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## Replacing NATO F-34: Technologies and economic aspects of using secondary carbon sources for Power-to-Fuel production

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## Replacing NATO F-34: Technologies and economic aspects of using secondary carbon sources for Power-to-Fuel production

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### Abstract

The burning of fossil carbon based fuels – of which NATO F-34 is one - contributes significantly to global warming, ground-level ozone building and health hazards. Several NATO members actively strive to reduce the negative environmental impacts of their military activities while ensuring energy security for their forces. High priorities have the substitution of fossil fuels and the reduction of primary carbon sources for fuel production. Power-to-Liquid technologies can use synthetic gas to produce a vast array of organic components, which can be further processed to synthetic fuels of great purity. Synthetic gas is a mixture of hydrogen and carbon monoxide. Combining hydrogen derived from electrolyzers powered by electricity from renewable sources with carbon monoxide derived from non-fossil carbon dioxide sources, can make a contribution to reduce environmental and health hazards.

Hydrogen production from electrolyzers is a well-established technology on industrial scale. Carbon dioxide capture from point sources is established, but not widespread. Retrofitting of existing plants is possible when emitted flue gases are treated. Retrofitting is more difficult when the carbon dioxide accumulates in early productions steps. A wide array of possible carbon dioxide point sources from industrial processes with high concentrations and purity is described. In contrast, carbon dioxide capture from ambient air is in early development stages and not a mature technology yet. Finally, the technologies for the production of synthetic fuels are well known.

The main cost drivers of Power to Fuel are the costs of electricity since electrolysis and carbon dioxide capture technologies have high energy demands. Availability of cheap electricity supply from renewable sources is a key factor for reducing the costs. The costs decrease with the maturity of the production technology used and with the yearly running time of the installation. Comparisons between e.g. geothermal/hydro power in Iceland and solar/wind farms in the global Sunbelt show, that production costs in Iceland are the lowest. This reflects the mature technology and the full use of production capacity. However, currently even the lowest Power to Liquid production technologies and production sites are at least twice as expensive as fossil-based fuels.

The article gives an overview on carbon dioxide capture technologies from point sources and ambient air as well as cost estimates of several combinations of Power to Liquid (PtL) technologies and production locations.



## Introduction

In 1998 NATO agreed to use F-34 (NATO Code) as the main liquid fuel<sup>40</sup> for military aviation, ground based tactical vehicles and generators. F-34 is a kerosene and therefore fossil carbon based liquid fuel known internationally also as J-8 in military aviation. It is chemically also very similar to the civil aviation fuel type A-1<sup>47</sup>. The chemical properties are described in the NATO Logistics Handbook from 1997<sup>40</sup> as well as in data sheets of industrial suppliers<sup>47</sup>. F-34 fuel is currently widely used for aviation within NATO forces and can be easily transformed using some additives in the field to diesel fuel for trucks and generators. Up to date F-34 is almost exclusively produced from crude oil which is a “primary” fossil source, indicating that the carbon comes direct from mineral oil or gas extraction. In operation NATO forces equipment inevitably releases carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matters (PM) and unburned volatile organic components (VOC’s) during operation of their equipment causing environmental pollution. Also, CO<sub>2</sub> and NO<sub>x</sub> exhausts contribute to atmospheric warming<sup>36</sup> and in consequence to climate changes while NO<sub>x</sub>, PM and VOC’s do have substantial ground-level ozone (O<sub>3</sub>) building potentials harming human health (O<sub>3</sub>)<sup>11,26</sup>.

NATO forces are an integral part of democratic societies and have to adhere to environmental standards set by their governments for protecting the health and wellbeing of their population. Consequently, NATO members actively strive to reduce the negative environmental impacts of their military activities while maintaining combat readiness and ensuring energy security for their forces. High priorities have the substitution of fossil fuels used by NATO forces with more environmentally friendly, cleaner fuels and the reduction of primary carbon sources for fuel production. Technological options to achieve these goals were investigated as far back as 2007<sup>41</sup>.

The most pressing environmental problem for our societies as well as for our armed forces are the currently increasing global temperature with all its negative consequences like rising sea levels melting of the permafrost areas and changing weather patterns with more droughts and severe storms. Stabilising the mean global temperatures at 2 °C above the preindustrial values is one of the main goals of the international community. The most important greenhouse gas (GHG) responsible for atmospheric warming is CO<sub>2</sub> originating from burning of fossil fuels and industrial processes<sup>36</sup> Not setting it free, or at least reusing it for fuel production from so called “secondary carbon sources” like the atmosphere or industry and converting it by means of renewable energy into fuel would be a major achievement in combatting global warming.

This article provides an overview of available power-to-liquid technologies and the steps involved to produce liquid fuels for replacing fossil carbon based F-34 and diesel for propulsion and transportation purposes. We will look at technologies for producing liquid fuels from CO<sub>2</sub> and electricity as well as technologies for capturing CO<sub>2</sub> from air streams. Furthermore, this article identifies the most promising places to do so with respect of costs, geographic regions and promising secondary CO<sub>2</sub>-sources.



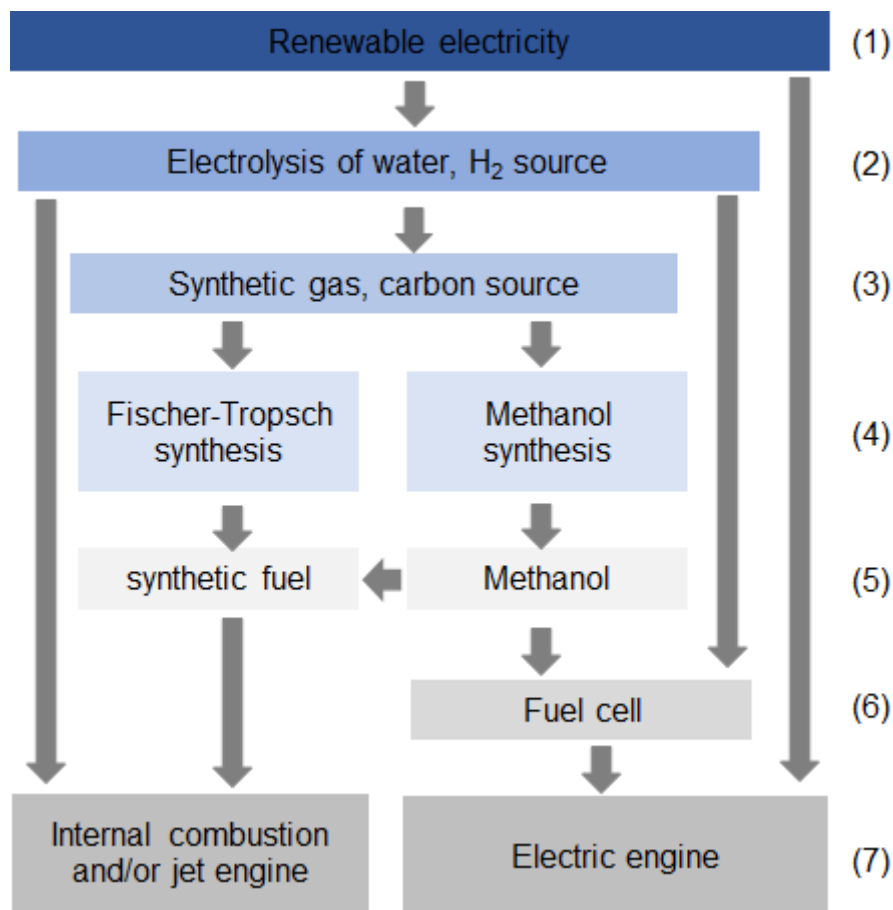


**Figure 1:** Fuel truck of the French Army Corps d' Essence in a field camp in Niger loaded with NATO F-34 fuel. The fossil carbon based F-34 is currently the standard liquid fuel for military aviation and also the basis of truck diesel in NATO forces.<sup>45</sup>

