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Criteria for the production of sustainable PtL for aviation

Derivation and definition of implementation criteria for the generation or procurement of sustainable electricity and CO_2 as feedstock for PtL for aviation

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1 Introduction

1.1 Initial situation

The implementation of the German national climate protection goals is facing great challenges. These goals demand the complete defossilisation of our economy by the middle of the 21st century, i.e., assuming a highly developed industrial society with net zero fossil CO_2 emissions. While this seems achievable in the electricity sector via steady expansion of renewable energies (especially wind and solar), the transport sector faces a greater challenge. Considering that the emissions inventory of the transport sector has been stagnating for years, the German government's climate protection plan[1] aims for an ambitious 40-42 % reduction of emission levels by 2030 compared to 1990.[2] This target relies on sector coupling between electricity and transport, specifically the increase of e-mobility with renewable electricity, in addition to a simultaneous implementation of measures for traffic avoidance and modal shift.

Lower-emission or "zero-emission" fuels are seen as one of the building blocks for achieving this goal. The current Renewable Energy Directive (RED)[3], and in particular its update (RED II)[4], is already focusing on "renewable fuels from non-biogenic sources", commonly referred to as power-to-liquid (PtL) or e-fuels. These fuels are sometimes referred to as "emission-free" or greenhouse gas (GHG) neutral, since the CO_2 that will be released during combustion must have been extracted either from the air or from an existing emission source. Synthesising this CO_2 feedstock into a fuel with hydrogen produced from renewable electricity results in strongly reduced emission loads. However, more detailed analyses of the possible production chains of PtL show that a differentiated view is required.[5]

While decarbonisation for ground-based transport appears to be largely manageable using electrification, the question of the availability of low-GHG or GHG-neutral fuels arises for air transport and to some extent for shipping.

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[1] BMUB. (2016). Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung; Berlin: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Retrieved from https://www.bmu.de/filead-min/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf

[2] International air traffic is not included in this figure.

[3] EU Directive 2009/28/EC (RED): on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC; of 23 April 2009; amended by EU Directive (EU) 2015/1513 (iLUC Directive): amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources; of 9 September 2015.

[4] EU Directive (EU) 2018/2001: on the promotion of the use of energy from renewable sources (recast) of 11 December 2018.

[5] Report within the framework of the PtX project in the Copernicus programme

The RED and its update RED II set requirements for proving the sustainability of biofuels. So far, such proof has not been available for PtL, primarily due to the novelty of this technological approach. Even though extensive research has been conducted on this technology for several years, practical experience is still lacking.

1.2 Aim and approach of this study

The aim of this study is to derive and define implementation criteria for the generation and procurement of PtL for aviation. Given the highly innovative nature of such criteria, it was considered that they should be

- meeting a high standard of sustainability and not being limited to the level of legal minimum requirements, while
- not slowing down technology development by setting up too restrictive rules.

In order to facilitate a rapid start to implementation, a staged approach was taken. The study presented here develops criteria for a first stage, which are based on a

1. location constraint: production in Germany, and a
2. time frame constraint: until the year 2030.

In a possible next stage, the framework will have to be expanded to include PtL produced abroad and imported to Germany, as all major scientific scenarios for the energy transition assume that the future demand for PtL in Germany can only be met by imports from countries with extensive renewable electricity capacities (e.g., Middle East and North Africa or Iceland).

After a brief analysis of the demand for PtL for aviation (chapter 2) and a description of the state of the art of PtL production technology (chapter 3), criteria are developed on the basis of global guard rails and sustainability goals (chapter 4). In the first step, these criteria are applied to the origin of CO_2 as feedstock and how this CO_2 is to be evaluated in each case (chapter 5). In the second step, the greenhouse gas neutrality of the electricity used for production is evaluated (chapter 6).

The final criteria should be as specific and measurable as possible, as third parties have to evaluate them in a certification process.

As an outlook, the pathway to more ambitious levels are laid out in chapter 7.

The commissioning party for this study has set essential requirements for this study. These are in particular the global guard rails and the respective derivation of environmental criteria (chapter 4), but also the quantity requirements for CO_2 from sources other than direct air capture (DAC) at national and global level, as well as the CO_2 sources from the plants. For synthetic kerosene production, the assumption is a significant increase of CO_2 production from DAC as feedstock, starting from zero today up to almost full coverage in 2050.

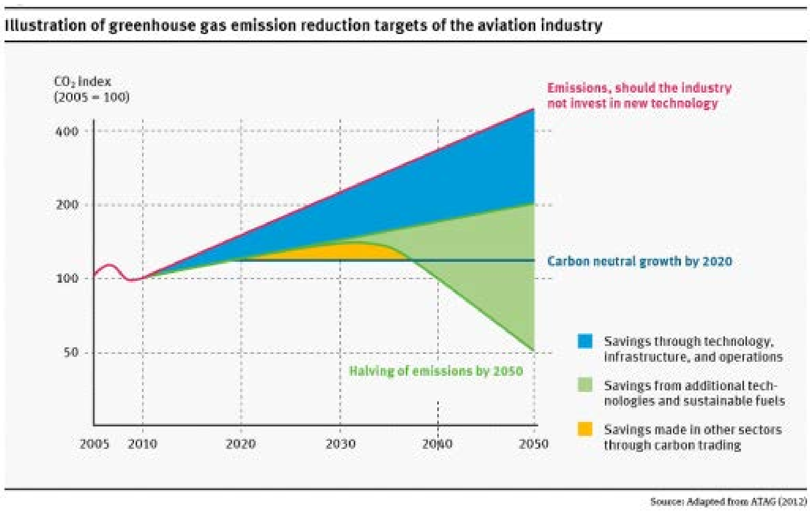
2 PtL demand for aviation

International air traffic has increased strongly in recent years and will continue to increase according to current forecasts. In contrast to road and rail transport, direct electrification is only possible to a limited extent (short-haul flights). Kerosene continues to be the primary option for fuel due to the high energy density requirements. Considering the long service life of aircraft (25 years), drop-in solutions that can be used in existing aircraft are advantageous. Biofuels and synthetic fuels can be used to reduce CO_2 emissions from aviation. However, further global warming effects – especially from contrails – can only be reduced to a small extent by these fuels.

The future demand for synthetic kerosene thus not only depends on the development of transport performance and efficiency of aircraft, but is strongly influenced by the CO_2 reduction targets set for the coming years and the use of biofuels.

2.1 CO_2 reduction targets for aviation

So far, there are no binding targets for the reduction of GHG emissions from aviation. However, the industry has developed their own commitments: In 2012, ATAG (Air Transport Action Group) published CO_2 reduction targets (ATAG 2012). These targets include CO_2-neutral growth from 2020 and a reduction of CO_2 emissions from aviation by 50 % by 2050 (compared to 2005). These (voluntary) targets are supported by a large part of the aviation industry.



Source: Schmidt et. al, 2016
Figure 1: Schematic representation of CO_2 reduction targets in aviation.

Even with very ambitious measures to improve the efficiency of the aircraft itself as well as other operational improvements (e.g., in airports, flight routes, flight altitudes, ...) given the expected growth rates the use of renewable energy sources in aviation will be essential to achieve these goals. According to AIREG (Aviation Initiative for Renewable Energy in Germany e.V.) the aim should be for renewable fuels to account for 10 % of kerosene fuelled nationwide in 2025 (www.aireg.de).

The ATAG voluntary commitment allows for a CO_2 compensation system. In autumn 2016 191 member states of the ICAO (International Civil Aviation Organization) agreed on a CO_2 compensation system CORSIA[1] (Carbon Offsetting and Reduction Scheme for International Aviation), which is to be introduced globally starting in 2020.

It should be mentioned that the additional GHG impact of aviation from non-CO_2 emissions at high altitudes (e.g. contrails) remains largely unchanged with conventional technology (combustion of fuels in turbines), even when the used fuels originate from 100 % renewable sources. Thus, a total greenhouse gas neutrality of aviation cannot be achieved with the current technology.

2.2 PtL demand for Germany

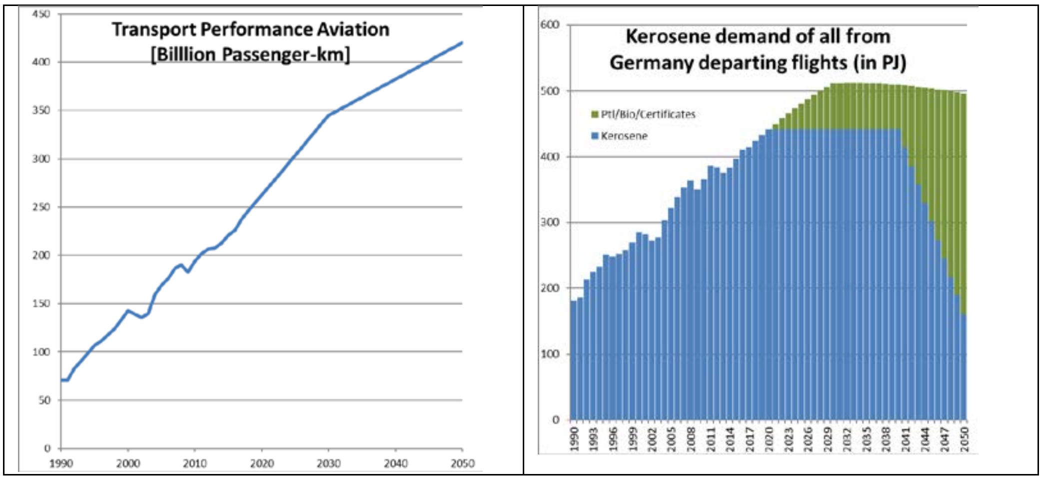
The German PtL demand is roughly estimated on the basis of the targets mentioned above and the expected energy consumption of domestic and outbound air traffic in Germany. German PtL demand for air traffic is calculated according to the origin principle : All flights departing from German commercial airports are counted up to the first (stopover) landing. Thus, both national air traffic (traffic between domestic commercial airports) and outbound international air traffic, including outgoing cross-border flights are considered. This consumption roughly corresponds to the final energy consumption according to the German Fuel Statistic.

