation and partnership with the demand countries	Saudi Arabia
UNCERTAIN CANDIDATES	• Partially unexplored RES potentials, possibly paired with ambitious national climate change policies • Powerfuels export in competition with growing national energy demand ➢ Powerfuels export motivation and potential unclear – may drive powerfuels technology development, however export uncertain	China

Figure 11: Typology of future powerfuels producers, adapted from (World Energy Council - Germany, 2018, p. 45).

4.2 Countries as powerfuels consumers

Powerfuels find their applications in almost all sectors and industries (see Chapter 5). Therefore, their theoretical potential corresponds to the current use of fossil fuels as energy carriers. Previous studies have attempted to estimate global demand in a similar way. World Energy Council - Germany estimates that demand could reach 20.000 TWh in 2050 and beyond(World Energy Council - Germany, 2018, p. 31), which corresponds to 20% of the current fossil fuel demand. It bases the estimate on the assumption that powerfuels will serve only selected applications in sectors where renewable electricity can be used directly, amounting to 10% of energy consumption in those sectors. However, they may constitute the majority of energy supply in sectors where no other de-fossilisation option is available (see Chapter 4).

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, 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.

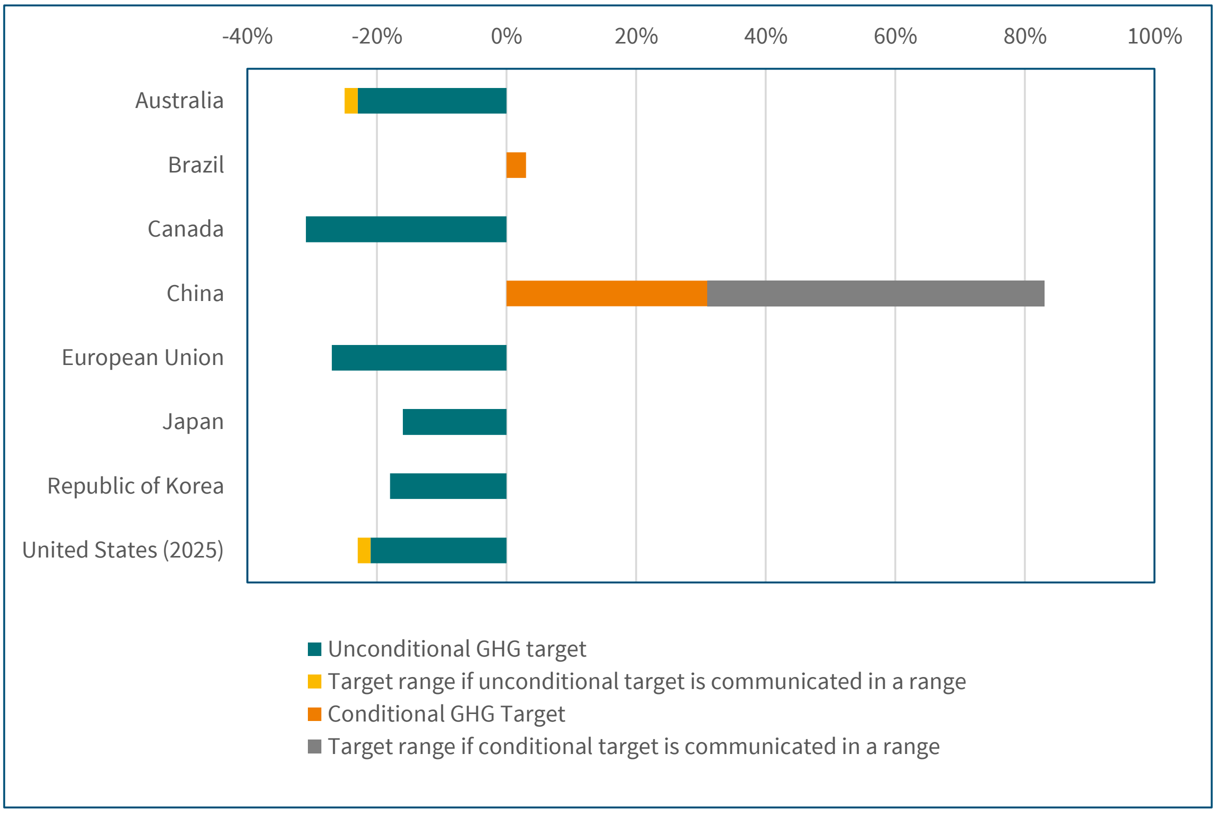

Figure 12: 2030 climate targets for selected countries versus 2010[57].

Figure 11 shows that even high-income countries vary in their ambition to reduce GHG emissions. Nonetheless, almost all strive to significantly reduce them until 2030, and beyond. For the most ambitious countries and regions, such as the European Union, powerfuels may constitute a necessary technology to

[57] Adapted from (Ross, Rich, & Ge, 2016)

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 (-31% in 2030) and the EU (-27% in 2030). It should be noted however, that several regions are even more ambitious, as evident by efforts in California to achieve carbon neutrality in 2045[58].

4.3 Excursus: recent developments in selected countries

4.3.1 Australia

Whilst energy resources in Australia are dominated by coal and gas, there has been a recent shift to invest more in hydrogen and synthetic products. From an economic standpoint, it is estimated that hydrogen, in conjunction with the $23 billion AUD LNG export industry can add an additional 2,800 jobs by 2030, and increase the value of the export chain by $1.7 billion AUD.[59] Increasingly, projects in this area are given the approval by council, state and national governments. In the Latrobe Valley, Victoria, a blue hydrogen supply project valued at $500 million AUD has been approved in early 2019. ARENA announced of $22.1 million AUD in funding across 16 hydrogen projects[60]. Furthermore, electrolysis pilot projects are awaiting approval in the Port Lincoln region of South Australia and Pilbara region of Western Australia with a central focus on producing ammonia for fertilisers. [61]

From an international perspective, the large technical potentials for powerfuels (as well as carbon-neutral blue hydrogen from fossil sources and CCS) have led many neighbouring countries to foster cooperation in this area. For example, Japan and South Korea have demonstrated interest. Australia has and will continue to play a major through the global energy transition. In particular, because it has:

- (1) an abundant and secure supply of renewable energy for powerfuel production
- (2) a willingness to test and develop further technologies such as hydrogen
- (3) the existing infrastructure and value chain to be able to distribute all means of powerfuels both domestically and globally

Despite all these positive aspects there have been barriers from a political standpoint. Australian energy policy has recently reflected uncertainty and instability. Several changes in governments and a weak desire to accomplish global emissions targets allow conventional coal and gas to continue as the primary energy source in the power sector. With no carbon tax or Emissions Trading Scheme’s in place, the Australian government also rejected Dr. Alan Finkel’s recommendations for a clean energy target (CET) in favour of lowering electricity prices.