## 1 Power-to-liquid

The use of electricity from renewable sources and non-fossil CO<sub>2</sub> is called Power-to-X (PtX) technology while Power-to-gas (PtG) summarises technologies for producing gaseous components which contain hydrogen (H<sub>2</sub>) from electrolyser technologies<sup>38</sup>, liquefied ammonia (NH<sub>3</sub>) and methane (CH<sub>4</sub>) as secondary products. Power-to-liquid (PtL) technologies are used to produce carbon-based liquid fuels for the transportation sector, mainly for usage in jet engines or internal combustion engines ("Diesel and Otto type engines"). For PtL two main commercial processes are in use. a) Liquefaction of gas from a PtG process, mainly using methane CH<sub>4</sub>. Since liquids are easier to handle in transportation and storage they are preferred over gases. The additional energy needed for liquefaction generally outweighs the advantages of liquids. Liquids have a higher energy density compared to gases and require less safety measures as well as less storage space than gases. (b) Synthesis of liquid components on the basis of synthesis gas (syngas). These technologies often result in a mixture of different components, depending on the conditions of the reaction and the catalyser used, and need further refinement processes<sup>50</sup>. Power-to-fuel (PtF) summarises PtL and PtG technologies.

The main production steps, inputs, uses and engine types for PtF products are shown in Figure 2<sup>23,39</sup>. Electricity from renewable power sources mainly originates from solar, wind or hydropower plants (1). Electric energy can be used for charging the batteries of electric engines (7) or for hydrogen ( $H_2$ ) production (2)<sup>20</sup>. Hydrogen can be used directly in fuel cells (6) which drive electric engines (7) or for producing syngas which may be used for methanol synthesis with high yields of pure methanol (4, 5)<sup>14,28</sup>. Methanol can be used in fuel cells (6) providing power for electric engines (7) or it can be added to the products of Fischer-Tropsch-reactions (4) and processed to fuels (5). Feeding syngas into Fischer-Tropsch-reactors results in a mixture of short-chained, oxygen free, saturated and unsaturated aliphatic hydrocarbons<sup>14,28</sup>. Depending on the conditions in the reactor (temperature, catalyser) low boiling fractions (gases) or middle boiling fractions (petrochemicals) and waxes are formed<sup>14,21</sup>. Petrochemical fractions can be processed in the same ways as the analogous fraction from fossil carbon sources. Each conversion step from (1) to (7) results in a new product and inevitably in a loss of free (i.e. usable) energy.



**Figure 2:** Schematic of the most common power-to-fuel (PtF) production pathways and the usage of the products for mobility at different stages. (1) Electricity production from renewable sources. (2) Electrolysis of water, production of hydrogen ( $H_2$ ). (3) Production of synthetic gas (syngas) with  $H_2$  and  $CO_2$  from non-fossil sources. (4) Reactors for the synthesis of organic compounds. (5) Main product of the chemical reactions in (4). (6) Fuel cell for electricity production. (7) Engine technologies useable for different types of fuels. Electricity from the producing plants can be used directly in electric engines.  $H_2$  can be used in fuels cells, which power electric engines or directly in internal combustion engines. Modified after<sup>23,39</sup>.

Several fuels types for use in different types of engine technologies can be obtained from PtF processes (Figure 2). In this article we focus on liquid fuels for internal combustion engines and jet engines. As mentioned before, whether or not a PtF process is CO<sub>2</sub>-neutral - adds primary fossil CO<sub>2</sub> to the atmosphere - is defined by the carbon source of the syngas used.

**Second law of thermodynamics and total degree of efficiency:**

According to the second law of thermodynamics, each physical or chemical process results in free (i.e. usable) energy losses. Free energy is the amount of energy available to perform work. This concept is known as “entropy”. Each energy transformation process inevitably leads to substantial losses in free energy<sup>23,32</sup>. The least efficient processes transforms chemical energy into kinetic energy (e.g. combustion of fuels in internal combustion engines).<sup>10</sup> All efficiency rates in this chapter are calculated with respect to the electricity produced in a electricity producing plant. With respect to PtX in cars the most efficient transformation is the direct use of electricity from a battery with an electric motor resulting in a conversion efficiency of 69%<sup>23</sup>. The usage of electricity to produce H<sub>2</sub> and its subsequent use in a fuel cell has an efficiency of 26 %<sup>23</sup>. The lowest efficiency (13 %) has the synthesis of liquid fuels for use in conventional internal combustion engines<sup>23</sup>. See Figure 3. The possible use of intermediate energy forms is shown in Figure 2.

A) Electric car, battery	B) Electric car, fuel cell	C) Car, internal combustion engine	
Renewable electricity (100%)	Renewable electricity (100%)	Renewable electricity (100%)	(1)
Transmission network (95%)	Transmission network (95%)	Transmission network (95%)	(2)
	Electrolyser (70%)	Electrolyser (70%)	(3)
		Power-to-liquid (70%)	(4)
	H <sub>2</sub> compression/transport (80%)	Transport (95%)	(5)
Battery (90%)	Fuel cell (60%)		(6)
Electric engine (85%) mechanics (95%)	Electric engine (85%) mechanics (95%)	Internal combustion engine (30%) mechanics (95%)	(7)
Total degree of efficiency: 69 %	Total degree of efficiency: 26 %	Total degree of efficiency: 13 %	(8)

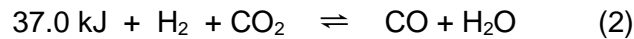
**Figure 3:** Total degrees of efficiencies for cars powered by A) electric engine and battery, B) electric engine and fuel cell and C) internal combustion engine. Each thermodynamic process is coupled with an energy loss in terms of energy able to perform work. (1) Electricity produced in the plant is given as 100%. (2) Transmission of electricity in networks. (3) Electrolysers producing H<sub>2</sub>. (4) PtL processes. (5) Transport and transport related processes. (6) Electricity production and provisioning. (7) Engine technology and losses due to mechanics. (8) Total degree of efficiency on the basis of the electricity produced in the plant (1). All degrees of efficiencies are given as percentage of usable free energy relative to the initial energy content. Modified after<sup>23</sup>.

## 2 Syngas in power-to-fuel processes

Syngas is the key to all industrial technologies for producing liquid fuels, either in PtL or in conventional processes and it is used as a chemical base material in industrial processes since the begin of the 20<sup>th</sup> century. Syngas is predominantly produced from fossil natural gas or by thermal cracking of coal<sup>14,28</sup>. It contains of a mixture of carbon monoxide (CO) and H<sub>2</sub><sup>14,28</sup> and is used as hydrogen and/or carbon source (see equation 1).



Syngas can also be produced by the reverse water-gas shift (RWGS) reaction, using CO<sub>2</sub> and H<sub>2</sub> in fuel cells. RWGS is not yet a mature technology but a few demonstration plants already exist worldwide and research and development efforts intensified in the past years.<sup>32,42,49</sup>



The RWGS technology is crucial for CO<sub>2</sub>-poor or -neutral PtL production because secondary carbon sources (carbon from previously emitted CO<sub>2</sub>) can be used instead of fossil sources such as natural gas, coal or oil. CO<sub>2</sub> molecule could be used even several times, when cascade use is applied. The necessary technologies for capturing already emitted CO<sub>2</sub> for PtL processes will be described in the following chapter.