Passenger air transport performance (pkm) more than tripled between 1990 and 2017, and freight transport performance (tonne-km) quadrupled. Within ifeu's emission calculation model TREMOD (Version 6.0) a further strong growth in air traffic from/in Germany by 78.7 % between 2010 and 2030 is assumed. This is followed by a weaker growth of 21.9% between 2030 and 2050. Furthermore, a reduction in specific fuel consumption of 1 % per year until 2030 is assumed, related to the operating performance (transported passengers/freight). This assumption is adopted in TREMOD for the entire period until 2050 and is in line with more recent estimates by the International Air Transport Association (IATA), which indicate a reduction potential in the range of 0.7 to 1.2 % p.a. until 2050 (IATA 2013).

Due to this strong increase in air traffic, kerosene consumption increases until 2030. After 2030 it remains roughly constant due to the assumed slowdown in the increase in air traffic performance accompanied by an increasing energy efficiency. From 2040 on kerosene consumption is slightly decreasing. About 70 PJ of fossil kerosene (equivalent to approx. 1.6 Mt) would have to be replaced by sustainable synthetic kerosene from 2030 onwards in order to achieve CO_2-neutral growth (ATAG target) – given the

[1] https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx

assumed growth rates, efficiency developments and reduction pathways (see Figure 2).



Source: TREMOD 6.0 and own assumptions for the development of PtL/bio/certificate demand
Figure 2: Development of transport performance and kerosene consumption.

However, instead of relying solely on the contribution of synthetic kerosene, the ATAG target could also be achieved through the CO_2 compensation system CORSIA. Accordingly, the demand for synthetic kerosene in Germany would be lower than otherwise anticipated.

Figure 3 shows the approximate share of fossil kerosene that would have to be replaced to achieve the IATA targets. Assuming that CO_2-neutral growth would be achieved by utilising synthetic fuels only, their share would increase from about 8 % in 2025 to 14 % in 2030. In practice, a mix of certificates (CORSIA), biofuels and other measures will probably be used alongside synthetic kerosene.

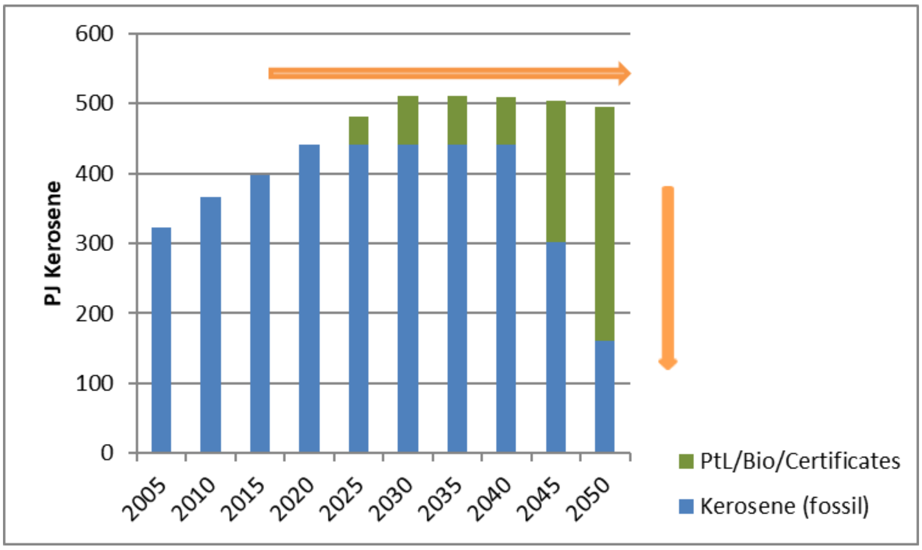


Figure 3: Self-commitment of ATAG and resulting demand for renewable energy sources or certificates.

The long-term demand for synthetic kerosene depends heavily on both, the future development of aviation (growth, technical and operational efficiency increases, electrification) and the fulfilment of climate protection targets.[1]

Significant reductions of GHG emissions are needed to achieve the goal to limit global warming to two degrees Celsius. According to SBT (2015), the total emission budget between 2011 and 2050 for global passenger aviation is 36 billion t CO_2. In 2018, CO_2 emissions from global passenger aviation were approximately 0.747 billion t CO_2. (Graver et al. 2019)

The path to a greenhouse-neutral Germany is shown in UBA (2019). For international aviation, a necessary import of 43 PJ (approx. 1 million t) of synthetic fuels in 2030, 336 PJ (approx. 7.9 million t) in 2040 and 288 PJ (approx. 6.7 million t) in 2050 is determined for the GreenEe scenario.

UBA (2019b) considers it to be reasonable to import around 10 TWh (36 PJ or 0.8 million t) to 20 TWh (72 PJ or 1.7 million t) of sustainable PtL as early as 2030 in order to reduce greenhouse gas emissions from aviation to zero by mid-century. This corresponds to about 10 % of the kerosene needed for Germany today (about 10 million t). The study "RESCUE – Wege in eine ressourcenschonende Treibhausgasneutralität" (UBA 2019c) also identifies ways to reduce German (and Germany's attributable) greenhouse gas emissions by 2050. To achieve greenhouse gas neutrality for Germany by 2050, various scenarios are presented. For example, in the "GreenEe1" scenario, almost 12 TWh (43.2 PJ or 1 million t) of synthetically produced, low greenhouse gas PtL is assumed to be used in aviation in 2030 (around 10 % of the total amount of aviation fuel utilised in Germany today).

Table 1 shows the PtL demand for aviation in Germany based on the TREMOD baseline scenario presented above, assuming an increasing share of PtL until 2050 (exemplary scenario PtL ramp-up).

Table 1: Illustration of the amount of PtL required for aviation in Germany as a function of the PtL share.

	2020	2025	2030	2035	2040	2045	2050
Kerosene [million t]	10	11	12	12	12	12	12
PtL share		2 %	10 %	30 %	50 %	75 %	100 %
PtL absolute [million t]		0.2	1.2	3.5	6	9	12
PtL absolute [PJ]		9	50	150	250	374	496
CO2 demand PtL [million t]	0	0.7	3.8	11.3	18.9	28.4	37.8
DAC CO_2 absolute [million t]	0	0	0.4	3.4	9.5	21.3	37.8
CO_2 from non-DAC sources [million t]	0	0.7	3.4	7.9	9.5	7.1	0

Sources: TREMOD for the development of kerosene demand; estimates by atmosfair: ramp-up PtL share and DAC CO_2 absolute; all other values are derived mathematically.
DAC: Direct air capture (see chapter 3.2.2)

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[1] https://sciencebasedtargets.org/wp-content/uploads/2015/05/Sectoral-Decarbonization-Approach-Report.pdf

BCG, Prognos (2018) assume a demand of 378 PJ synthetic kerosene for 2050 for the 95 % scenario. According to Bergk (2016), the demand of PtL for aviation in 2050 is 450 PJ in the 95 % scenario (see Figure 4).