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58 (Executive Department State of California, 2018)
59 (Hydrogen Strategy Group, 2018, p. 2)
60 (Palmer, 2018)
61 (Hydrogen Strategy Group, 2018, p. 3)

4.3.2 Germany

Germany has been a front-runner in establishing ambitious climate targets, which is backed by strong commitment in both policy and general population. It has also strong track record of increasing the share of renewables in power sector. However, this has not led to strong emission reduction overall due to exit from nuclear power and an exit from coal recently proposed by a government commission on Growth, Structural Change and Employment.

Beyond the power sector, there are several specific challenges on the way to reaching climate targets. Around half of German final energy demand is used for heating and cooling in buildings and processes. While heat pumps constitute a solution for low-temperature residential heating in renovated buildings, renovation rates remain low, despite strong political efforts. Further, overall emissions in the transport sector, which accounts for another third of final energy demand, have not declined in recent years. Increases in efficiency have been consumed by increase in transport volumes, both in commercial and private applications.

To address these challenges in light of ambitious climate targets, powerfuels are increasingly seen as a necessary group of energy carriers in many sectors. Several major studies on the energy system backed by German industry and research in 2018[62] have determined that powerfuels are needed in large quantities for reaching 95% emissions reduction target in 2050, and addressed the need to start market development immediately. Therefore, there is strong and increasing awareness amongst policy makers to take action.

Germany’s situation as a large and densely-populated country with limited space for renewable energy generation in the long run will mean that it will continue importing primary energy from abroad, but needs to switch to renewable energy at the same time. As a current net exporter of goods and services it is well equipped to do so in the future. With large engineering expertise along the entire supply chain of powerfuels, it currently boasts the largest number of powerfuels pilot projects (more than 30)[63]. Nonetheless, there does not exist a national strategy on powerfuels yet, and there are no measures undertaken to make the necessary step from pilot projects to industrial scale.

4.3.3 Japan

As a potential demand market, Japan possesses several distinct characteristics which make it a likely first adopter of powerfuels. First, it imports around 95% of primary energy demand from overseas. This translates into a strong dependence on a few exporting countries. Due to geographical conditions and high population density there is also limited potential for significantly expanding domestic renewable power generation. Secondly, as an island it does not have strong pipeline infrastructure in place, as is typical for similarly industrialized countries in Europe or Northern America. Thirdly, Japanese companies possess strong expertise in energy engineering. Fourth, since the earthquakes are frequent, there is a strong preference for decentralised and more resilient energy solutions.

These factors have led Japanese policy to focus on the import of climate-friendly energy. Hydrogen has been identified as powerfuel of choice, because there is little need for overland transport, less use for waste heat and high interest in using imported fuels as efficiently as possible. Becoming a “hydrogen society” is now at the centre of Japanese energy policy[64]. Hydrogen initiatives in Japan are characterized by strong

[62] (Energiesysteme der Zukunft, Bundesverband der deutschen Industrie e. V., Deutsche Energie-Agentur, 2019)
[63] (Strategieplattform Power-to-Gas, 2019)
[64] (Agency for Natural Resources and Energy, 2019)

government-industry cooperation in a number of large-scale pilot projects. Notable successes on industrial scale have been decentralized fuel cell cogeneration systems (with on-site reforming from natural gas) ENE-Farms, of which more than 270.000 have been deployed in the country, while retail prices reduced to a third and subsidies by around 95%[65]. Further, Japanese car manufacturers lead the way in hydrogen passenger cars, next to their Korean counterparts.

Also on the international level, Japanese energy policy is determined to accelerate hydrogen deployment. In October 2018 it hosted a first ministerial dialogue on hydrogen, with representatives 21 countries. Currently, the focus of market development lies in creating viable business cases and applications, as well as facilitating large-scale import of hydrogen by ship. Two projects are under development, testing liquefaction and LOHC technologies for transport from Brunei and Australia. Both use fossil energy sources and CCS - but electrolysis from renewable power is on the agenda as well, as costs fall.

4.3.4 Middle East and North Africa

As evident in Figure 11, the Maghreb region offers excellent RES potentials and is also in close proximity to European demand markets. Some of the countries in this region are oil and gas exporters today. 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. Powerfuels produced from these countries could be used to target these import countries which also have high willingness to pay for green energy carriers.

Some countries in this region are dependent on fossil fuel imports to meet their energy demands. In these countries, the development of powerfuels could also benefit the local population. For example, Morocco imports over 90% of its energy supply primarily in the form of fossil fuels - mainly coal, oil and gas. Through its National Energy Strategy of 2009, Morocco plans to accelerate the development of renewable electricity generation (2 GW of wind power, 2 GW of solar power by 2020). Since Morocco also has abundant renewable electricity production potential, it could be used to produce powerfuels which could reduce their import dependency and since the capital is invested within the country it could lead to additional social benefits. Irrespective of whether the powerfuels produced are used for local consumption or for exports which may fetch higher profits, power fuel production would be beneficial for Morocco.

[65] (Shimizu, 2017)

5 Powerfuels create value in major global 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 pre-existing infrastructure with long investment cycles.
2. Powerfuels can replace both energy-based and also feedstock use of fossil fuels in industries.
3. De-fossilisation of specific industries will need specific types of powerfuels. As today there is no common fuel type that fits all needs.

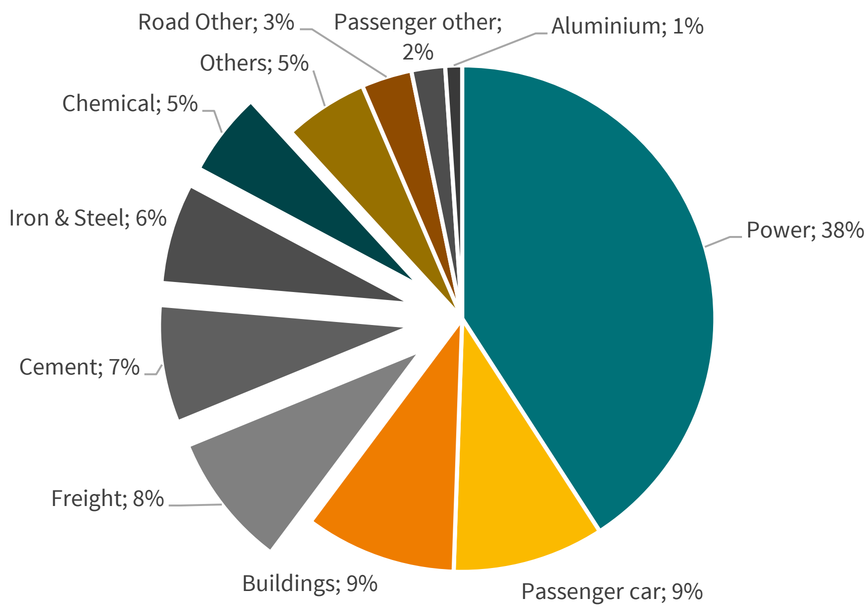

Figure 13: Breakdown of global energy-related CO_2 emissions by sector in 2015, highlighted are sectors that do not have an economically viable option for deep decarbonisation today[66].