## 3 CO<sub>2</sub> capture technologies from secondary carbon sources and further processing

CO<sub>2</sub>-emissions and -concentrations are monitored and controlled in a wide range of environments due to its toxicity to humans<sup>18</sup>. Many countries e.g. Germany - as well as other countries - define a maximum of 5 000 ppm (0.5%) of CO<sub>2</sub> in the atmosphere as mean daily exposure allowed at human workplaces<sup>17</sup>. This threshold value is only about 12 times higher than the actual ambient air concentration<sup>13</sup>. Therefore, CO<sub>2</sub> is not only a problematic greenhouse gas but also potentially toxic in handling for workers, consumers and citizens living in close proximity of CO<sub>2</sub> handling plants

Industry is one of the main producers of carbon emissions (mostly flue gases) next to transportation and heating, Flue gases originate from industrial high temperature combustion processes e.g. from blast furnaces in the iron and steel sector while waste gases originate from small scale processes e.g. internal combustion engines in cars or biological processes e.g. biogas plants. Both, flue and waste gases vary greatly in chemical composition and their concentration in the gas mixture. For capturing CO<sub>2</sub> for PtL from such emitted gases, its concentration in the flue or waste gas is important. The higher the concentration, the simpler the technology applied and the lower the production costs (see Table 2).

The actual global ambient air concentration of CO<sub>2</sub> varies around 405 ppm (0.04%)<sup>13</sup>. In contrast, flue gases may contain up to 30% CO<sub>2</sub> and waste gases even up to almost 100% CO<sub>2</sub>, which makes both valuable CO<sub>2</sub> sources<sup>32</sup>. Several techniques and technologies for CO<sub>2</sub>-capture from such high concentration point sources as well as from ambient air have been introduced. Some of them are mature, others are in pilot or demonstration phase<sup>46</sup>. With respect to the politically demanded mitigation of global warming, CO<sub>2</sub> capture from both, point



sources and ambient air must be considered. CO<sub>2</sub>-capture from large industrial point sources is attractive but not 100% efficient. To capture the CO<sub>2</sub> emissions from the multitude of small emitters such as private and public transportation and heating or agriculture is impractical<sup>25</sup>. The third option, CO<sub>2</sub>-capture from ambient air is called direct air capture (DAC) and several technologies exist at early commercial stages<sup>25</sup>. All carbon capture technologies require energy input, which lowers the efficiency rate of the main PtL process<sup>30</sup>. An overview of available carbon capture options is presented in Figure 4.

### 3.1 CO<sub>2</sub>-capture from point sources

In order to obtain CO<sub>2</sub> from point source flue or waste gases, three principal separation techniques and several technologies exist. For choosing the best technique and technology, the technical details of the plants, other toxic components in the flue/waste gas, which needed treatment as well as possible nearby uses of the captured CO<sub>2</sub> need to be considered. Some CO<sub>2</sub> capturing technologies are used in several separation techniques, as the chemical or physical principals are the same.<sup>30,46</sup> Typically, CO<sub>2</sub> capture rates from the flue/waste gas point sources are within the range of 50-94 %<sup>25</sup>.

#### *Post-conversion capture*

Post- conversion capture, in power plants also known as post-combustion capture<sup>30</sup>, involves the separation of CO<sub>2</sub> from flue/waste gas streams after the conversion of the carbon source to CO<sub>2</sub>. This technique is used in natural gas and coal power plants, during the production of ethylene oxide, in the iron or steel production as well as in the cement industry and during biogas sweetening (technical term for the removal of acid gaseous components or their precursors which cause corrosion, e.g. CO<sub>2</sub> and H<sub>2</sub>S). As shown in Figure 4 various technologies are available, but most commonly used is the adsorption by chemical solvents or in some cases by solid materials (often called filters, which they aren't in a chemical sense). Some techniques require heat for the regeneration of the solvent, therefore they are best suited for plants with a potential for recoverable heat either from the main process or from nearby providers. Post-conversion capture techniques represent the most mature technologies and are in use since 1990. Retrofitting of existing plants for post-conversion CO<sub>2</sub> capture is an-add on technology and can be done easily.<sup>9,30,46</sup>

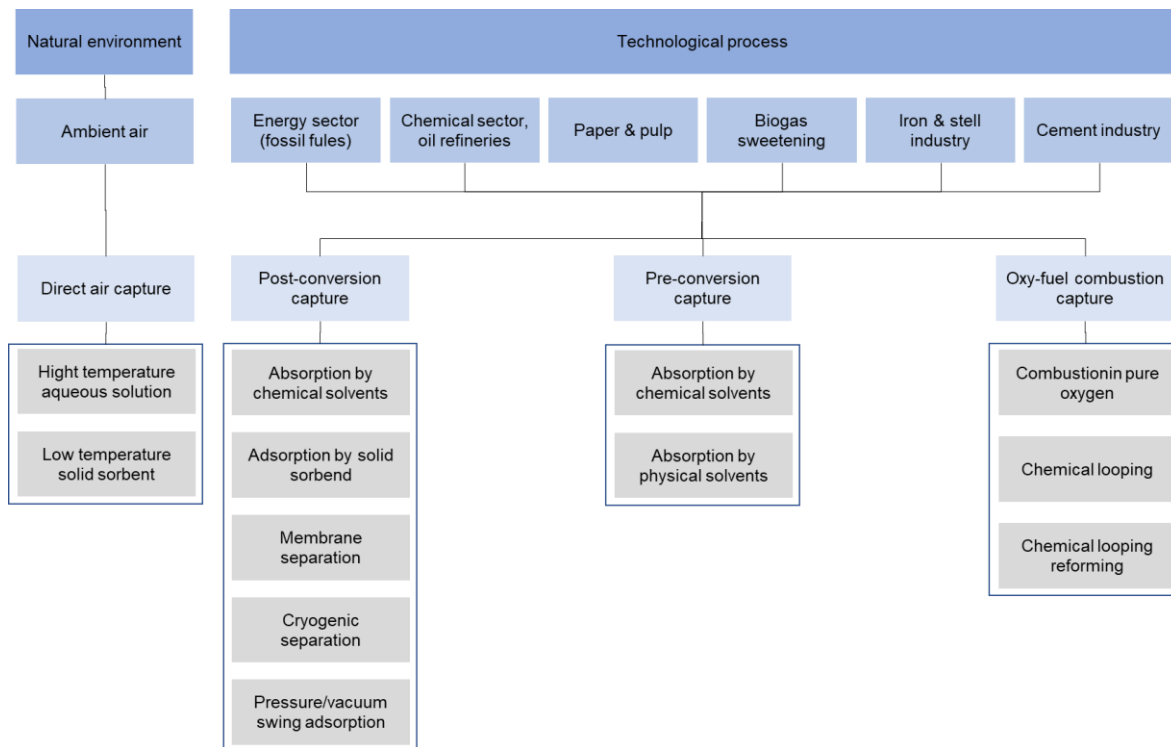
#### *Pre-conversion capture*

Pre-conversion capture, also known as syngas/hydrogen capture<sup>30</sup> refers to capturing CO<sub>2</sub> which was generated as an undesired co-product of an intermediate reaction during a conversion process. It is most common in steam methane reforming (SMR) when only the hydrogen is needed, e.g. for ammonia production. Chemical and physical adsorption technologies are in use. Retrofitting of existing plants is difficult as it requires drastic changes in the power supply and the main industrial process itself.<sup>30,46</sup>