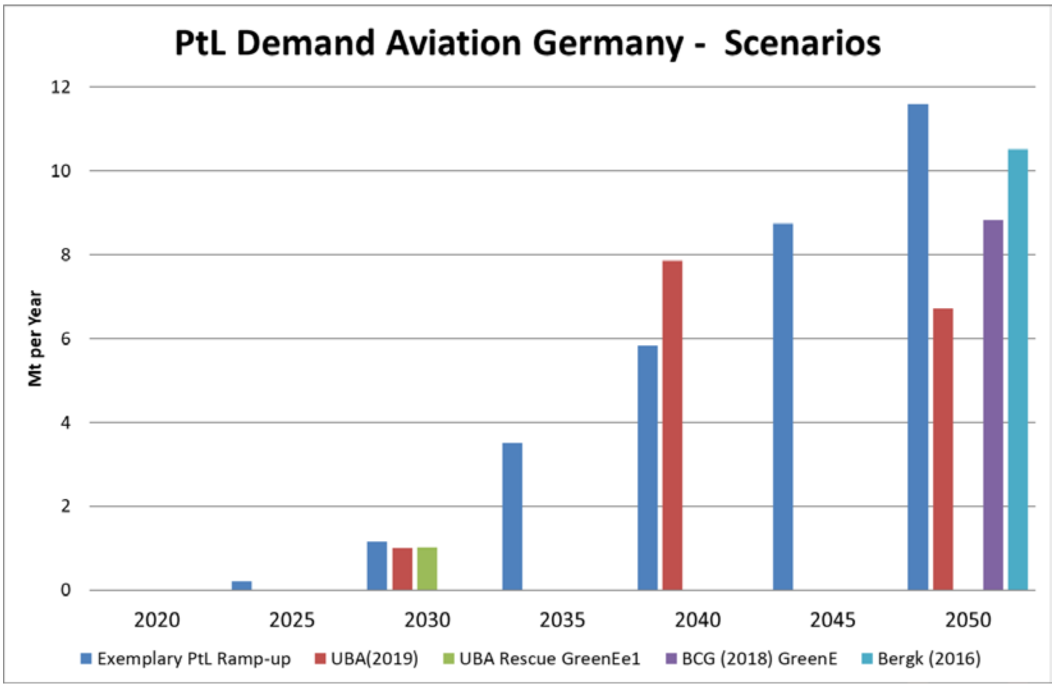

Figure 4: PtL demand for aviation – overview of selected scenarios for Germany.

3 Brief description of state-of-the-art PtL production technology

The following facilities are required for the production of PtL fuels:

- An electrolyser for the production of hydrogen through water electrolysis
- A plant for CO_2 capture and supply
- A synthesis plant (with the subcomponents synthesis gas generation and synthesis reactor, as well as hydrocracker and product preparation/refining in the Fischer-Tropsch process, or separation column, DME (dimethyl ether) synthesis, olefin synthesis, oligomerisation and hydrotreating in the methanol process).

These process steps do not necessarily have to be implemented at a single site. Hydrogen and CO_2 can be stored and transported, which however leads to an additional energy demand for compression or liquefication. The potential to use the waste heat from the synthesis reactors in-process for CO_2 separation or electrolysis is also of advantage if the process steps are located at a one site.
The raw products from the synthesis processes (Fischer-Tropsch crude or methanol) can be transported with less effort and, if necessary, refined in central processing plants.

3.1 Electrolysers

Most of the world's hydrogen production of 65 million t/a is results as a by-product or co-product from chemical industry processes and is also consumed by the respective industry itself in other processes. In 2007, 48 % of the world's hydrogen was produced from natural gas, 30 % from oil and process gases from refineries and the chemical industry, 18 % from coal and 4 % from electrolysis (Brinner et al., 2017).

Starting around 2010, the interest in power-to-gas technology for the production of electrolytic hydrogen and the subsequent production of synthetic natural gas from hydrogen and CO_2 has increased. Currently, there are over 20 PtG plants in Germany (https://www.powertogas.info/projektkarte/).

Water electrolysers can be divided into three relevant technologies based on the type of electrolytes used:

- alkaline electrolysis (AEL) with aqueous potash or caustic soda as the electrolyte,

- polymer electrolyte membrane electrolysis (PEMEL) with a proton-conducting membrane as electrolyte, and
- solid oxide high-temperature electrolysis (SOEL) with a ceramic ion-conducting membrane.

An overview of the current status of the most important techno-economic key figures of these three electrolysis technologies is provided in Table 2.

Table 2: Techno-economic key figures of the electrolysis technologies AEL, PEMEL and SOEL (as of 2016).

Criterion	AEL	PEMEL	SOEL
Stack efficiency (in relation to calorific value) [%] *)	60-84	46-84	> 100 **)
System efficiency (in relation to calorific value) [%]	51-79	47-79	n/a
Operating temperature [°C]	60-80	50-80	700-1,000
Max. operating pressure [bar]	< 50	< 350	1
Current density [A/cm²]	0.2-0.4	0.6-3.0	0.4-2.0
Min. partial load capacity [%]	20-40	~ 10	n/a
Available stack size [Nm³/h]	800	250	5.7
Precious metal demand [mg/cm²]	-	2 (Ir); 0.5-1 (Pt)	-
Stack lifespan [h]	< 90,000	< 60,000	3,500
System size [kW]	1.8-5,300	0.2-400	< 40
Investment cost [€/kW]	1,000-1,200	1,500-2,300	2,500

*) related to the use of electrical energy
**) substitution of electrical energy by high-temperature thermal energy
n/a: not applicable

Currently, electrolysers with power up to more than 5 MW_{el} are available on the market as alkaline electrolysis and up to approx. 2 MW_{el} as PEMEL electrolysis. SOEL electrolysis is currently only being tested[1] in the 180 kW_{el} power range. However, the available electrolysers are not series products, but are manufactured as one-offs with the associated high costs due to the current lack of a market. The first commercial products for stationary and mobile energy applications in mass markets are not expected until between 2020 and 2030. The stages of development of the individual technologies are still very divers: alkaline electrolysis is the most mature technology, with PEMEL catching up. SOEL electrolysis has only just entered the pilot plant stage. The Technology Readiness Levels (TRL) within the individual electrolysis technologies also vary, as smaller plants have been much better researched and developed so far. Up to now, large-scale plants merely consist of several electrolysis stacks connected in parallel.

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[1] https://www.sunfire.de/de/unternehmen/news/detail/naechste-generation-der-hochtemperatur-elektrolyse-gestartet

Further development depends mainly on how well the materials and concepts used today prove themselves in larger plants. Success is anticipated for AEL, while PEMEL is catching up and SOEL still need further research for this step. New materials need to be developed in this context, also to reduce system costs.

3.2 CO_2 sources

CO_2 can be obtained from various sources: from the atmosphere, from flue gas streams produced during the combustion of biogenic or fossil fuels, from gas streams in industrial processes, or from fermentative processes in which CO_2 is generated as a reaction product. In most of the processes that are technically realised to date, CO_2 must first be separated from the raw gas and purified before it is fed into the PtL synthesis.

3.2.1 Process for CO_2 separation

The separation of CO_2 can be carried out based on different physical-chemical methods or processes, which can be divided into the following process groups:

- Absorption methods
- Processes with gas-solid reactions
- Adsorption processes
- Cryogenic processes
- Membrane processes

The separation of CO_2 from gas flows using liquid **absorbents** (so-called scrubbing) represents the process with the greatest technical maturity and is already being used on a large scale today. Absorption is the process of dissolving gases in a liquid and binding them by physical or chemical forces.

- **Physical scrubbing** is one of the most commonly used type of process in Europe for the separation of unwanted components in (biogenic) gases. In **pressurised water scrubbing** (PWS), water is used as an absorbent. Some **organic solvents** such as polyethylene glycol dimethyl ether (trade name for example Genosorb® or Selexol®) have a significantly increased solubility for CO_2 and H_2S compared to water and are also used in physical scrubbing processes.
  Advantages: lower power requirement with organic solvents compared to PWS, proven commercial technology, lower methane losses in biogas upgrading compared to pressure swing adsorption (PSA), no pre-desulphurisation necessary, long solvent stability.
  Disadvantages: higher costs for operating materials and disposal, heat demand for desorption.

- **Chemical amine scrubbing** is a CO_2 removal process that uses diluted solutions of monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA) and numerous other amine formulations. Amines are hazardous to

water, harmful to human health and corrosive. CO_2 separation with chemical scrubbing has been in use for about 80 years and is applied in industrial processes and biogas treatment.
Advantages: very selective scrubbing, low methane slip in biogas upgrading, proven commercial process.
Disadvantages: amine solutions partly environmentally hazardous (water), high heat demand for desorption, high costs (depending on solvent for plant, operating materials, disposal), corrosion protection partly necessary.

Processes with **gas-solid reactions** mostly use solid alkaline earth oxides, which are converted into carbonates by chemical reactions with CO_2. Temperatures of 700-1100 °C are necessary to release the CO_2. In recent years, there have been a number of research projects and some pilot plants for this so-called carbonate looping process.

In **adsorption,** molecules adhere to the surface of a substance through physical forces.

- **Pressure swing adsorption** (PSA) is a long-established process in air separation and hydrogen processing. Activated carbons, molecular sieves (zeolites) or carbon molecular sieves are usually used as adsorbents.
- **Temperature swing adsorption** (TSA) uses of the temperature dependence of adsorption.

  Advantages: dry process – therefore no waste water, little or no heat required, usable waste heat (compression to 6-10 bar causes heating from 25-35 °C to 60-90 °C), proven commercial technology.
  Disadvantages: high energy demand for pressure or temperature change, high costs for adsorbents, also for their disposal, relatively high methane losses in biogas upgrading.

Two process concepts are summarised under the term **cryogenic gas treatment**: low-temperature rectification, as used e.g. for air separation, and the freezing out of CO_2 under increased pressure.
Disadvantage: high investment and energy costs.

Membrane processes exploit the fact that atoms and molecules are transported or retained through the pores of the membrane based on their size. So far, this process has only been used sporadically in biogas treatment in Germany; membrane technology is inferior to chemical absorption for power plants and industry.
Advantages: simple technical design, no operating materials required - thus low costs in operation, simple process control, high environmental friendliness in operation.
Disadvantages: high power consumption, high plant costs.