5.1 Mobility sector

The mobility sector accounts for 25%[67] of fossil energy demand globally. In most countries, If we breakdown emissions per sector, mobility constitutes a high percentage of the emissions. In mobility, there has been tremendous growth in the capabilities of battery-electric and alternative fuel vehicles in recent years however they still make up a small percentage of the overall number of vehicles available. Further to this,

[66] Based on (IRENA, 2017, p. 34)
[67] (Rodrigue, 2017)

Pricewaterhouse Coopers (PWC) believe we will likely see a change in the economics of powertrains[68] allowing for further development and demands for particular fuel cell batteries to grow.

Due to the nature of the mobility sector accounting for a large proportion of CO_2 emissions globally, the tightening of emission standards has increased the TCO of ICE with conventional 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 previous year. especially for surface transport. This is likely to continue, combining the advantages of chemical energy carriers with electric traction but there will be a shifting focus only so that energy carriers must be renewable in the future.

From a technical standpoint, there are still many mobility applications that require large volumetric or specific energy densities provided by oil, 64%[71] of mobility sector to be exact. Over all mobility applications, this occurs mainly for vehicles that need long range without refuelling/recharging, move heavy loads or need to be lightweight. Later in this chapter we will address particular areas of the mobility sector and show how the need for powerfuels and regulation supporting the technology is unique for all applications. Ultimately, the results from the analysis indicate that powerfuels constitute a large opportunity for de-fossilisation. In some applications there is no known alternative, hence powerfuels can help mitigate risks for market stakeholders in the wake of upcoming regulation.

5.1.1 Aviation

Global GHG emissions/consumption of fossil fuels and sources of emissions

For years now, aviation has been improving its energy efficiency and carbon footprint around the world. Despite high growth rates, aviation has accounted for more than 2% of CO_2 emissions globally[69]. By comparison, the share was 2.92 percent in 2000. This is due to increasingly efficient flights ensuring that the absolute CO_2 emissions in the aviation sector grow at a lower rate than emissions from other sectors. In 2015, intra-European flights accounted for 0.52 percent of total CO_2 emissions in the EU, while in Germany the share of CO_2 emissions from domestic flights was 0.3 percent of total German emissions.[70]

Worldwide aviation fuel consumption through jet fuel (kerosene) is estimated to be at 200 to 225 million tonnes.[71] European fuel consumption makes up approximately one quarter of this figure at around 54 million tonnes.[72] At a conversion factor of 3.16[73] tonnes of CO_2 per tonne of kerosene burned, this corresponds to a CO_2 emission of about 650 to 700 billion CO_2 worldwide, and about 170 million tonnes of CO_2 from uplifts in Europe. If present growth processes persist, these emissions will double or triple by 2050.[74] It is also important to recognise that there is some ground emissions from aviation, but those emissions only amount to 1 to 2% of flight CO_2 emissions.[75] What is also important to be recognised is that CO_2 emissions are also dependent on the particular location of the plane whilst taking into account the altitude to which the emissions are being produced.

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[68] (PwC Strategy & Germany, 2018)
[69] (European Commission, 2016)
[70] (IEA, 2019b)
[71] Surveyed experts based on the SWAFEA study.
[72] Surveyed experts based on Eurostat
[73] This is the conversion factor used in CORSIA. The ETS currently uses a conversion factor of 3.15, but will in the future align with CORSIA.
[74] (ICAO, 2016)
[75] There is no comprehensive report on these emissions, but the European Aviation Environmental Report 2019 states 2017-2018 direct emissions under the full control of the airport to have been 1.985 million tonnes of CO_2 . To this, some additional emissions by airlines and third party operators must be added, but these are not exactly known.

Potential abatement options

In 2009, airlines, aircraft manufacturers, air navigation service providers and airports worldwide agreed on a climate protection plan: to increase fuel efficiency by approximately 1.5 percent per year; to achieve carbon-neutral growth in air travel by 2020; and to halve net CO_2 emissions by 2050 compared to 2005 levels. These goals will be achieved by implementing the following measures:

- Already today: increase efficiency – reduce CO_2 increase
  Reducing the specific energy requirements of aircraft will cut fuel consumption and, in turn, CO_2 emissions. The measures designed to achieve this improvement include technical innovations by aircraft and engine manufacturers, optimally coordinated operational processes on the ground and in the air, and implementation of the Single European Sky.
- The goal: fly carbon-neutral
  In order to be able to fly CO_2 -neutral in the long term, we need to see the development of new airplanes, alternative fuels and drives, combined with the political support to make their use commercially viable.
- On the way to the goal: compensate carbon growth
  As global air traffic continues to grow by about five per cent per year, the reduction in specific fuel consumption is not enough to stop the increase in CO_2 emissions. Therefore, at the UN level, the international CO_2 offsetting system CORSIA was adopted by the Civil Aviation Organization ICAO. As part of CORSIA, growth-related CO_2 emissions of international flights will be compensated by financing carbon offset projects from 2021 onwards. It should be noted that whilst it is clear that offsetting is helpful in the short run since it is a rather 'cheap avoidance option' for regulatory governing bodies and airlines, at the same time it does not foster technological progress for CO_2 avoidance in the aviation sector.

Figure 13 illustrates that it is almost certain that the future growth of air traffic will overcompensate potential efficiency gains. Therefore, the large-scale use of renewable energy carriers (such as powerfuels) has to be seen as key pillar towards GHG-reduction within the aviation sector.[76]

[76] (Schmidt et al., 2016, p. 10)