#### *Oxy-fuel combustion capture*

As the name suggest, oxy-fuel combustion can only be applied to processes involving combustion processes, e.g. power generation in fossil-fuelled plants or in the iron and steel and the cement industry. Since pure oxygen (O<sub>2</sub>) is used for the combustion process and nitrogen from ambient air is absent, no toxic combustion products like NO<sub>x</sub> are produced. The CO<sub>2</sub>-concentration in the resulting flue gas is highly enriched. Pure oxygen is an expensive feedstuff and the production via liquefaction of air is an energy intensive process, in which CO<sub>2</sub> may be released, depending on the energy source<sup>28</sup>. Retrofitting of existing plants is difficult as it requires drastic changes in the power supply setup and the industrial process itself.<sup>30,46</sup>





**Figure 4:** Overview of available CO<sub>2</sub>-removal (carbon capture) techniques from ambient air (top left) or from products of technological processes like waste gases or flue gases (top centre and right). Modified after<sup>25,46</sup>

### 3.2 CO<sub>2</sub>-caputre from ambient air

Direct air capture is a new technique, with very few existing plants in industrial production<sup>24</sup>. Two main technologies are discussed and tried: (a) high temperature aqueous solution (HT) and (b) low temperature solid sorbent (LT) technology. HT technologies use chemical reactions to absorb CO<sub>2</sub> while LT technologies use physical adsorption. Both technologies are analogue to pre- and post-conversion technologies for point sources<sup>25</sup>. Plants for DAC can be built virtually anywhere, but the required area for such installations is considerable. For DAC plants to operate without noticeable depletion of the ambient CO<sub>2</sub> concentration in the vicinity, about 25 km<sup>2</sup> of area per one MtCO<sub>2</sub> capture per year are needed. Therefore, such plants are more likely to be built in rural or remote areas. Modell calculations show, that CO<sub>2</sub>-depletion in ambient air caused by DAC around the plants – with the resulting decrease in efficiency rates – should not be problematic for adjacent vegetation and the DAC plant itself<sup>25</sup>. Both technologies share a considerable energy demand, moving air through the capture units by fans. When operated with electricity obtained from fossil fuels, the CO<sub>2</sub>-capture efficiency is considerably decreased. Optimal scenarios use energy from renewable sources<sup>25</sup>. Depending on the technologies used, considerable amounts of (a) water, which could be provided by desalinations plants or (b) low-grade heat are needed. Cheap and environmentally friendly produced heat could be provided as waste heat from nearby plants or by heat pumps<sup>23,25</sup>.

**Table 1:** Annual CO<sub>2</sub> fixation capacities (tons per hectare) for natural terrestrial vegetation, oceans, and industrial (DAC) systems.

\* Terrestrial global surface is 151.2 x 10<sup>6</sup> km<sup>2</sup>, ocean surface 361.9 x 10<sup>6</sup> km<sup>2</sup>.

\*\* Uptake rates for vegetation indicate net primary production (NPP) expressed as carbon equivalents (CO<sub>2</sub>) fixed by photosynthetic uptake; for ocean surfaces it is the two-way gross exchange of CO<sub>2</sub> between the atmosphere and ocean surface and for DAC the uptake capacity of a plant with a 25 km<sup>2</sup> footprint.

	<b>Process</b>	<b>CO<sub>2</sub> uptake</b> [t CO <sub>2</sub> / ha year]
Temperate forests** <sup>29</sup>	Photosynthesis	23
Tropical rain forests** <sup>29</sup>	Photosynthesis	29
Croplands (Agriculture)** <sup>29</sup>	Photosynthesis	16
Sugarcane plantation (Maximum yield)** <sup>15</sup>	Photosynthesis	433
Ocean surface, global average <sup>29</sup>	Solution in water	9
Terrestrial surface, global average <sup>29</sup>	Photosynthesis	15
Direct air capture (DAC) plants** <sup>25</sup>	Physical/chemical process	approx. 400

### 3.3 Further processing

Depending on its further uses, the captured CO<sub>2</sub> has to be further purified. The captured CO<sub>2</sub> gas has to be dried and poisonous and/or corrosive components like H<sub>2</sub>S or radon have to be removed below the threshold values given by local legislation. Highest purity grades (>99% CO<sub>2</sub>) are needed for medical (e.g. endoscopy) and foodstuff (e.g. sparkling beverages) applications. Lower purity grades are acceptable for cooling, welding or for fire extinguishers. Even lower grades can be used in carbon storage projects. Depending on its use and scale of demand, CO<sub>2</sub> is handled and delivered in three states of aggregation. For cooling purposes, it is used as a pre-cooled (below -78.5 °C) solid block, known as dry ice. For all other uses, the scale of the demand determinates the state during transport. Small scale consumers use pressurized cylinders or tanks where the CO<sub>2</sub> is in liquid phase. It expands into a gas during the release from the vessel. Big scale consumers use pipelines in which the CO<sub>2</sub> is transported as a gas. Several thousand km of CO<sub>2</sub>-pipelines in various countries are already in use.<sup>8,9,33</sup>

## 4 Secondary carbon sources

Since the industrial revolution, fossil fuels are the primary energy source for mobility, transport, electricity production and heating. Fossil carbon serves also as raw material for the industry, the service and the agricultural sector, government and private households. All carbon releasing or emitting processes, including their waste and by-products, are valuable point sources of secondary carbon. An overview of major point sources is given in the following chapters (Table 2).

### 4.1 CO<sub>2</sub>-capture from fossil sources

Considerable amounts of CO<sub>2</sub> are being set free during the production of base chemicals for the chemical industry via the synthesis from syngas<sup>14,28</sup> and subsequent stages of production. Syngas contains of a mixture of carbon monoxide (CO) and H<sub>2</sub><sup>14,28</sup> and can be used as hydrogen and/or carbon source (see equation 1). The bulk of the annual world production is generated by gasification of coal, oil or natural gas. Several pathways of CO<sub>2</sub> emissions are possible: (a) As a waste- and/or by-product in the syngas production or the following processes producing base chemicals. The multitude of these processes and products are termed “chemicals and petrochemicals” and “coal to chemicals (gasification)” in Table 2. (b) During the syngas production when H<sub>2</sub> is needed e.g. for petrochemical processes or NH<sub>3</sub>

production<sup>28</sup>. In this case CO<sub>2</sub> is a waste product. NH<sub>3</sub> is a base chemical for organic and inorganic synthesis. Processed to ammonium (NH<sub>4</sub><sup>+</sup>) it is used in fertiliser production<sup>28</sup>. Oxidised to nitric acid (HNO<sub>3</sub>) and added to glycerine the explosive nitro-glycerine is formed<sup>14,28</sup>. When NH<sub>3</sub> is further processed to urea and when done at the same plant, CO<sub>2</sub> emissions do not occur, as the CO<sub>2</sub> from the syngas is used as the carbon source<sup>14</sup>.