The choice of process for CO_2 separation from a raw gas and the amounts of energy required as electricity and heat depend on the CO_2 concentration in the raw gas and its pressure level as well as the availability of e.g. (waste) heat sources from coupled processes. Section 3.2.5 shows a summary of typical values for CO_2 concentrations and energy demands.

3.2.2 CO_2 capture from the air

The concentration of CO_2 in the atmosphere is about 400 ppm[1] (= 0.04 vol.-%), which is very low compared to the concentrations of other sources. Due to the associated high gas volumes that have to be moved, cooled or heated (1 m^3 of CO_2 is contained in 2,500 m^3 of air), the capture of CO_2 from the atmosphere (Direct Air Capture, DAC) is very energy-intensive.

The main **absorption** technique in experimental use is carbonate scrubbing. This produces a carbonate from which the CO_2 is dissolved by using an acid. Alternatively, the CO_2 can be dissolved from the carbonate compound by high temperatures, e.g. using a natural gas burner. (Goeppert et al., 2012; Socolow et al., 2011). The company Carbon Engineering[2] operates an absorption pilot plant in Canada with a capacity of one tonne of CO_2 per day.

In the **adsorption** process, CO_2 is first bound to an adsorption medium[3] and then released using heat at a relatively low temperature level (< 100 °C). The adsorption process used by the Swiss company Climeworks is currently being applied commercially on the scale of pilot and demonstration plants. (Climeworks, 2017).

Since the different DAC variants have only been used for a short period of time and on a small scale, further technical developments are anticipated for the future.

The capture of CO_2 from natural outgassing is a special case. Natural outgassing processes are due to volcanic activity: gases, often CO_2, escape from so-called mofettes through fissures in the earth's crust. This process occurs in volcanic lakes (e.g. Laacher See in the Eifel, Germany), or gases can escape from the earth's surface. The use of such outgassing's is already being practised in some cases[4]. This practice can be considered unproblematic if the gases escape independently and enter the atmosphere without human intervention. Drilling wells, on the other hand, should be viewed rather critically, as this may mobilise CO_2 sources that could be kept sealed and locked if undisturbed.

3.2.3 Biogenic CO_2 sources

3.2.3.1 Biogas processing

In biogas plants, raw biogas[5] is produced from energy crops (e.g. maize, miscanthus, wood from short-rotation plantations), agricultural residues (e.g. straw, liquid and

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[1] According to the most recent measurements, the global carbon dioxide concentration is 407.38 ppm; see: https://www.umweltbundesamt.de/daten/klima/atmosphaerische-treibhausgas-konzentrationen#textpart-1

[2] https://carbonengineering.com/

[3] Polyethylenimine (PEI) on a cellulose fleece.

[4] https://www.carbo.de/de/ueber-uns/

[5] Raw biogas consists of 50-75 vol.-% methane (CH_4), 25-45 vol.-% carbon dioxide (CO_2), 2-7 vol.-% water vapour (H_2O), < 2 vol.-% oxygen (O_2), < 2 vol.-% nitrogen (N_2), < 1 vol.-% ammonia (NH_3) and < 1 vol.-% hydrogen sulphide (H_2S).

solid manure) or organic municipal waste (e.g. green waste, biowaste). Currently, most plants convert the raw biogas into electricity (and heat) on site. Only a small part[1] of the biogas is presently upgraded and fed into the natural gas grid, as so-called biomethane. In the required biogas upgrading process, CO_2 and other unwanted gas components are removed, thereby increasing the methane content. Usually, the CO_2 separated in the process is released into the atmosphere. In some pilot plants, however, this CO_2 is already being used to produce synthetic natural gas (SNG) (Zuberbühler et al., 2011).

Currently, various treatment processes are used in practice for the separation of CO_2 from biogas in Germany. The four most common are: pressure swing adsorption (PSA), pressurised water scrubbing (PWS), physical absorption with organic solvents and chemical absorption processes. The gas mixture separated from the raw biogas is called lean gas. Table 3 shows the most important process data. The lean gas from PSA and chemical adsorption has very high CO_2 concentrations, while the CO_2 is more diluted in the lean gas from the other processes due to the necessary stripping of the respective absorption medium with air.

Table 3: Process data of the most common biogas upgrading processes currently in use. Source: (FNR 2014, Dunkelberg 2015, Billig 2016)

	Pressure swing adsorption (PSA)	Pressurised water scrubbing (PWS)	Physical Absorption (org.)	Chemical Absorption
CO_2 concentration in the lean gas [%]	87-99	14-22	26-32	99.99
Electricity demand [kWh/Nm^3]	0.20-0.25	0.20-0.30	0.23-0.33	0.06-0.15
Heat demand [kWh/Nm^3]	0	0	0.3	0.5-0.8
Temperature of process heat [°C]	-	-	55–80	110-160
Process pressure [bar]	4-7	5-10	4-7	0.1-4
Methane slip prior to lean gas aftertreatment [%]	1.5-2.3	1-2.5	1	0.1
H_2S content prior to lean gas treatment [ppmv]	< 1.5	20-90	< 1	< 1
Exhaust gas treatment (EEG & GasNZV)	yes	yes	yes	no
Fine desulphurisation of raw gas necessary?	yes	no	no	yes
Water demand	no	yes	no	yes

3.2.3.2 Municipal wastewater treatment

A special form of biogas production and processing takes place in municipal wastewater treatment plants when the sewage sludge resulting from wastewater treatment is fermented in digesters. In the absence of air, bacteria decompose the organic matter into sewage gas, which contains between 50 % and 70 % methane and

[1] Approx. 10 % based on the calorific value in 2016 (DENA, 2017).

correspondingly between 30 % and 50 % CO_2. As in biogas plants, the sewage gas from municipal plants is currently either burned in CHP[1] units or processed into biomethane and fed into the natural gas grid. In Germany, wastewater is treated in wastewater treatment plants of various sizes, which are subject to different legal forms and responsibilities. According to official statistics, a total of around 12,600 wastewater treatment plants were registered in 2010, with 9,600 of them being belonging to the public services sector and 3,000 operated as commercial enterprises. Industrial wastewater is also fed into public plants in regionally varying amounts, while municipal wastewater is only occasionally treated in non-public plants (DWA 2015).

3.2.3.3 Bioethanol production

Alcoholic fermentation is used on a large scale for the production of bioethanol as a biofuel. Sugar, starch-rich or lignocellulosic materials serve as raw materials, which are converted into sugar through upstream processing. This sugar is fermented into alcohol by yeasts. The raw ethanol is then distilled and purified. In 2017, around 673,000 t of bioethanol were produced in Germany. This fermentation process generates 0.96 kg of CO_2 per kg of bioethanol (Meisel et al., 2015), which has to be removed and is thus available in a relatively high concentration (98.8-99.6 % on a dry basis) (IEAGHG, 2011). Currently, most of the CO_2 created by these fermentation processes is discharged into the atmosphere.

3.2.3.4 Biomass heat and power plants

Biomass CHP plants are used to generate electricity and heat from biomass. The CO_2 content in the flue gas differs somewhat from that of fossil power plants. Usual concentrations are in the range of 14-17 vol.-% CO_2 (Global CCS Institute, 2010). For CO_2 separation from the flue gases of biomass CHP plants, chemical absorption processes are the focus of current process development.

3.2.3.5 Paper and pulp production

The pulp and paper industry is among the five most energy-intensive industries in Germany. A large part of the energy used is obtained from the raw material wood and is therefore considered climate-neutral, since sustainable forestry releases approximately as much CO_2 per year as is bound in the renewable wood. The main CO_2 source in the most commonly used sulphate process is the combustion of concentrated black liquor in the recovery boiler. CO_2 concentrations in the flue gas are around 13-14 %. The suitable separation method is chemical scrubbing (Möllersten 2004) (Kuparinen 2019).

In principle, it is also possible to obtain biogas from the wastewater treatment of the paper and pulp industry or from the fermentation of paper sludge (Bienert et al.

[1] CHP: cogeneration of heat and power, combined heat and power plants

2015). However, this is hardly ever practiced. Instead, the paper sludge is energetically used or burned as waste.

3.2.4 Industrial sources

3.2.4.1 Exhaust gases from gas, oil and coal-fired power plants or other energetic combustion plants

In the classic **power plant process** with the combustion of hard coal or lignite, the CO_2 concentrations in the flue gas are usually between 12-15 vol.-%. Gas-and-steam power plants fuelled by natural gas yield CO_2 concentrations between and 3-4 %. CO_2 capture is mainly practiced by amine scrubbing. However, the regeneration of the solvent requires a high energy input, which leads to efficiency losses of the power plant of between 7 and 13 percentage points (Markewitz et al., 2017). The combustion with (almost) pure oxygen (**OxyFuel process**) yields CO_2 concentrations of 55-80 vol.-%. The energy input for CO_2 separation is thus significantly reduced for this process, but pure oxygen must be provided from an air separation plant. Accordingly, the efficiency losses of a coal-fired OxyFuel power plant are reported to be in the range of 8-11 percentage points.