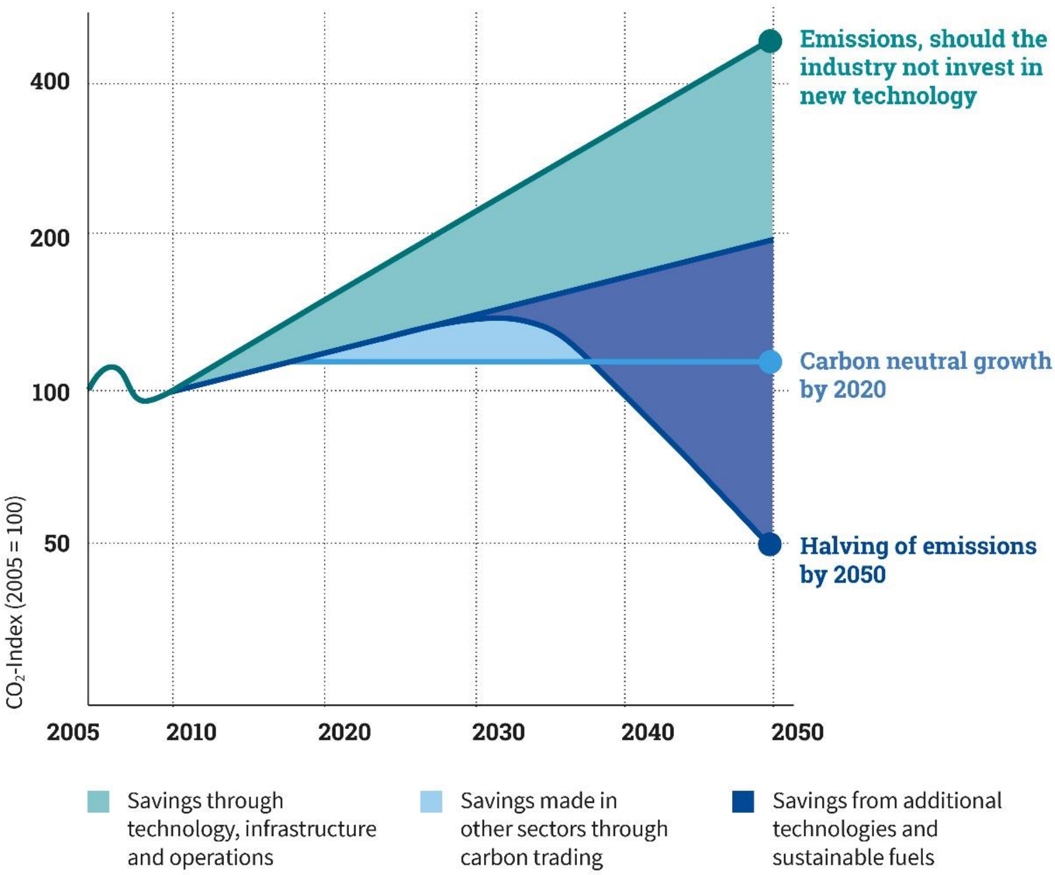

Figure 14: Illustration of greenhouse gas emission reduction targets of the aviation industry[77]

The Aviation sector is very much characterized by the need for fuels that exhibit both volumetric and gravimetric energy density. Although there have been some tests with hydrogen (DLR) and hybrid (Siemens) or battery-electric[78] propulsion, for long-haul commercial flights there is consensus that there is no alternative to liquid hydrocarbon fuels for the foreseeable future.

Possible applications for powerfuels

Ideally, powerfuels could replace all fossil kerosene. The regional distribution corresponds to that of air traffic, i.e. the focus is on the US, Europe, the Middle East and Asia.[79] Air traffic growth is expected to be considerable over the next couple of decades, and fuel consumption is expected to grow correspondingly, albeit at a lower rate owing to technical improvements. Powerfuels fuels should be drop-in, hence should have no impact on operations. The alternative to powerfuels fuels are other renewable liquid fuels, like biofuels.

Barriers

Powerfuels will need to be REACH registered and ASTM certified. However, these are minor issues compared to getting powerfuels production going. For example, some synthetic fuels (Fischer-Tropsch based) have

[77] Source: based on (Schmidt et al., 2016, p. 11)
[78] Flugrevue, EasyJet wants electric aircraft for short-haul flights, https://www.flugrevue.de/zusammenarbeit-mit-wright-electric-easyjet-will-elektroflugzeuge-fuer-kurzstrecken/
[79] (Airbus, 2018)

already been approved according to ASTM D7566 and can now be used in blends of up to 50% with conventional jet fuels, [80] but other developments of powerfuels are still not ASTM approved. One particular mean in tacking this potential barrier is to build we build up a global standard and database for alternative sustainable fuels like NABISY[81] 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 price. This may to some extent be industry specific, as aviation is facing rather high demand elasticity, particularly if such price increases are not global. Ultimately there needs to be a shift in environment to see prices become more affordable for commercial use.

5.1.2 Maritime Shipping

Global GHG emissions/consumption of fossil fuels and sources of emissions

In 2012 the maritime transport sector emitted about 796 million tonnes of CO_2 , which represented about 2.2% of global emissions.[82]Due to the increasing role of global trade, emissions of this sector are expected to increase in the future. For example, in a scenario with no additional policies, CO_2 emissions from global shipping are projected to reach 1090 Million tonnes by 2035 (23% growth compared to 2015).[83] Consequently speaking, although global regulation on mandatory energy efficiency standards in shipping was introduced in 2013, various studies project shipping's GHG emissions to grow if additional measures are not taken.

Potential abatement options

The large majority of GHG emissions attributed to the maritime transport sector originates from the combustion of fossil fuels within the ships' engines. Therefore, potential abatement options to reduce emissions within the maritime transport sector either represent measures to reduce the fuel consumption of ships or focus on the substitution of fossil energy carriers with alternative fuels. The fuel consumption within the maritime transport sector can be reduced by technological and operational measures. Weight reduction (e.g. by replacing heavy steel by lighter material such as aluminium) and optimisation measures to scale down the friction of ships (e.g. slender hull design, hull coatings and air lubrication) fall within the first category. This also holds for the recovery of waste heat for on-board needs and the application of more efficient propulsion devices. The fuel reduction potential of these options are not easy to assess, as they highly depend on respective ship characteristics, but estimates of various scholars are mainly below 10%. Moreover, as the relation between ship size and emissions is not linear, economies of scale could be realised if larger ships were used. [84]

Furthermore, fuel consumption could be influenced by the mode ships are operated. The most promising option here is to reduce ships' speed, which could yield an estimated CO_2 reduction potential of up to 60% depending on the speed decrease. However, slower speeds automatically come with the need of more ships to keep the transport service frequency stable. This would yield to an increase in investment cost.[85]

[80] (Schmidt et al., 2016, p. 14)
[81] (Bundesanstalt für Landwirtschaft und Ernährung, 2019)
[82] (IRENA, 2017, p. 34)
[83] (ITF, 2018, p. 13)
[84] (ITF, 2018, pp. 26, 29)
[85] (ITF, 2018, p. 28)

Possible applications for powerfuels

It is not controversial that to meet the 2° climate target, a strong de-fossilisation 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.[86] In this regard, the most promising fuels within the shipping sector are:

- Electricity
- Advanced biofuels
- Hydrogen (either fuel cell or internal combustion)
- Ammonia (either fuel cell or internal combustion)
- Methanol
- Synthetic diesel

With respect to our definition (see chapter 2), hydrogen, ammonia and methanol represent powerfuels, if their energy content is based on renewable electricity.