Ethylene oxide is a chemical base material used in a multitude of organic syntheses. Most of the products are then base materials themselves. About 80% of pure ethylene oxide is formed by the oxidation of ethylene at ca. 250°C and at pressures between 1 – 2 MPa using silver as catalyst, the rest of 20 % CO<sub>2</sub> is formed as waste gas.<sup>14</sup> Ethylene oxide is a precursor in the production of the toxic mustard gas (known as Yperite or LOST)<sup>14</sup> and often not freely tradeable to foreign countries, depending on local laws.

Dry natural gas in pipeline quality is required for many industrial and private uses. Natural gas from wells typically is a mixture of methane and several other, sometimes toxic or radioactive components, being gaseous, liquid or even solid. It may contain inorganic gases e.g. CO<sub>2</sub>, hydrogen sulphide (H<sub>2</sub>S) and radon, organic gases e.g. ethane, propane as well as mercury, water and organic liquids as hexane. Some of these components are of economic value and are further processed or sold while CO<sub>2</sub> is separated from the raw gas by chemical absorption in amines or by membrane technologies as described in chapter 3.1.<sup>9</sup>

The smelting and reduction of iron ore during iron and steel production can be performed with coal or with electricity. Electricity is used in countries with no natural coal deposits or abundant and cheap electricity supply. Coal fired blast furnace processes are the main technology. The production of one ton of iron consumes - among other things - about one ton of coke and releases seven tons of hot blast furnace gas. Furnace gas contains – among other components – about 25–30 % CO, 10–16 % CO<sub>2</sub>, 1–5 % H<sub>2</sub> and 0–3 % methane.<sup>28</sup> The European Union is presently funding a research project which captures CO<sub>2</sub> and H<sub>2</sub> from a steel production site in Sweden to produce methanol which is used as fuel in a ferry commuting between Gothenburg, Sweden and Kiel, Germany<sup>34</sup>. In Iceland methanol is produced from CO<sub>2</sub> and electricity from geothermal sources (Figure 5)<sup>19</sup>.

Cement contains 58–66 % of calcium hydroxide (Ca(OH)<sub>2</sub>) and is obtained from burning limestone (CaCO<sub>3</sub>) at 900–1000 °C. The heat is normally provided by fossil fuels and additional CO<sub>2</sub> is released during the chemical transformation process.<sup>28</sup> Global cement production is enormous - if the global cement industry would be one country it would be the third largest CO<sub>2</sub> emitter worldwide<sup>12</sup>.

Electricity and heat production from fossil fuels are major CO<sub>2</sub> emitters. Electricity production is normally done at industrial scale, therefore point sources can be accessed easily to provide CO<sub>2</sub> from the waste gas. In contrast, heat production occurs in small and local units and its decarbonisation is a huge challenge, best tackled by the installation of district heating systems or heat pumps run with electricity from renewable sources. District heating systems can be supplemented with waste heat from industrial sources or surplus electricity transformed to heat from fossil or renewable sources<sup>43</sup>.

Electricity consumption of aluminium smelters with fused-salt electrolysis is very high and is accompanied by the emissions from the electricity production. An additional CO<sub>2</sub> source is due to the anodic reaction of the aluminium reduction process, in which oxygen is formed. The anode is made of coal and the oxygen and carbon react to CO<sub>2</sub>.<sup>28</sup>



**Figure 5:** View of the Carbon Recycling International (CRI) plant in Iceland. The electricity is generated from geothermal sources. The carbon dioxide is captured from geothermal sources as well. Both raw materials are synthesised into methanol, which can be used as fuels in internal combustion engines (here as brand name “Vulcanol”), fuel cells and as chemical base material<sup>19</sup>.

## 4.2 CO<sub>2</sub>-capture from renewable or biogenic sources

In Europe bioethanol is mainly produced from grain and to a lesser degree from sugar beets via alcoholic fermentation. With monosaccharides as substrate each molecule of ethanol produced releases one molecule of CO<sub>2</sub>. The CO<sub>2</sub> gas is about 1.5 times heavier than ambient air and accumulates above the fermentation substrate, thus further increasing the fermentation rate. It can easily be recovered in high rates and purity in the fermentation waste gas.<sup>3</sup>

Biogas is produced by bacteria from biomass like corn, waste from the food industry, manure or sewage sludge etc. Biogas is a water vapour saturated mixture of CH<sub>4</sub> (45-65 vol%) and CO<sub>2</sub> as by-product (35-55 vol%). The content of the gas is mainly influenced by the substrate used and the degree of oxidation in the bioreactor. On-site use of biogas requires purification from water and H<sub>2</sub>S. It then can be used in combined heat and power plants. Following further cleaning it can be fed into the natural gas grid.<sup>3</sup>

Paper production is a very energy intensive process. When used paper is processed, printing ink and additives/admixtures have to be removed by floatation techniques (de-inking). The waste of this process is toxic and is often incinerated. When wood or e.g. straw is used, the cellulose for the paper production process has to be extracted which is normally done by boiling the raw material for several hours with added chemicals. Finally, the paper pulp is formed into sheets and actively dried which requires substantial energy input.<sup>6</sup>



**Table 2:** Sources of CO<sub>2</sub>-emissions, total global emission, CO<sub>2</sub> content in the waste gas and costs of carbon capture for several highly CO<sub>2</sub>-emitting processes. Costs are mostly calculated based on models or small prototypes than on long term averaged costs of running plants.

Process	Total global emission [Gt <sub>CO2</sub> /year]	Percentage of CO <sub>2</sub> in gas emitted [%]	Capture cost [US\$/tCO <sub>2</sub> ]
<b>Fossil bases sources</b>			
Coal to chemicals (gasification)	1.20 <sup>35</sup>	98-100 <sup>32</sup>	15-25 <sup>32</sup>
Chemicals and petrochemicals	1.08 <sup>30</sup>		
Ethylene oxide	n.n	98-100 <sup>32</sup>	25-35 <sup>32</sup>
Natural gas processing	n.n.	96-100 <sup>32</sup>	15-25 <sup>32</sup>
Ammonia	n.n.	98-100 <sup>32</sup>	25-35 <sup>32</sup>
Hydrogen	n.n.	30-100 <sup>32</sup>	15-60 <sup>32</sup>
Iron and steel	2.08 <sup>35</sup> 2.32 <sup>30</sup>	21-27 <sup>32</sup>	60-100 <sup>32</sup>
Cement	2.18 <sup>35</sup> 2.24 <sup>30</sup>	15-30 <sup>32</sup>	60-120 <sup>32</sup>
Electricity and heat	15.01 <sup>30</sup>	n.n.	n.n.
Aluminium	0.33 <sup>35</sup> 0.25 <sup>30</sup>	n.n.	n.n.
<b>Renewable/biogenic based sources</b>			
Bioethanol		98-100 <sup>32</sup>	25-30 <sup>32</sup>
Biogas plants		35-55 <sup>3</sup>	n.n.
Paper and pulp	0.22 <sup>35</sup> 0.25 <sup>30</sup>	n.n.	n.n.
<b>Atmospheric sources</b>			
Direct air capture	n.n.	0.4 <sup>13,35</sup>	10-200 <sup>32</sup> 11-395 <sup>25</sup> 100 <sup>24</sup>

## 5 Cost of Power-to-Liquid derived fuels

Crucial to the usage of alternative liquid fuels are their production cost. Fossil fuels are currently at a long term price low<sup>2,16</sup> and difficult to compete with. Transparency of the total production costs and their specific drivers at all production stages is important. The production costs for PtL are subdivided according to the main production steps (Table 3). The specific efficiency rates for each stage of production differ according to the author. The four stages of production of diesel equivalent fuel from PtL processes are shown in Table 3.