However, fossil power plants are being phased out in Germany in the course of a transformation to a climate-neutral economy and will therefore not be available as a CO_2 source in the long term.

3.2.4.2 Waste gases from thermal waste treatment plants (TWT)

The 'Interest Group of Thermal Waste Treatment Plants in Germany' (Interessengemeinschaft der Thermischen Abfallbehandlungsanlagen in Deutschland e.V., ITAD), lists these different types of thermal waste treatment plants (TWT):

- waste incineration plants (waste to energy, WTE)
- substitute fuel cogeneration plants (refuse-derived fuel, RDF)
- sewage sludge incineration plants, municipal sewage sludge
- sewage sludge incineration plants, industrial sewage sludge

A clear distinction between these plants is difficult in individual cases. WTEs mainly incinerate residual municipal waste, while some plants may have a permit to use various other types of waste, e.g. for the co-incineration of sewage sludge. Refuse-derived fuel (RDF) as a term is not precisely defined. Usually, the source waste is a mixed waste such as household waste, mixed commercial waste, fractions from the sorting of light packaging (LP) or other mixtures from production processes. The distinction between these first two types of facilities is therefore blurry.

The purpose of RDF production is to obtain a high-calorific fraction from the mixed waste, by separating inert and wet fractions as well as metals. The calorific value of RDF is therefore higher than that of the original waste: it often ranges between 12 and

15 MJ/kg, while household and commercial waste lies between 9 and 11 MJ/kg. RDF is enriched mainly in plastics and paper and the ratio of fossil to non-fossil carbon is thus shifting towards the fossil. The decisive factors are the exact composition of the source waste and the processing technology. According to studies by Schwarzböck et al. (2018), the proportion of fossil C ranges between 60 and 80 %.

Sewage sludge incineration also utilises a combination of municipal and industrial sewage sludge in some cases. The carbon content in the dry matter of digested sewage sludge is 30 %. This results in a potential of approx. 3.6 million t CO_2 from sewage sludge.

According to ITAD (2002), sewage sludge from municipal plants contains approx. 80 % biogenic carbon. The fossil carbon is due to fossil raw materials or synthetic products that are difficult to degrade. Much lower shares of biogenic carbon can occur if commercial wastewater is added: according to ITAD, the range of biogenic carbon in mixed wastewater is between 28 and 71 %.

As far as the capture of CO_2 from the flue gas of a thermal waste treatment plants is concerned, the techniques described for power plants can be considered as suitable.

3.2.4.3 Industrial processes

An estimated 27 % of global CO_2 emissions are caused by industrial processes (Masanet et al., 2016). About three quarters of these emissions come from large point sources found in the iron and steel, cement, refinery and other industrial processes (e.g. gas treatment, H_2-manufacturing, ammonia production, etc.).

Cement production

Cement consists to a large extent of cement clinker, which is produced at approx. 1400-1450 °C from a mixture of limestone ($CaCO_3$) and additives. In the process, the limestone is converted to calcium oxide (CaO) and CO_2 is released These process-related CO_2 emissions represent about 2/3 of the total emission, the rest is caused by the incineration of fuels. The CO_2 concentration in the flue gas is between 14 and 33 vol.-% (IPCC, 2005). Chemical scrubbing or the carbonate looping process are suitable CO_2 capture techniques.

In the course of the transformation to a climate-neutral economy, the cement production will probably change (e.g. through firing with methane from PtG production, lower production volumes through reduction of the clinker factor and new types of binding agents). However, a considerable part of today's emissions from this industry will still exist in 2050. The total extent of this amount depends on the development of cement production volumes, on the development speed of alternative binders and on the use of hydrogen as a renewable fuel. But even under optimistic assumptions, as outlined in (UBA 2019c), at least 20 % of today's direct emissions should still occur in the cement industry in 2050.

Steel production

During iron and steel production, CO_2 is produced in the blast furnace during the oxidation of the coking coal. The blast furnace gas contains between and 20-25 % CO_2, which can be separated by chemical or physical scrubbing. Recycled steel is melted from steel scrap in an electric arc furnace. During this process, the graphite electrodes are consumed and CO_2 is produced.

In the course of the transformation to a climate-neutral economy, CO_2 emissions from the steel and iron industry will probably disappear completely. Companies in the steel industry[1] are planning to switch to CO_2-free production in the future by using electrolytic hydrogen as a reducing agent.

Ammonia production / hydrogen production

The production of ammonia (NH_3) requires the two starting materials hydrogen (H_2) and nitrogen (N_2). Hydrogen is usually obtained by reforming natural gas (CH_4) with the addition of steam (H_2O):

$$CH_4 + 2\ H_2O \rightarrow 4\ H_2 + CO_2$$

CO_2 is separated from the product mixture by scrubbing to obtain pure hydrogen. The process produces 1.2 kg of CO_2 per kilogram of ammonia. Some of the CO_2 is already used today, especially for urea synthesis and in the food and beverage industry. However, a considerable part is currently still released into the atmosphere.

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[1] https://www.thyssenkrupp-steel.com/de/unternehmen/nachhaltigkeit/klimastrategie/

The CO_2-intensive process step of hydrogen production via natural gas reforming will probably be substituted by the production of hydrogen by electrolysis using renewable electricity in the course of the transformation to a climate-neutral economy.

Mineral oil refineries

For hydrocracking and desulphurisation of products, mineral oil refineries consume large quantities of hydrogen, some of which comes as a by-product of refinery processes (petrol reforming, gasification of heavy residues). Most of the used hydrogen is produced via steam reforming of natural gas as described above. In a renewable future, the hydrogen demand of refineries will be covered by electrolytically produced hydrogen.

Natural gas conditioning

Natural gas can be contaminated with acid gas components (especially H_2S and CO_2), depending on the respective gas field. These components need to be removed (via deacidification, sweetening) because H_2S and CO_2 are corrosive in the presence of water. Furthermore, H_2S is toxic and the calorific value of the natural gas decreases with increasing CO_2 content. The processing of natural gas is currently the main application for carbon dioxide separation techniques (chemical or physical scrubbing or cryogenic processes).

In the course of the transformation to a climate-neutral economy, natural gas conditioning as a CO_2 source will phase out along with the use of natural gas as an energy carrier.

3.2.5 Summary: CO_2 concentrations and energy requirements

Table 4 shows typical values for different CO_2 sources and capture processes.

Table 4: Characteristics of the most important CO_2 sources and capture processes (von der Assen et al., 2016; Fischedick et al., 2015; Vatopoulos / Tzimas, 2012).

CO_2 source	Available in the long term?	CO_2 concentration [vol.%]	Separation technologies	Electricity demand (GJ/t $CO_{2,prod}$)	Heat demand (GJ/t $CO_{2,prod}$)	Fuel demand (GJ/t $CO_{2,prod}$)
Air (absorption)	yes	0.04 %	CL	1.3	4.2	
Air (adsorption)	yes	0.04 %	**TSA/PSA**	2.5	7.9	
Biogas	yes	20-45 %	**CS, PWS, DWA,** M, PW	1.0 (PWS, PSA) 0.4 (CS)	2.6 (CS)	
Bioethanol production[1]	yes	99 %	--	0.40	0.01	
Biomass CHP	yes	14-17 %	CS	1.22		
Natural gas CCGT power plant	no	3-4 %	CS	1.60	--	
Refinery	no	3-13 %	CS	0.91	3.16	
Coal-fired power plant	no	12-15 %	CS	1.22	--	
Iron and steel production[2]	no	17-35 %	CS, PS	0.35-0.5 (CS) 0.77 (PS)[3]	2.5-4.4 (CS)	
Integr. pulp and paper production	yes	13-14 %	CS	0.04	1.57	
Cement factory	part.	14-33 %	CS, CL	0.65 (CL) 0.49 (CS)	-- 3.65 (CS)	2.17 (CL)
Integrated Gasification Combined Cycle power plants (coal)	no	40 %	**PS**, PSA, TSA, CS	0.40	--	0.81
Ammonia production[1]	no	100 %	--	0.40	0.01	
Natural gas conditioning[1]	no	100 %	--	0.40	0.01	

Abbreviations for the separation technologies: Chemical Scrubbing (CS), Pressurised Water Scrubbing (PWS), Pressure Swing Adsorption (PSA), Temperature Swing Adsorption (TSA), Membrane Separation (M), Physical Scrubbing, e.g. Polyglycol (PS), Cryogenic Separation (C), Carbonate-Looping (CL), most common process: **bold.**

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[1] Compression only, heat requirement for gas drying (after (Farla et al., 1995))
[2] Without compression of the raw gas, which often aims at a subsequent use of the gas (gas turbine).

3.3 Fischer-Tropsch and methanol synthesis

As shown in the Figure 5, there are essentially two pathways to produce PtL fuels: Fischer-Tropsch (FT) synthesis and methanol synthesis. Both technologies are based on the use of hydrogen and electricity as well as CO and/or CO_2. The subsequent processing steps may vary to some extent.