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. Additionally, the electric vessel was shown to be the least profitable alternative fuel options[87]

In contrast, biofuels are sometimes seen as the most profitable zero-emission solution. [88] 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.[89] In regards to hydrogen, it can be used in fuel cells or as substitute (either completely or partly as blends) for heavy fuel oil (HFO) in combustion processes. For, example a fifty-fifty-mixture of HFO and hydrogen can reduce CO_2 emissions by up to 43% per tonne-kilometre.[90]

When addressing ammonia, the reduction potential is of similar size. [91] 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. However, within the shipping industry it has not been tested yet and there exists no operational ship powered by ammonia today.[92] However, MAN Energy Solutions announced an engine in early 2019[93]. Finally, methanol also represents an alternative fuel option that has already been tested 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 there is produced from natural gas. [94] Further, MOL operates an methanol-powered methanol carrier since 2013. [95]

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[86] (Lloyds's Register Marine and UCL Energy Institute, 2014)
[87] ibid
[88] ibid
[89] (ITF, 2018, pp. 32–33)
[90] (Bicer & Dincer, 2018)
[91] ibid
[92] (ITF, 2018, p. 35)
[93] Ammonia Energy: Link
[94] (ITF, 2018, p. 36)
[95] (Ammonia Energy, 2019)

Given the variety and diversity of the shipping industry, it is obvious that there will be no one-size-fits-all option to reduce GHG emissions of this sector. However, it was shown that powerfuels such that hydrogen, ammonia and methanol represent promising alternatives to HFO and thus huge opportunities for the maritime transport sector.

Barriers

Whereas powerfuels are promising, their practical application within the shipping industry is still very limited to pilot projects. This can be mainly attributed to the fact that they are not yet cost competitive compared to HFO. For example, a study by Lloyd's register estimates that throughout different scenarios none of the above mentioned alternative fuels options will be more profitable than a HFO reference ship in 2030.[96] This indicates that market forces are insufficient to induce a broad fuel switch and thus highlights the importance of regulation.

5.1.3 Cars

Global GHG emissions/consumption of fossil fuels and sources of emissions

Passenger cars account for a significant share of emissions worldwide, emitting approximately 3.5 Gt of CO_2 per year. This constitutes 45 % of all transport emissions and approx. 10 % of the global GHG emissions.[97] Despite strong progress in recent decades, car manufacturers are increasingly under pressure by both consumers, general public and regulators to further reduce local and GHG emissions.

Potential abatement options

Vehicle manufacturers are looking at addressing the issue by making the manufacturing process, as well as the final product for consumers more carbon neutral. Further, the last years have seen increased efforts in the development of affordable and reliable electric vehicles (EV's). Besides, stakeholders are increasingly addressing a shift to other, more sustainable modes of transport.

Over the next decade, it is predicted that in addition to Internal Combustion Engine (ICE) vehicles, there will more than likely be plug-in hybrid electric vehicles (PHEV's), fully battery-powered electric vehicles (BEV's), and fuel cell electric vehicles (FCEV's) running on hydrogen.[98] Studies have shown that system costs are lower for BEV cars in a driving range considered short to medium, however if the range is considered medium to long in distance, FCEV's have a lower system operation cost.[99] Liquid powerfuels can be a viable option to reduce GHG emissions in the existing vehicle stock.

Possible applications for powerfuels

Car manufacturers that are currently in the production phase of Hydrogen fuel-cell based cars include:

- Honda (FCX Clarity and Clarity Fuel Cell)
- Toyota (Mirai)
- Mercedes-Benz (GLC F-Cell)

[96] (Lloyds's Register Marine and UCL Energy Institute, 2014)
[97] (IEA, 2018a)
[98] (PwC Strategy & Germany, 2018, p. 5)
[99] (National Organisation Hydrogen and Fuel Cell Technology (NOW), 2018, p. 5)

- Hyundai (Tucson FCEV and Nexo)
- Riversimple (Rasa)

In addition, car manufacturers are also involved in pilot synthetic fuel production projects, for example the Audi e-gas plant in Werlte and the Audi e-diesel plant in Laufenburg.

Most manufacturers addressing several of the potential abatement options mentioned above. The replacement of hydrogen from fossil origin in refineries by renewable hydrogen could be one of the first measures to reduce well-to-wheel emissions.

Barriers

There is no current regulation to help incentivise power fuel driven cars. Through efficiency measures, we have seen the reduction of GHG emissions and fossil fuel use. Due to each type of technology having specific parameters influencing their affordability and accessibility, the overall price of each technology is symbiotic of one another individual markets:

- **ICE:** due to industry regulations and standards in order to achieve these climate change goals, the cost of ownership will increase. This is primarily due to new equipment in these vehicles to reduce pollution, including particle filters, exhaust gas recirculation, and catalyst heaters for tailpipes.
- **BEV's**: demonstrate the opposite outcome to ICE power vehicles. The cost of ownership will decrease consistently over the next decade. This is due to the value of the battery and the industrial processes behind particular production costs predicted to decrease, consequently resulting in less battery cells being produced due to an increase in energy density within the system.[100]
- **FCEV's**: there will be a slight decline with owning a FCEV. Whilst the cost to produce and store hydrogen is predicted to also decrease, the reason behind the behaviour of FCEV costs is dependent on fuel cell stack costs. The other possible drivers for the decline in costs is that the electrical motor and power electronic parts used in FCEV's are identical to the ones used in BEV's.[101]
- **PHEV's**: dependent on the results of BEV's and ICE engines.

5.1.4 Trucks & Buses

Global GHG emissions/consumption of fossil fuels and sources of emissions

Whilst there has been a shift towards electric heavy vehicles in recent years, trucks and buses continue to be dominated but internal combustion engines that are powered by fuels. In urban agglomerations, public transport also causes high CO_2 emissions. In most developed countries, the buses used in public transport are almost exclusively diesel vehicles.[102] It is also common knowledge that there is a direct correlation between the burning of fuels and CO_2 emissions. Additionally, heavy vehicles are aligned with notions of long distance travel and high transport capacities, climate-friendly fuels with high energy density are necessary. There is a necessity for powerfuels as we continue to see a demand for the usage of heavy duty vehicles. According to the IEA, heavy duty vehicles emit approximately 2 Gt of CO_2 per year. Which accounts for 29% of all transport emissions worldwide and 6% of global GHG emissions.[103] 2017 in Europe saw two key

[100] (PwC Strategy & Germany, 2018, p. 7)
[101] (PwC Strategy & Germany, 2018, p. 7)
[102] (Strategieplattform Power-to-Gas, 2018a)
[103] (IEA, 2019a)

phenomena occur; first the amount of new car registrations increased to a record high of 15.2 million. This was the highest total we have seen since 2007.[104] Second, average emissions levels for new passengers increased by 1g/km now taking the total 119 grams per kilometre.[105]

Potential abatement options

As previously mentioned in the cars chapter, manufacturers are looking at developing both electric and hydrogen fuel cell batteries. Most of the technologies currently available are feasible and available for distribution trucks but further research and developments are being made to make the technology more efficient. From an operational costs, the potential for battery electric heavy-duty long-haul trucks is limited because of a limited range without significant payload penalty. Therefore, installing overhead catenary wires along express highways is proposed.