The starting point for PtL fuel production is the generation of the electric energy needed. This corresponds to stages (1) and (2) in Table 3C. The next step of the production is the electrolysis of water for H<sub>2</sub> generation corresponding to (stage (3) in Figure 3C). The third stage contains the costs of CO<sub>2</sub> capture, syngas production and Fisher-Tropsch synthesis. These are summarised into costs of PtL at stage (4) in Figure 3C. The last stage is transportation/distribution of the synthetic fuel (level (5) in Figure 3C). All calculations discussed in this article were done under the following three preconditions (if not mentioned otherwise): (a) DAC is used to provide CO<sub>2</sub>. (b) Electricity plants, DAC and PtL are in close proximity to each other. Large networks for delivering power and CO<sub>2</sub> are therefore not needed. (c) Transportation is only needed for the finished fuel product<sup>23,32</sup>.

**Table 3:** Main stages of production of diesel equivalent fuel from PtL processes<sup>23</sup>. For each stage of production, the efficiency is given based on the respective upstream step (third column). Electricity production is defined as 100% efficiency. Total efficiency related to electricity production is given in the fourth column. The main cost driver of the total costs is given in the last column. FLH = full load hours. CAPEX = capital costs. OPEX = operational costs.

Stage of production	Production stage as shown in Figure 3C	Efficiency based on step before [%]	Total efficiency [%]	Main cost driver
Electricity production	1	100		
Transmission network	2	95	95	CAPEX, FLH
Electrolyser	3	70	67	OPEX
CO <sub>2</sub> -capture Syngas Fischer-Tropsch	4	70	47	OPEX
Transportation	5	95	44	OPEX

With respect to PtL processes, all technologies discussed in this paper are not yet in a mature state. The only exception is the production of electricity from geothermal plants and large hydropower dams<sup>48</sup>. Significant cost reduction potentials are predicted for realisation of these not yet mature technologies according to the established theory of the “learning curve” in economic science<sup>22,23,48</sup>. Specific technologic designs will reduce the capital costs (CAPEX) as well as the operating costs (OPEX) for each additional production unit established<sup>51</sup>. As soon as a plant is operative, the absolute amount of CAPEX is defined and can only be changed by a change in technology or an upgraded version of the same technology. In this situation, the costs per unit produced (kWh, H<sub>2</sub>, fuel, transported fuel with respect to the chosen steps of production) directly dependent on the full load hours (FLH) of the installation and the amount of years the plant is in service. The FLH are a measure of the degree of capacity utilisation. The higher the FLH, the lower the CAPEX per unit and therefore the total costs per unit (economy of scales). The more CAPEX intensive a technology, the more important are high FLH to reduce costs. 8 000 yearly hours - out of 8 760 h total yearly hours – are considered a continuous working mode. Electrolysers, PtL-plants, transport facilities and electricity production from geothermal plants, as well as in some cases hydro plants, can technically be run in a continuous working mode.

Continuous electricity production from solar and wind as renewable sources cannot run in a continuous mode without a large storage option. OPEX of electricity producing solar and wind plants are low and basically defined by the maintenance costs of the plants. OPEX for fossil and nuclear plants also contain fuel costs. OPEX in planning and building of the plants and the necessary machinery may vary due to costs for employees, raw material, intellectual property rights etc.. It is important to recognise, that the total costs per unit of the upstream production step is always part of the OPEX of the downstream production step.

The main input required for PtL processes is electric energy for the electrolysis of water and DAC. Therefore the costs of electricity matter most and are discussed in greater detail below.<sup>23,32</sup>

## 5.1 Costs of electricity and the influence of capacity utilisation

The levelled costs of electricity (LCOE) are generally used to compare production cost of different technologies. They contain CAPEX, OPEX, weighted average cost of capital (interest rate for the planned investment, WAAC) and the produced kWh in the respective period of time. Costs for CO<sub>2</sub>-certificates are not included in the results shown below<sup>22,44,48</sup>.

FLH do affect the total cost most profoundly<sup>22,23,48</sup> (see Table 4). With respect to security of the electricity supply, geothermal plants can potentially work as near in a continuous mode as technically possible (>8 000 h per year) and must be shut down for maintenance work only. Potential FLH are comparable to fossil fuel and nuclear power plants run at full capacity. Second in reliable electricity production and first in terms of its possible storage capacities for electricity production are hydropower- and pumped hydropower plants (Figure 6). Solar plants and wind farms do normally not have more than 4 400 potential FLH<sup>22,23</sup>, depending on the location. Combined solar and wind farms in the global sunbelt (see Figure 7) may reach 5 000 FLH<sup>23</sup>. Plants with FLH lower than the above mentioned indicate low use of their capacity. In Germany the currently low FLH of fossil fuel plants show the negative economic consequences of a fast transition from fossil and nuclear plants to renewable electricity sources without because fossil power plants are in this case used for providing energy security in periods of insufficient supply from renewable sources<sup>27,38</sup>.

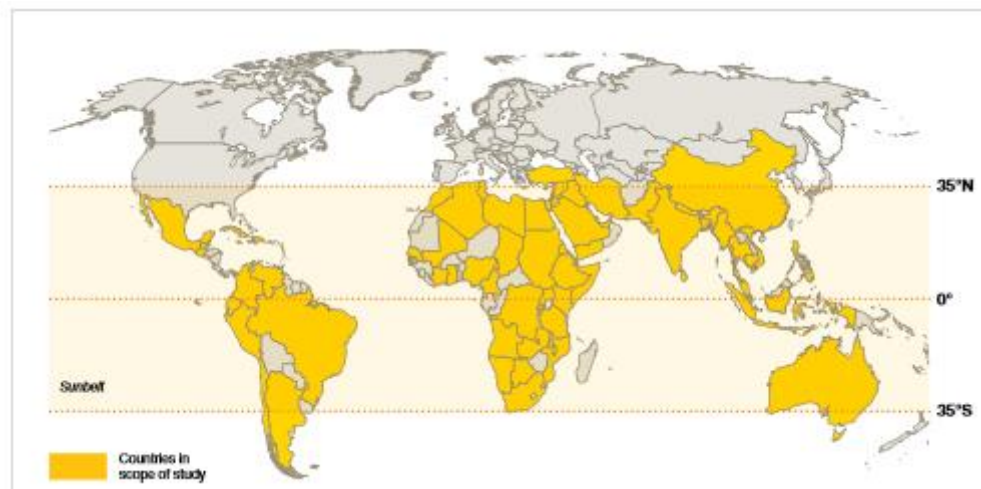


**Figure 6:** Pumped storage hydropower station Hohenwarte II in Thuringia, Germany which is owned by the Swedish company Vattenfall GmbH. The upper reservoir is filled with pumped water from the lower reservoir/river power plant in times of surplus electricity production. The water from the upper reservoir powers on demand the eight turbines in the machine hall, the height of drop is 304 m.<sup>4,5</sup>



## The Global Sunbelt:

The term Global Sunbelt refers to the regions between 35th degrees of northern and southern latitude. In this region the annual global solar irradiance at the land and ocean surfaces is highest on earth. These regions have the highest potential for solar power plants<sup>37</sup> and 148 out of 201 countries (accounting for approximately 80 % of the world's population) belong partly or completely to this region. NATO-members with state territory partly or completely in the global sunbelt are Greece, Italy, Portugal, Spain, Turkey and the United States of America, while Malta is a Euro-Atlantic Partnership Council (EAPC) member. NATO partners in the global Sunbelt are Afghanistan, Australia, Colombia, Iraq, Japan Republic of Korea and Pakistan.