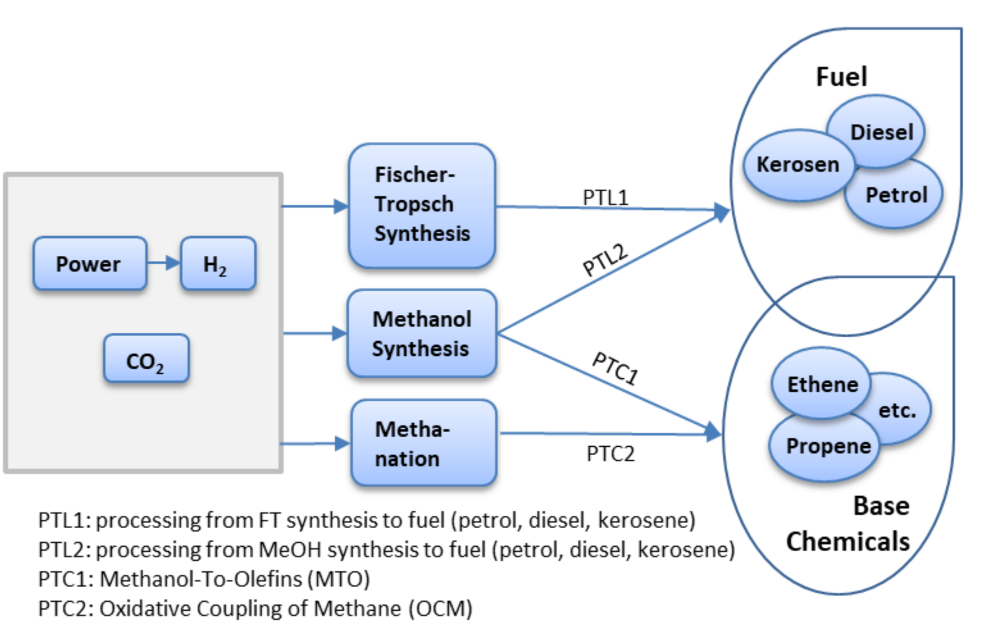

Figure 5: Schematic of the synthesis of PtX products from hydrogen and CO_2 by Fischer-Tropsch and methanol synthesis (Arnold et al., 2018).

The FT process consists of CO_2 capture, followed by synthesis gas generation, the Fischer-Tropsch synthesis, hydrocracking and product treatment/refining. In a so-called reverse water-gas shift reaction (rWGS), synthesis gas is produced: CO_2 and H_2 are converted into CO and water at temperatures up to 1,000 °C and pressures up to 50 bar. In the Fischer-Tropsch synthesis, hydrocarbons are catalytically synthesised at pressures between 20 and 40 bar and temperatures around 200-300 °C. The output of the Fischer-Tropsch synthesis consists of liquid hydrocarbons in different compositions, depending on the process conditions. These hydrocarbons are processed into a fuel mix by hydrocracking, isomerisation and distillation. This process can be varied or adjusted depending on the process conditions; 50-60 % production of fuel suitable for aviation use can be achieved. Subsequent oligomerisation can increase this proportion even further.

In a similar way, the methanol process consists of an upstream CO_2 capture, followed by synthesis gas generation, methanol synthesis and a separation column. Methanol synthesis is operated at temperatures of 40-260 °C and pressures up to 100 bar, commonly by using a copper catalyst. The synthesised methanol is further processed via DME (dimethyl ether) synthesis, olefin synthesis, oligomerisation and hydrotreating, yielding a mix of products: mainly petrol, diesel and kerosene. In recent years the direct synthesis of methanol from CO_2 and H_2 has be develop to a high technology readiness level.

3.4 PtL plants

The production of synthetic fuels from fossil carbon and hydrogen sources – both via the Fischer-Tropsch route and the methanol route – is an established industrial process. Several trans- or multinational companies such as Shell and Sasol operate in this field. The South African company Sasol, with subsidiaries in Germany a.o., is one of the world's largest producers of synthetic fuels. From the 1990s onward, these processes have been relying mainly on coal and partly on natural gas. Starting in 2012, Shell has been operating the so-called Pearl plant in Qatar, producing the synthetic fuel GTL from natural gas commercially and on a large scale. The production of PtL is still being researched and developed. The PtL research field is still relatively small in comparison to the development of other fuels (e.g. very active and widespread biofuels research) and PtG, which is extensively researched and discussed in a variety of publications. The company "Sunfire" from Dresden/Germany is one of leading players in the field of actual synthetic fuel production in Europe (Arnold et al., 2018).

Currently, two relevant and technically similar plants can be identified for methanol synthesis utilising regeneratively produced hydrogen and CO_2, using different CO_2 sources:

- The George Olah commercial direct methanol plant in Iceland using CO_2 from geothermal sources with an annual capacity of 50,000 l.
- The plant operated as part of a research project at the Lünen coal-fired power plant using CO_2 from flue gases.

Judging from the projects realised so far, a time frame of around 10-15 years, from planning to commercialisation, can be derived. All currently running projects have been relying on public research funds.

Currently, PtL demonstration plants exhibit relatively high technology maturity levels (TRL 5-8). Methanol shows slight development advantages compared to the Fischer-Tropsch processes. However, the mentioned TRLs do not apply to plants in flexible operation (partial load operation, fast load changes for demand side management (DSM), energy-efficient coupling with other processes). If these aspects were additionally demanded, the TRL values would be approx. 1-2 levels lower as estimated by (Ausfelder, 2015).

Further research on the choice and production of suitable catalyst materials is needed for both PtL technology paths (Fischer-Tropsch and methanol synthesis). In addition, the plant conditions and concepts must prove to be operational on a larger scale: the reaction conditions, the design of the reactor type, energy and mass transport as well as catalyst formulation, and the lifetimes of catalysts (under realistic production conditions).

Experts consider the focus of a technology on one product for an exclusive use as a potential economic risk. On the one hand, such a risk is anticipated for Fischer-Tropsch-based PtL fuels in road transport, where they compete with electrification. On the other hand, there are few to no alternatives to Fischer-Tropsch kerosene for aviation, considering the given need for GHG-neutral fuels. In contrast to this uncertainty, the methanol pathway could also be used as part of power-to-chemicals, reducing the investment risk in the medium to long term.

4 Global guard rails and international sustainability goals for the development of criteria

Ever since the World Environment Summit in Rio de Janeiro in 1992, sustainability has become an obligatory task for every global and local development action. However, for a long time there was no universally valid agreement on a practical definition of sustainability or on criteria for its verification. The first globally agreed catalogue of goals for sustainable development is contained within the year 2000 UN Millennium Development Goals (MDGs).

4.1 Sustainable Development Goals (SDGs)

With the 2030 Agenda for Sustainable Development, the UN adopted the *Sustainable Development Goals* (SDGs) in 2015. They include 17 sustainability goals, each with fixed completion time targets, setting a milestone that calls on all states to align their actions accordingly. The UN resolution contains 169 sub-goals, each with indicators for measurement.

Figure 6: The 17 Global Sustainable Development Goals (SDGs) of the 2030 Agenda.

The following selection of SDGs and sub-goals is considered relevant to the task at hand in this study:

- **SDG 2**: End hunger, achieve food security and improved nutrition, and promote **sustainable agriculture**
  - 2.3: Increase agricultural productivity (double by 2030)
  - 2.4: Ensure sustainability of food production systems by 2030
- **SDG 7**: Ensure access to affordable, reliable, **sustainable** and modern **energy** for all
  - 7.2: Significantly increase the share of renewable energy in the global energy mix by 2030
- **SDG 9**: Build resilient infrastructure, promote inclusive and sustainable industrialisation and support innovation
  - 9.4: By 2030, modernise infrastructure and retrofit industries to make them sustainable, with more efficient use of resources and increased use of clean and environmentally sound technologies and industrial processes.
- **SDG 10**: Reduce inequality within and between countries [1]
- **SDG 12**: Ensure sustainable consumption and production patterns
  - 12.1: Implement sustainable consumption and production patterns
  - 12.a: Strengthen developing countries' technological capacities[198]
- **SDG 13**: Take urgent action to combat **climate change** and its impacts
  - 13.2 Integrate climate action into national policies, strategies and planning.
- **SDG 15**: Protect, restore and promote the sustainable use of terrestrial ecosystems, manage forests sustainably, combat desertification, halt and reverse land degradation, and end the loss of biodiversity
  - 15.5: Reduce the degradation of natural habitats in order to halt the loss of biodiversity.
- **SDG 17**: Strengthen means of implementation and breathe new life into the **global partnership** for **sustainable development**[198]
  - 17.2: Strengthen investments in least developed countries

4.2 Further guard rails and standards

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[1] As this work focuses on German domestic production, this SDG does not apply for the time being. It may gain in importance if the framework is expanded to include production abroad (emerging and developing countries).

The SDGs were integrated into a concept of planetary guard rails by the WGBU (2014). On the other hand, the concept of planetary boundaries by Rockström et al. (2009) and Steffen et al. (2015) formulates "planetary boundaries" for nine key natural systems and processes. Both approaches are suitable for inferring criteria for sustainability.