Possible applications for powerfuels

The Ports of Los Angeles and Long Beach in the USA are planning to electrify highways for drayage operations.[106] However, if electric heavy-duty vehicles for which the electricity is supplied by overhead catenary wires are to reach a significant share of overall freight transport services, a grid of overhead wires across the whole EU would be required.[107] Only a few member states, among them Germany and Sweden, are discussing overhead catenary wires 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 primarily on lines with a high vehicle load factor are an needed supplement to the direct the use of powerfuels is a sensible supplement to direct electrification, especially on routes with high vehicle utilization. Powerfuel-based drives currently have longer ranges and significantly shorter refuelling times than Electric Vehicles.

Barriers

The technological barriers are similar to the ones mentioned in the cars chapter however, further barriers have been identified from a fuel cost perspective. From a commercialisation standpoint, the cost of hydrogen varies between $10 to $15 per kilogram. Whilst the efficiency of hydrogen is a positive in comparison to diesel or petroleum fuels, improvements still need to be made in terms of advancing power density, capital costs and efficiency[108]. Further to this, whilst there is existing infrastructure for fuelling stations already present, each fuelling station would now need additional infrastructure and increase operational and safety costs in order to fulfil the requirements to refuel heavy-duty vehicles.

5.1.5 Rail

Global GHG emissions/consumption of fossil fuels and sources of emissions

In 2015, the global energy-related CO_2 emissions of the rail sector mounted to 336 million tonnes CO_2 , thus making up a share of 4.2% of global transport emissions. Although declining since 2005, the share of fossil oil

[104] (ICCT, 2017, p. 2)
[105] (ICCT, 2017, p. 3)
[106] CE Delft & DLR, 2013; SCAQMD, 2015a
[107] (Deutsche Energie Agentur & Ludwig-Bölkow Systemtechnik, 2017, p. 34)
[108] Advance Clean Tech News, Hydrogen Fuel Cell Future Is Promising for Heavy-Duty Trucks, 31 October 2018 https://www.act-news.com/news/hydrogen-fuel-cell-vehicles/

products (diesel) in the global railway fuel mix still represents a significant fraction of 56%.[109] This can be attributed to the fact that 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) [110]. However, even in industrialized countries, a large part of rail traffic is not electrified, but runs on diesel.

For example, in Germany, about 40 percent of the rail network are not electrified and necessitates 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.[111] Their joint annual diesel consumption mounts to more than 400 million litre diesel with associated emissions of about one million CO_2 -equivalents.[112]

Potential abatement options

Theoretically, the full electrification of train traffic combined with the use of electricity of renewable energies is an abatement 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).[113] Furthermore, emissions could be reduced by improving the fuel consumption of trains. Examples for potential measures are braking energy recovery or weight reduction. Nevertheless, these measures will only lead to limited reduction in GHG emissions, as long as the combustion engine is further fed with fossil-based fuels.

Possible applications for powerfuels

The use of alternative propulsion technologies such as hydrogen fuel cells represent a promising abatement option for non-electrified rail transport, if electrification is (economically) not feasible. In case, the used hydrogen has been produced based on renewable electricity, such hydrogen trains do not emit GHG emissions or other pollutants at all.

The first pilot projects have already proven the suitability of this technology for the rail sector. The Coradia iLint hydrogen fuel cell train that has been developed by Alstom can serve as example here, as it is the first regular operating train that is powered with hydrogen. In 2018, two pilot trains equipped with fuel cells that convert hydrogen and oxygen (from the ambient air) into electricity took up commercial service and have been operating on a regional connection in Lower Saxony (Germany) since then.[114]

Barriers

A challenge lies in the production, transport, storage and supply of hydrogen. With full compensation of railway associated diesel demand in Germany alone, 120,000 tonnes of hydrogen will be needed. This would probably require an installed electrolysis capacity of 1 to 1.5 GW.[115]Furthermore, from a logistical

[109] (IEA & UIC, 2017, p. 22)
[110] (IEA & UIC, 2017, p. 23)
[111] (Strategieplattform Power-to-Gas, 2018a)
[112] (BMUB, 2017, p. 37)
[113] (Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), 2018, p. 44)
[114] https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower
[115] (Strategieplattform Power-to-Gas, 2018a)

perspective, the use of so-called on-site electrolysers would be an option - these generate the hydrogen directly adjacent to the railway infrastructure.

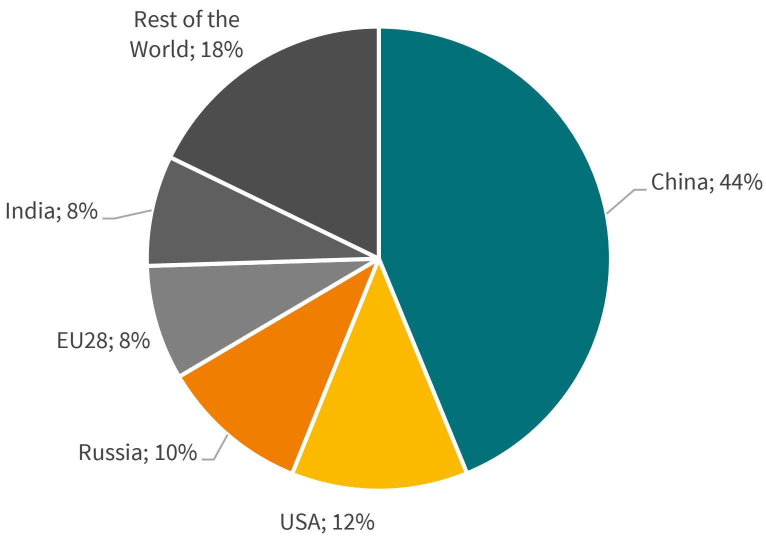

Figure 15: Share of railway CO_2 emissions by geographic area (2015)[116]

5.2 Basic Industries

5.2.1 Steel Production

<u>GHG emission perspective and potential solutions to barriers</u>

The steel industry is recognised as one of the most critically dependent industries worldwide due to its popular use in many applications. As a result, steel is a heavily traded commodity amongst all countries. Whilst crude steel production saw growth of 4%[117] in 2017, issues surrounding environmental impacts continue to be a focal point. To add to this figure, most of the top 10 countries (China, Japan, India, United States, Russia, South Korea, Germany, Turkey, Brazil and Italy) who produce steel have also been identified in chapter 3 as countries who could considerably benefit from the use of powerfuels.