**Figure 7:** The region between 35 degrees of northern and southern latitude is referred to as the Global Sunbelt. Countries marked in yellow are included into a study of <sup>37</sup>. Countries within the sunbelt marked in grey are not included in a detailed analysis of the European Photovoltaic Industry Association <sup>37</sup>.

The levelled costs of electricity for several power plants technologies from two different studies for power plants commissioned in 2018 (Table 3) show Table 4 similar trends: The IRENA-Study<sup>48</sup> calculates worldwide average LCOE with 5<sup>th</sup> - 95<sup>th</sup> percentile values showing that LCOE vary greatly with respect to the size of the plant. The Fraunhofer-ISE-Study<sup>22</sup> lists minimal and maximal LCOE for plants in Germany. Nuclear power plants under construction in 2015 incur LCOE of 3.6 - 8.4 €-ct<sub>2015</sub>/kWh without considering the cost of radioactive waste disposal<sup>44</sup>. Globally the cheapest newly build renewable power plants (hydropower, bioenergy and offshore wind parks) show lower average LOCE than fossil fuel power plants built in 2018<sup>22,48</sup>. Considerable further reductions in costs are predicted for the years and decades to come, with higher cost reduction effects for renewable technologies than for fossil and nuclear power plants<sup>22,23,48</sup>. In terms of production costs and energy supply security hydropower plants are the best choice. Nevertheless, many countries do not build new hydro dams because of the negative environmental impacts and social issues<sup>27</sup>.



**Table 4:** The levelled costs of electricity (LCOE) for renewable and fossil fuel electricity producing plants commissioned in 2018 according to two major studies by IRENA<sup>48</sup> and Fraunhofer ISE<sup>22</sup>. The electricity source is given in the first column and the second column shows the 5<sup>th</sup>-95<sup>th</sup> percentile of global average LCOE for plants commissioned in 2018. Columns 3 and 4 refer to the LCOE of plants commissioned in 2018 in Germany with column 3 showing the performance range with respect of the local solar radiation or the FLH and column 4 showing the LCOE.

Electricity source	LCOE IRENA-Study 5 <sup>th</sup> -95 <sup>th</sup> percentile [\$-ct <sub>2018</sub> /kWh] <sup>48</sup>	LCOE Fraunhofer-ISE Study <sup>22</sup>	
		Performance	Min-max costs [€-ct <sub>2018</sub> /kWh]
Solar, small (private households)	10.9 - 27.2	950 - 1 300 kWh/(m <sup>2</sup> year)	7.23 - 11.54
Solar, medium (industrial)			4.95 - 8.46
Solar, large (solar parks)			3.71 - 6.75
Wind, onshore	4.4 - 10.0	1 800 - 3 200 FLH	3.99 - 8.23
Wind, offshore	10.2 - 19.8	3 200 - 4 500 FLH	7.49 - 13.79
Biogas		5 000 - 7 000 FLH	10.14 - 14.74
Bioenergy (direct combustion and gasification)	4.8 - 24.3	n.n.	n.n.
Hydro	3.0 - 13.6	No new plants in Germany in 2018	
Geothermal	6.0 - 14.3		
Lignite fired power plants	5.6 - 17.5	6 450 - 7 450 FLH	4.59 - 7.98
Coal fired power plants		5 350 - 6 350 FLH	6.27 - 9.96
Gas and steam power plants		3 000 - 4 000 FLH	7.78 - 9.96
Gas fired power plants		500 - 2 000 FLH	11.03 - 21.94

## 5.2 Total costs of synthetic fuel production

A large German study (AGORA-study<sup>23</sup>) on the costs of synthetic fuel production quantifies potential minimum and maximum total costs of the production for synthetic fuels. Several renewable electricity sources and DAC as source of CO<sub>2</sub> in different places of the world were considered. Also the respective variation of FLH and the transport costs for delivery of the fuel to the German border (without fees and taxes) was taken into account (Table 5). The resulting fuel costs vary with the CAPEX of the chosen technology for electricity production and the assumed FLH. The cheapest production is possible in Iceland with mature, low cost electricity production using geothermal energy and hydro plants in a continuous production mode. This is also in accordance with the production costs of geothermal plants commissioned in 2018 (see Table 4)<sup>48</sup>. The highest fuel costs result from offshore wind parks located in the North Sea and Baltic Sea due to the high building and network costs in terms of connection to the mainland grid and relatively low FLH. The costs of fuel from solar plants in North Africa and the Middle East do not vary greatly. Increasing the FLH of these plants by installing nearby wind plants could improve the FLH but increases the electricity costs since additional CAPEX are needed for installation of wind parks. The range of minimum and maximum costs of solar

and combined solar/wind plants in North Africa and the Middle East do not vary greatly. For all renewable power generation technologies, even in the most suitable locations, the resulting fuel costs would be at the moment at least twice as high as the projected costs for premium fossil gasoline fuel (given prices for the year 2020).

**Table 5:** Minimum and maximum total costs and FLH of renewable plant site locations with favourable preconditions for energy production. Fuel costs are compared with the price of premium gasoline fuel as projected for 2017- 2020. kWh<sub>PtL</sub> refers to the energy content in kWh of the fuel produced.<sup>23</sup>

Location/technology	FLH of electricity production [h]	Agora-Study [€-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	
		Minimum costs	Maximum costs
North Africa / solar	2 100-2 500	16.52	19.29
Middle East / solar	2 200-2 600	16.10	18.71
North Africa solar / onshore wind	3 485-5 015	16.65	22.67
Middle-East solar / onshore wind	3 910-4 335	18.21	21.29
Island geothermal / hydro	8 000-8 000	11.25	11.73
North-, Baltic Sea / offshore wind	3 500-4 400	21.93	33.17
Premium fossil gasoline	n.a.	4.66	

For the Iceland scenario with lowest total fuel costs and the North- and Baltic Sea scenario with the highest total fuel costs a detailed overview for the production stages Table 3 are shown in Table 6. The Island scenario shows the lowest electricity costs but long transportation routes for the fuel produced in order to reach Germany. The North- and Baltic Sea scenario involves high electricity costs at an expected lower than 50% capacity use but no costs for transportation. This difference is explained by the H<sub>2</sub> production costs. The lower amount of FLH in the North- and Baltic Sea scenario results in approx. twice the amount of production costs related to this step of production<sup>23</sup>. This fact is in close accordance with the fact, that the total efficiency rate – based on the electricity input – is 67 % (Table 3).