Specific sustainability criteria for the actions of states, national economies, producers and consumers have been developed, proposed or made binding by various parties. In particular over the past fifteen years, there have been activities in the context of the use of bioenergy. The RED[1] mentioned earlier is the first set of legal regulations containing sustainability criteria for specific products (biofuels and liquid biofuels) that are binding and subject to verification. In the meantime, an ISO standard on sustainability criteria and indicators for bioenergy has been adopted.[2] The 24 sustainability indicators of the Global Bioenergy Partnership (GBEP)[3] serve as another reference in the bioenergy context. Table 5 shows the guard rails and criteria from the mentioned sources sorted thematically.

Table 5: Guard rails and criteria of different standards

SDG	WGBU	Planetary boundaries	RED / RED II	ISO 13065	GBEP
13.2	Limit climate change to 2 °C	Climate change	Greenhouse gas saving	Greenhouse gas saving	Greenhouse gas saving
14	Limit ocean acidification to 0.2 pH units	Acidification of the oceans			
15 esp.: 15.5	Halting the loss of biodiversity and ecosystem services	Intactness of the Biosphere	No conversion of primary forest	Biodiversity protection	Biodiversity protection
15.3 2.4	Stop land and soil degradation	Land use change	No conversion of C-rich areas	Protection of the soil	Protection of the soil Land use and LUC
	Limit exposure to persistent anthropogenic pollutants	Aerosol content in the atmosphere O_3 in stratosphere New Subst., GMO		Air pollutants	Air pollutants
	Stop the loss of phosphorus	Biochemical fluxes (P + N)		Protection of water quality	Protection of water quality
6		Freshwater use		Water as a resource; Water rights	Water as a resource

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[1] Directive 2009/28/EC
[2] ISO 13065.2015: Sustainability criteria for bioenergy
[3] http://www.globalbioenergy.org/programmeofwork/task-force-on-sustainability/gbep-report-on-sustainability-indicators-for-bioenergy/en/

1, 3			Land rights, food prices	Land rights, food prices
2.3, 2.4		No food competition		Food prices

Explanation: LP: Guard rails according to WBGU (2014), PG: Planetary boundaries according to Steffen et al. (2015); RED: Renewable Energy Directive; ISO: ISO 13063.2015

4.3 Developing criteria based on global guard rails and standards

The task of deriving implementation criteria for PtL generation for aviation presented here follows the described guard rails of global objectives and existing standards on sustainability criteria. The SDGs identified as relevant are the primary benchmark. These are analysed in Table 6 regarding the extent to which they should serve as an implementation criterion or provide a directional statement for a criterion.

This task is extremely complex, as the global guard rails, objectives and standards are formulated in a general, globally valid sense, whereas the object of assessment is highly specific in our case (especially with regard to the CO_2 source). One example is the of the connection between the increase in agricultural productivity and the use of CO_2 from a biomethane processing plant. Even though it may be difficult to state a direct connection, indirect interactions can occur due to a multitude of factors – a complexity that cannot be solved within the framework of this study.

The implementation criteria for assessing the sustainability of CO_2 sources in particular are therefore derived by establishing coherent connections between the global sustainability goal requirements and the technical-ecological knowledge about the CO_2 sources. A first analysis step establishes the connection, a next step highlights the significance of this connection for the assessment of sustainable PtL, and a final step deduces a principle and criterion for the assessment.

These steps are shown in Table 6. The following principles to be fulfilled by the CO_2 sources are derived from this:

1. Fossil CO_2 sources are to be generally excluded, i.e. the CO_2 source shall be biogenic or the atmosphere; exceptions may be possible for a transitional phase under certain conditions.

The provision of CO_2 should be associated with as little environmental impact as possible. This can be addressed by the following two principles:

2. The origin of the CO_2 is strictly residual; therefore, no environmental burdens of the origin process are attributed to it.
3. The CO_2 source process does not have any serious environmental impacts.

The conditions for exceptions regarding principle 1 are based primarily on the following:

4. The risk of lock-in effects must be avoided; i.e. the CO_2 source technology or the products cannot be dispensed with or substituted even in the long term, or the technology has no other possibility for zero CO_2 emissions.

In chapter 5.2 the pattern of principles and criteria is explained in detail and applied to various CO_2 sources. The criteria for additionality of renewable electricity are described in detail in chapter 6.

Table 6: Compilation of criteria and derived guard rails for the assessment of renewable electricity and CO_2 sources.

Topic	SDG	Analysis	Significance for the evaluation of sustainable PtL	Principle/criterion for assessing sustainable PtL
Increase agricultural productivity	2.3	Cultivation of biomass for food purposes only Livestock farming must be reduced (requires too much use of resources)	CO_2 from cultivated biomass is to be assessed as disadvantageous. CO_2 from livestock farming (liquid manure etc.) for PtL is to be assessed as disadvantageous	CO_2 source: Severity of the environmental impact of the CO_2 source process
Sustainable food production	2.4	Excess of nitrogen agricultural production, therefore artificial fertiliser must be cut back	CO_2 from ammonia synthesis is to be assessed as disadvantageous	
Increase renewable energy share	7.2	This requires additionality of renewable electricity for PtL	Electricity must be proven to come from additional renewable energy sources	Electricity: Additionality criteria for electricity
Environmentally sound technologies	9.4	Steel, cement, glass, paper/pulp etc. without CO_2 emissions must be produced in line with SDG 13 (climate)	CO_2 from cement, steel, ceramics, etc. production is critical or even disadvantageous	CO_2 source: Fundamental exclusion of fossil CO_2 Residual character of the CO_2 Avoid the risk of lock-in effects
Sustainable production patterns	12.1			
Climate protection measures	13.2	According to the principle of the emissions budget, the global economy must be decarbonised by 2036 in order to achieve the 1.5 °C target.	CO_2 for PtL from fossil sources is to be excluded	CO_2 source: Fundamental exclusion of fossil CO_2 Electricity: Basic premise: Electricity only from additional renewable energy sources
No soil degradation	15.3		CO_2 from cultivated biomass is to be assessed as disadvantageous. CO_2 from livestock farming (liquid manure etc.) for PtL is to be assessed as disadvantageous	CO_2 source: Severity of the environmental impact of the CO_2 source process Residual character of the CO_2
Biodiversity protection	15.5			
Protection air, water	6			

5 Assessment of CO_2 sources

5.1 Availability of CO_2 sources

The CO_2 sources described above are available in different quantities. CO_2 from direct absorption or adsorption from the air (DAC) may in principle be considered available in *unlimited* quantities, with an absolute amount of around 3,000 billion tonnes of CO_2 in the Earth's atmosphere[1]. The actual limits are based on the technical and economic availability.

Hereafter, the theoretically available quantities of CO_2 from biogenic and industrial sources are compiled considering the given boundary conditions.

5.1.1 Availability of biogenic CO_2 sources

As described in chapter 3.2.3 there must be a differentiation between the source of CO_2 as a by-product of biomethane upgrading from biogas or bioethanol production on the one hand and CO_2 from the combustion of bioenergy sources and subsequent capture on the other hand: CO_2 as a by-product of biomethane upgrading or bioethanol production is virtually directly available from existing plants, while for CO_2 from combustion, the existing of future plants (e.g. biomass CHP plants) must be equipped with separation technology. In the short term, this separation technology and thus the CO_2 that could be extracted by its application it is not available. Looking ahead to 2030, however, corresponding investments in this technology can be expected, at least for larger plants.

Current studies can serve as literature, although they mainly focus on the quantities of biomass, biomethane and bioethanol instead of directly investigating the potential of separable CO_2. The respective amounts of CO_2 produced can be deduced directly from these studies. Fehrenbach et al. (2019) serves as a key reference, evaluating over 50 biomass potential studies from recent years. Other important works are Brosowski et al. (2015) and Thrän et al. (2019).

5.1.1.1 Biogas upgrading

As shown in Table 3 CO_2 can be captured with purities from only 14-30 % up to as far as 100 %, depending on the treatment technology. Accordingly, technologies exhibiting low CO_2 purities from biogas upgrading have no advantage over capture

[1] http://igss.wikidot.com/co2mass

from combustion flue gases. Therefore, the development and dissemination of techniques must considered.

Regardless of this, the total potential quantity of CO_2 from biogas upgrading adds up to a total of 14.0 million t CO_2 per year. The given figures rely on the amount of biogas currently produced from renewable resources, based on data from Daniel-Gromke et al. (2017). As shown in Table 7 slightly more than half of this amount is coming from cultivated biomass and thus requires area for agriculture. The remaining potential amounts to 6.3 million tonnes CO_2 per year from biogenic waste and residues. Excluding the CO_2 potentials from livestock farming (manure and slaughterhouse wastes), the remaining potential is 2,8 million tonnes CO_2.

Currently, based on Daniel-Gromke et al. (2017), 9.7 million t of biogenic CO_2 are produced from biogas upgrading in existing biogas plants, predominantly in smaller plants with a power output of < 750 kW. However, only 0.72 million t are produced in biomethane plants and would thus be practically directly available for use. Almost 90 % of this quantity is based on renewable raw materials.