From a resource management perspective, the world steel association believes that in 2016, wasteful excess materials from all steelmaking process accounted for 2.4%[118] of the net products combined. This demonstrates that the industry is self-conscious about its footprint however the barriers to reduce CO_2 emissions lie within the manufacturing processes itself. However the problem with reducing steel industry CO_2 emissions, however, is that today's production facilities can hardly be optimized any further.[119] Through analysing steel-mills, climate-damaging smelting gases, such as carbon monoxide, hydrogen and methane,

[116] (IEA & UIC, 2017, p. 22)
[117] (World Steel Association, 2018, p. 9)
[118] (World Steel Association, 2018, p. 5)
[119] Siemens - Steel Production – without CO_2 Emissions? (https://www.siemens.com/innovation/en/home/pictures-of-the-future/research-and-management/innovations-carbon2chem-environmentally-friendly-steel-production.html)

are produced. After steel production, these gases are burned in power plants to generate electricity. But the catch is that this process also generates CO_2 emissions. Right now progress is being made on low-carbon industrial innovation as it is crucial to achieve the 2 degree scenario with non-OECD countries.[120] Powerfuels can be used to solve this problem as 28%[121] of the world crude steel production is powered by electricity. As renewables and iron ore deposits are used to power electrolysis processes for electrical steel production, by replacing the following with powerfuels, it is believed that with green saving hydrogen there will be a 95% in CO_2 emissions via the blast furnace route turn.[122]

5.2.2 Chemical industry

GHG emission perspective

Chemicals and petrochemicals is globally the industrial sector with the highest energy demand, accounting for approximately 10% of total final energy consumption and almost 30% of industrial final energy consumption. The chemical sector is also the largest industrial consumer of both oil and gas, accounting for 14% and 8% of total primary demand for each fuel respectively[123]. The Chemical Industry is unique as about half the sector's energy input is not combusted but is consumed as feedstock i.e. as raw material for production of other products. The other half is used to provide direct heat, steam and electricity to drive the sector's processes. Consequently, emissions from chemical industry, can be classified into process related emissions (emissions resulting from the use of chemicals as feedstock) and energy related emissions. Total CO_2 emissions from the chemical sector are approximately 1.5 $GtCO_2$ per year globally, or 18% of industrial CO_2 emissions. 85% of the total emissions originate from the energy related use and the remaining 15% is from the process related emissions. It should also be noted that chemical feedstock usage accounts for 600 Mtoe of energy usage[124] which is the equivalent of 1,8 Gt CO_2 if burned[125].

Despite the substantial complexity of the chemical sector, only seven primary chemicals - ammonia, methanol, ethylene, propylene, benzene, toluene, and mixed xylenes – provide the key building blocks on which the bulk of the chemical industry is based. These primary chemicals account for approximately two-thirds of the sector's total consumption of final energy products

Potential abatement options

The energy related emissions for the Chemical industry are expected to be transformed in similar ways as the electricity sector, through efficiency increases, using renewable electricity for covering the heating and power needs. Cases where the fossil fuels are used as feedstocks for their carbon and hydrogen content, alternative sustainable sources are needed. Biomass and recycling of waste could provide valuable contributions, however these can't supply the volumes that are required. Hence powerfuels (E-chemicals) are required in the long-run to replace the fossil fuel use in the feedstock applications of fossil fuels. Of particular mention are Power to Methanol and Power to Ammonia processes which directly replace the present use of natural gas in these applications[126].

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[120] (IEA, 2015, pp. 94–95)
[121] (World Steel Association, 2018, p. 10)
[122] (Strategieplattform Power-to-Gas, 2018a)
[123] (IEA, 2018b, p. 27)
[124] (IEA, 2018b, p. 28)
[125] Own calculation, based on naphtha, emission factor 73,3 tCO_2 /TJ, UBA-Emissionsfaktoren https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/co2_ef_2018_komplett.xlsx
[126] (IEA, 2017)

Pilot projects

- Power to Ammonia[127]
- Power to Methanol[128]

Barriers

Technologies for power fuel production (electrolysis, carbon capture) are evolving and there is huge potential for cost reduction through economies of scale. The time taken for this process depends on the intensity and extent of the regulatory frameworks. Even in the most optimistic scenarios it is expected to take till 2030 when these technologies are cost competitive and mature. Production of e-chemicals requires water, CO_2 source and renewable electricity at the same site, without which significant transport infrastructure/costs are required. Utilising same water sources as the general public, especially in areas of water shortage could create local acceptance issues.

5.3 Energy Sector

5.3.1 Electricity

Global GHG emissions/consumption of fossil fuels and sources of emissions

In an industry that continues to see rapid growth due to the its demand as an end use final product, the current landscape of electricity generation supply has seen a shift towards renewable technologies. Keeping this in mind however, fossil fuels continue to be the major supplier for to generate electricity accounting for 65% of the overall share.[129] Hence, the greatest source of GHG emissions comes from the power sector accumulating to a touch over 40% of total energy related GHG emissions[130]. Furthermore, from a consumption standpoint, growth will continue to try and meet the demands of households and industry over the next twenty five years.[131]These statistics alone bring reasoning as to why electricity and the power sector continues is a focal point for limitations surrounding the Paris Agreement Goals.

Potential abatement options

Possible abatement options in both the electrical and power sector involve looking at many different components such as; switching the generational supply from coal to gas, increasing power plant efficiency by improving technological components within the generation phase or using renewable energy supply for the generation of electricity. Regarding the first two proposals, switching from coal to gas or improving power plant efficiency has cost benefits as it is quite cheap to switch sources and improve efficiency, however when looking at increasing de-fossilisation processes, with the most up to date technology available, this is quite limited. From a political lens, there are measures found at on all levels of governance which see appropriate measures to reduce greenhouse gas emissions whilst producing electricity. These include:

- Emissions Trading Schemes

[127] (Institute for Sustainable Process Technology (ISPT), 2017)
[128] Carbon Recycling International – George Olah Plant in Iceland.
[129] (IEA, 2018d, p. 281)
[130] (IEA, 2018d, p. 319)
[131] (IEA, 2018d, p. 279)

- Green Certificates
- Carbon Taxes
- Voluntary Industry specific agreements

Whilst in recent years, there has been a shift to electricity providers using renewable energy sources, the hard facts are that renewable energy systems are getting cheaper. There are however further variables that need to be addressed. These include peak generation times with wind and PV, and how region also influences these peak figures. This is where powerfuels could step in and be a solution to such a variable as there is a need for dispatchable power generation. Due to the fact powerfuels are chemical energy storage, they have the capacity to provide dispatchable power generation.