**Table 6:** Total minimum costs for synthetic fuel production including transport onto the German border with respect to the stages of production and in dependence of the degree of capacity utilisation for the year 2020. Costs are given without distribution, fees and taxes. Comparison to price of premium gasoline projected from 2017 to 2020. kWh<sub>PtL</sub> refers to the kWh of the produced fuel.<sup>23</sup>

Stage of production	Island geothermal/hydro plants (8 000 FLH) [€-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	North- and Baltic Sea offshore wind plants (4 000 FLH) [€-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]
Electricity production, Transmission network	5.091	17.179
Electrolyser	1.858	3.716
CO <sub>2</sub> -capture, syngas, Fischer-Tropsch	4.556	5.173
Transportation	0.014	0.000
<b>Total costs</b>	<b>11.520</b>	<b>26.468</b>
Price for premium gasoline	4.66	4.66

A study from the International Energy Agency (IEA)<sup>31</sup> calculated the minimum and maximum costs of synthetic fuel production according to the stages of production (c.f. Figure 3C). Costs of all technologies are grouped into CAPEX, OPEX, electricity and CO<sub>2</sub>. Cost for electricity supply were calculated for averaged renewable sources with 3 000 FLH. The cost for CO<sub>2</sub> supply is divided into a low cost version with CO<sub>2</sub> from a bioethanol plant and a high cost version with DAC. A calculation for the near future (2030) and the longer term (after 2030) is shown in Table 7. In the near future total costs are driven by the cost for electricity production and CO<sub>2</sub> supply by DAC. The production costs for both electricity and DAC are expected to drop in the future by approx. one third due to learning curve effects, however they remain the dominant cost factor.

The total costs for synthetic fuels in the Agora study<sup>23</sup> and the IEA<sup>31</sup> study are in the same order of magnitude, while the reference cost for fossil fuel may vary quite substantially in the future.

**Table 7:** Near (2030) and long term (>2030) minimum costs of synthetic fuel production without transport, fees and taxes as calculated from worldwide projects with different technologies for power and CO<sub>2</sub> production<sup>31</sup>. Fossil diesel price is calculated based on 75 US Dollar per barrel of crude.

	Unit	Near term (2030)	Long term (>2030)	Cost reduction [%]
FLH electricity production	[h]	3 000	3 000	n.a.
CAPEX	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	6.83	4.55	33
OPEX	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	1.82	1.38	24
Electricity costs	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	10.92	4.55	58
CO <sub>2</sub> feedstock costs – low	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	0.91	0.91	0
CO <sub>2</sub> feedstock costs - high	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	10.47	1.82	83
Total costs – low	[\$-ct <sub>2017</sub> /kWh <sub>PtL</sub> ]	20.48	11.39	11
<b>Total cost – high</b>	<b>[\$-ct<sub>2017</sub>/kWh<sub>PtL</sub>]</b>	<b>30.95</b>	<b>22.78</b>	<b>44</b>
Diesel price	[\$-ct/kWh]	4.81	4.81	n.a.

## Conclusions

The production technologies for synthetic fuels are well established<sup>21,23,38</sup>. Synfuels provide environmentally cleaner fuel emissions. If H<sub>2</sub> and CO<sub>2</sub> as precursors for synfuels are produced with electricity from renewable sources and the CO<sub>2</sub> is reused, these fuels also do not contribute to the increase of CO<sub>2</sub> concentrations in the atmosphere and help combatting climate warming. However, the production costs are currently not competitive at all compared to the much lower price for fossil fuels. In addition the technologies for H<sub>2</sub> production, CO<sub>2</sub> capture and fuel production are currently not yet in a mature state - but significant cost reductions are predicted for future large scale applications.<sup>22,23,25,48</sup> Since involved production processes are very electricity intensive cheap and secure renewable electricity sources are a prime prerequisite for making PtL competitive with fossil energy.

Since 2018 newly build renewable electricity plants can produce cheaper electricity than newly build fossil and nuclear power plants. This does not take into account, that solar and wind power plants suffer from an inherent non-continuous power generation and therefore require further intermediate storage options. Predictions do suggest that the trend in cost reductions for renewable technologies will continue in the coming years and decades. A report issued in

2010 predicted for the year 2020 a drop for LCOE of PV onto the range of 5 – 12 €-ct which fits the actual prices already reached in 2018<sup>37</sup>. The technology, and therefore the power source and the location of the PtL plants are the main determinants for the production costs. The most influential parameter is the degree of technical capacity utilisation, also expressed as full load hours (FLH). In this respect geothermal and hydropower plants are the most favourable energy provider for PtL technologies.

As the power production is the key parameter for the total costs of synthetic fuels, it seems favourable to concentrate all stages of production in the proximity of electricity plants. Industrial point sources of CO<sub>2</sub> provide very concentrated carbon but typically do not provide enough CO<sub>2</sub> for large scale PtL production or are not in proximity to low cost renewable energy. Therefore, ambient air is most likely to be used as carbon source in combination with direct air capture technology because DAC plants can be located next to renewable energy producers.

As DAC is a highly energy intensive process which is likely to be installed in remote rural areas, innovative combinations of electricity, H<sub>2</sub> and CO<sub>2</sub> production plants may offer interesting alternatives: One alternative would be to have geothermal or hydropower electricity production near large scale high concentration CO<sub>2</sub> emitters, - but these settings are extremely rare on a global scale. The second best solution would have CO<sub>2</sub> pipelines running from CO<sub>2</sub> emitters to the electricity plants. CO<sub>2</sub> pipelines are an established technology but they add additional costs to the final product<sup>33</sup>. A third option would be to combine solar/wind plants in the global Sunbelt. This setup however faces the same problems of obtaining sufficient and low cost CO<sub>2</sub> supplies as do geothermal and hydropower plants<sup>23,31</sup>. Since industrial processes with their high CO<sub>2</sub> concentrations and often impure waste gases are much cheaper carbon sources than DAC<sup>3,13,24,25,33,35</sup>, innovative measures are needed to link CO<sub>2</sub> emitters in industrial areas, PtL plants and renewable electricity power plant.

For the near future synthetic fuels are significantly more expensive than comparable fossil fuels<sup>23,31</sup> but synthetic fuels may become more competitive due to the predicted reductions in costs and the politically driven implementation ever more expensive CO<sub>2</sub> certificates. Nonetheless the costs are predictable and the supply lines secure, when established politically and economically stable countries of the world. The establishment of renewable energy plants with DAC in vulnerable regions or even so called failed states situated in the global Sunbelt would not contribute to a secure and stable supply line. In contrast to fossil oil prices synthetic fuel production costs are comparably stable since the input costs are predictable. The main cost drivers are CAPEX for the renewable energy plants, electrolysers, Fischer-Tropsch plants and CO<sub>2</sub> capture technologies. OPEX are reduced mostly to maintenance, as the renewable energy and CO<sub>2</sub> comes for free. Water for electrolysers may be expensive but can be achieved by desalination of sea water. In 2015 the OPEC predicted an oil price of 70 \$ per barrel for 2020<sup>2</sup> which fits the actual price in January 2020 quite well. The year 2020 has already brought oil price spikes in the wake of airstrikes to oil refineries in January<sup>1</sup> as well as negative oil prices in the aftermath of disagreements over supply rates between oil producing states by the mid of April as well as corona pandemic induced worldwide lockdowns and decreased demand for oil<sup>7</sup>. On an economic basis the world oil price defines which oil sources are exploited. Shale oil production in the USA and Canada for example is much more expensive than oil production from wells in the Middle East. The international oil price also influences or even dominates national budgets of many oil exporting nations like Russia, UAE or Venezuela. In these countries the crude oil price determines in consequence also the level of social benefits provided by the government to its citizens and therefore social and political stability.<sup>7</sup>





## ENERGY SECURITY: OPERATIONAL HIGHLIGHTS



For the near future it appears to be a prudent diversification strategy for NATO nations and partners to establish a balanced strategy of investments in Power to Liquid technologies at home and in politically stable regions. This will ensure own technological competence and leadership for promising technologies and secure a basic fuel supply for countries with small or no fossil fuel reserves. PtL investments in some volatile regions on the other hand may also contribute to stabilise NATO's partners and vulnerable neighbours.

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