Possible applications for powerfuels

Two pilot projects are currently live within Europe. First, Uniper SE has the Falkenhagen demo project producing power-to-hydrogen and power-to-methane. This is the first project in the world which is known for creating and storing gas from wind energy. Uniper SE claim the plant is capable of generating around 360 Nm^3/h of hydrogen by means of electrolysis and fed via a 1.6 km hydrogen pipeline into the gas grid operated by ONTRAS Gastransport GmbH, where the energy is available to the electricity, heating, mobility and industrial market as and when required, just like normal natural gas.[132]

Second, the Magnum project in the Netherlands is currently testing hydrogen use through means for power generation. A €1bn contract to the Mitsubishi Hitachi Power Systems (MHPS) was awarded by the previous owners Nuon to construct the gas-fire part of the power plant. Due to first failings with the operational factors by Nuon, MHPS has aligned with subcontractors to execute and manage the entire project. Whilst the hydrogen is planned to be blue hydrogen (SMR+CCS), it allows for the foundations to feed into a singular power-to-hydrogen unit.[133] This project like the Falkenhagen project is of small scale as production capacity is about 1.2MW. Whilst the foundations are being put forth by a small number of companies, it is vital for powerfuels to have more projects on the ground as soon as possible to further validate the necessity for everyday use.

Barriers

Within the electricity sector, barriers arise from the fact that the power market is a commodity market, hence they are homogeneous goods with high competition for low prices. From this, power generation using power-fuels is rather expensive. It will be "in the market" most likely targeting deep de-fossilisation scenarios due to its potential, but it will be indispensable and required in large volumes to balance renewable power and provide secure energy supply. The challenge is to bring a product to the market where there is the demand for a large scale project by 2050. In the current context to which this could be a possibility. The question is how to scale those technologies quickly enough to serve our needs by 2050.

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[132] (Uniper, 2019)
[133] (Power-Technology, 2019)

5.3.2 Oil & Gas industry

Oil & Gas is the main fossil raw material source for the industries discussed above (mobility, industries, heating & cooling, chemicals etc.). Moving from these fossil based sources to powerfuels is also beneficial for several reasons apart from achieving the GHG goals.

Infrastructure Utilisation

The general value chain of the Oil and Gas industry is shown in the flow chart below left hand side. Of these various steps, some are also relevant for powerfuels (highlighted in the black box). Exploration, Production are very specific to oil & gas deposits and hence the infrastructure and technologies here cannot be utilised for powerfuels. The refining, transport, storage and distribution infrastructure on the other hand can be directly used for powerfuels instead of fossil fuels with minimal modifications (Hydrogen is already injected into the natural gas grid in Germany and there are proposals to convert parts of the natural gas grid to transport only hydrogen[134]). Oil and gas is an internationally widely transported commodity. So the core competency of companies that operate in these areas of the value chain could be directly used for power fuel transportation. This cross utilisation of existing infrastructure built for the fossil based systems in the future by power fuel systems would be economically beneficial.

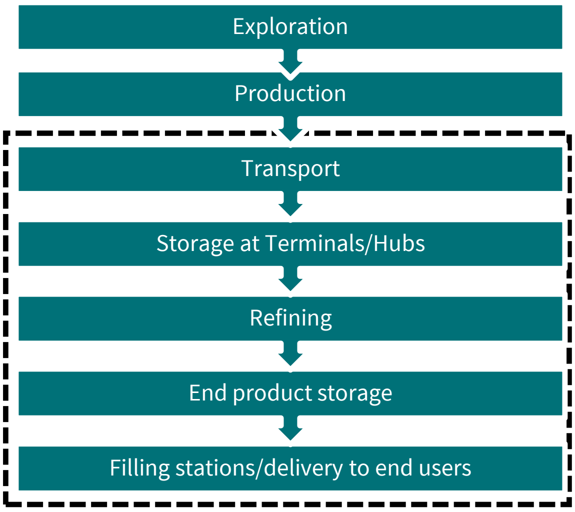

Figure 16: Simplified representation of oil & gas industry value chain.

Strategic next step

For the oil and gas majors the primary source of revenue today is naturally from the sale of oil and gas. The availability of oil reserves that are easily extractable (typically onshore based) are reducing. Extracting oil and gas from offshore fields is costlier than onshore fields thus resulting in increasing costs for oil and gas production[135]. From a long-term strategic perspective this is not sustainable from both economic and environmental perspectives.

[134] (Amprion and Open Grid Europe, 2019)
[135] (Shell, 2018, p. 35)

In the future, powerfuels could replace fossil fuels in several applications as discussed above. So the core competency of oil majors would not be enough to sustain in the future when they compete with powerfuels. Companies like Shell have realised the need for strategic transformation and have become active in other energy areas through its ventures initiative[136] and by acquisition of promising energy companies like Sonnen. Statoil was rebranded as Equinor in order transition from an oil and gas company to an energy company thus focusing on long term sustainability. 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 which would still be relevant for powerfuels. Involvement of multiple oil majors in pilot power-to-hydrogen projects could be seen as a step in this direction.

[136] (Shell, 2019)

6 Call for discussion

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 non-dispatchable nature of renewable energy sources like wind and solar.

We consider powerfuels to provide value for different countries in different ways either as powerfuel suppliers or technology providers or as green alternative for fossil-fuel import dependent countries. We see the need for an international powerfuels market where all countries could benefit and at the same time move towards climate change mitigation goals.

The development has already started

We observe a lot of movement throughout the world. Countries and industries in the fossil export 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 and diverse technologies and possibilities are being emphasized (example: hydrogen, ammonium, ethanol, synthetic natural gas). At the same time first international cooperation are taking place, for example trade of “solar fuel” between Japan and Australia.

Get in touch

By sharing our vision through this paper, we want to enable an international discussion on the different ideas, strategies and possibilities of global markets for powerfuels. We would like to call for your participation in this discussion. There are several opportunities to get in touch with us:

- Let us know what powerfuels mean for you:
    - What role could powerfuels play for the energy transition in your country/industry?
    - How do you compare the potential of importing/exporting powerfuels with respect to the import/export of fossil fuels to/from your country?
    - What are the specific technologies, fuel types and usage possibilities you primarily see for powerfuels?
    - What are the current political strategies, incentives or hurdles that are impacting the development of powerfuels in your country?
    - What timeframe do you envision for the development of a market for powerfuels in your country?
- Visit us at www.powerfuels.org and take part in the online discussion about this document.
- Attend one of our events.
- If you are interested in becoming a 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.

List of figures

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