Table 7: Volume potentials in Germany from biogas upgrading.

Sector	**Biomass substrate for biogas**	**Energetic potential [PJ/a]**	**CO_2[a)] potential [million t/a]**
Agriculture	Liquid manure	53	1.7
	Solid manure	49	1.6
	Crop residues	11	0.35
	Cultivated biomass [b)]	240	7.7
Municipal disposal	Green waste	5.6	0.18
	Bio waste	24	0.78
	Catering waste	0.7	0.02
	Sewage gas, municipal [c)]	22.7	0.73
Industrial refuse	Various substrates from the food and luxury food industry (except slaughterhouses)	23	0.74
	Waste from slaughterhouses	12	0.22
SUM			
Without cultivated biomass			**6.3**
Excluding cultivated biomass and livestock farming			**2.8**
Total			**14.0**

a) For the calculation, the energy potentials according to Fehrenbach et al. (2019) were assumed as biogas with a calorific value of 50 MJ/kg methane combined with 35 vol.-% CO_2 at a mass/gas ratio of 44 : 16 for CO_2 : CH_4.
b) For cultivated biomass, the currently produced biogas volume (according to Daniel-Gromke et al. 2017) is used, and it is assumed that a further expansion of this volume is not compatible with the policy goals.
c) Includes just under 5 % sewage gas from industrial wastewater treatment plants.

5.1.1.2 Biothanol production

According to the German Bioethanol Industry Association (Bioethanolwirtschaft e.V., BDBe), about 750,000 tonnes of bioethanol are produced in Germany every year.[1] About 79 % of this is based on feed grain and 21 % on sugar beet pulp. The reported share from residual and waste materials (e.g. from the food industry) is very low (about 1 %).

With each tonne of ethanol, about one tonne of CO_2 is produced.[2] The theoretical CO_2 potential of the bioethanol industry is therefore around 0.7 million tonnes per year and thus comparable to the CO_2 quantities currently produced in real terms in biomethane processing plants in Germany.

5.1.1.3 Biomass heating plants

The theoretical potentials of CO_2 to be captured from flue gases of biomass CHP plants – assuming that the total of the combustible biomass available according to Fehrenbach et al. (2019) is used in this way – are compiled in Table 8. They add up to a total of approx. 77.7 million t CO_2 per year.

Straw and forest wood together account for about 40 million t of this. The combustion of wood from municipal and industrial sources releases about 17 million tonnes of CO_2. Other combustible biomasses such as black liquor, sewage sludge or the biogenic portion of residual household waste are also already being burned in special plants; the corresponding amounts of CO_2 that could theoretically be sequestered add up to another 8 million tonnes per year.

In order to realise these potentials, the plant capacity of biomass CHP plants needs to be approximately doubled. Currently, in Germany 22.6 million solid cubic metres[3] are burned[4] in biomass CHPs of more than 1 MW power and 7.2 million solid cubic metres in smaller biomass CHPs (corresponds to about 15 million tonnes of dry matter and 27 million tonnes of CO_2). Including the special plants mentioned (waste incineration plants, etc.), the stock of plants thus produces approx. 35 million tonnes of CO_2. None of these plants is currently equipped with CO_2 capture technology.

Energy crops (e.g. energy grasses and wood from short-rotation plantations) also represent a potential raw material for biomass CHPs. However, as with the cultivated biomass listed in the previous section, such energy crops require area, which is a very limited resource due to competing uses. According to a survey by Statista[5], for years the cultivation of energy crops as solid fuels has occupied a total area in the range of 11,000 hectares. This value is used to infer the available quantity of energy crops; it

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[1] https://www.bdbe.de/daten/marktdaten-deutschland
[2] Stoichiometrically, 1 mole of CO_2 with a molar mass of 44 g is associated with 1 mole of ethanol with a molar mass of 46 g, so the exact ratio is 0.956 t CO_2/ethanol.
[3] Solid cubic metre = room measure for 1 m^3 solid wood mass
[4] https://mediathek.fnr.de/grafiken/daten-und-fakten/bioenergie/fest-biobrennstoffe.html
[5] https://de.statista.com/statistik/daten/studie/153072/umfrage/anbauflaeche-von-energiepflanzen-in-deutschland-nach-sorten-seit-2007/

corresponds to about 0.11 million tonnes of biomass and a theoretically separable CO_2 potential of 2 million tonnes of CO_2.

Table 8: Theoretical potential quantities of CO_2 to be captured from combustion flue gases of biomass CHP plants.

Sector	**Biomass**	**Dry matter [million t/a]**	**Energetic Potential [PJ/a]**	**CO_2[a)] potential [million t/a]**
Agriculture	Straw	11.2	187	19.7
	Landscape maintenance material	0.5	16	1.0
	Energy crops	0.11	2.1	2.0
Forestry	Forest wood [b)]	11.0	204	20.2
Municipal waste	Green waste (woody)	0.8	16	1.4
	Waste wood	4.6	85	8.3
	Sewage sludge, household waste (biogenic fraction), etc.	7.4	61.3	13.5
Industrial refuse	Industrial waste wood	3.9	55	7.1
	Black liquor, sludges	2.5	42.2	4.5
SUM		**42.1**	**669**	**77.7**
Existing combustion		**approx. 25**	**approx. 300**	**approx. 35**

a) Based on data according to Fehrenbach et al. (2019), about 50 % C was assumed for the biomasses in dry matter.

b) Only rough wood (> 7 cm diameter) is counted as forest wood potential, since it is not suitable for the sawmill industry.; the demand of the paper/pulp and wood-based industry is deducted. So-called forest residues (< 7 cm diameter) are excluded from the sustainably usable potential for reasons of biodiversity and nutrient cycles (see Fehrenbach et al. 2019).

5.1.2 Availability of other industrial CO_2 sources

The theoretical potentials of CO_2 from industrial sources other than biogas and biomass combustion are compiled in Table 9. They add up to a total of about 70 million tonnes of CO_2 per year. The Federal Environment Agency's scenarios for a *greenhouse gas-neutral Germany* (THGND) (UBA 2014) and a *greenhouse gas-neutral and resource-conserving Germany* (RTD) (UBA 2019) serve as data sources. The steel and cement industries make the highest contributions.

If the THGND and RTD scenarios are followed, then significant decreases in CO_2 emission quantities in the steel industry and the chemical industry are possible via technical measures (switch to renewable sources). For the cement, lime and glass industries, only minor reduction potentials are to be expected. These CO_2 sources will thus be available in the longer term. According to the RTD scenarios, over 13 million tonnes of CO_2 emissions per year can still be expected in these sectors by 2050.

Table 9: Theoretical potential quantities of CO_2 capture from other industrial sources.

Sector	Production volume of the target product [million t/a]	CO_2 potential [million t/a]
Cement industry, product cement clinker (fuel- and process-related CO_2)	23.6	21.0
Lime industry (fuel and process-related CO_2)	6.3	7.3
Glass industry (fuel and process-related CO_2)	7.2	3.8
Steel industry (oxygen and electric steel furnaces) (process-related CO_2)	43.8	28.3
Aluminium industry (process-related CO_2)	1.3	0.83
Petrochemical industry (hydrogen reforming)		
→ Ammonia production	1.7 (H_2)	7.4
→ Mineral oil refineries	0.18 (H_2)	0.78
SUM		**approx. 70**

Sources: Figures for 2010 from UBA (2014, 2019) and ENCON.Europe (2018).

5.1.3 Summary on the availability of CO_2 sources

In addition to atmospheric CO_2, a total of 140 million tonnes of CO_2 per year can be determined as theoretically available potential from the energetic use of biomass and from industrial sources. Biogenic sources account for about 56 %, industrial sources for the remaining 44 %.

Table 10: Summary of the potential quantities of CO_2 sources.

Sector	CO_2 potential [million t/a]
Biogenic sources:	approx. 90
• Biogas upgrading	
o Total	14.0
o Without cultivated biomass and livestock farming	3.0
• Bioethanol production	0.7
• Biomass heating plants	75.8
Industrial sources	70
• thereof steel industry	28.3
SUM	**approx. 160**

However, this potential can only be realised through extensive investments in plants for biomethane upgrading from biogas and facilities for CO_2 capture from the flue gases of biomass CHP, cement, lime and steel plants. About 0.7 million tonnes of CO_2 each are currently available from existing biomethane and bioethanol plants. The CO_2 emissions from steam reforming of hydrogen from natural gas or heavy oil (e.g. for ammonia synthesis) are available in separated and highly concentrated form. These emissions are already used on a large scale as a technical gas and in the beverage industry.

5.2 Criteria grid for sustainable CO_2 sources

The following implementation criteria for CO_2 sources aiming at the certification of PtL must meet the demanding sustainability requirement standards on the one hand, and, on the other hand, should be as specific and operable as possible in order to facilitate their measurement and evaluation by third parties.

5.2.1 Principles

The criteria are subdivided into the following basic principles in accordance with the derivation in chapter 4:

1. Basic exclusion of fossil CO_2 (including conditions for exceptions).
2. Residual character of CO_2 – increasing residual character leads to decreasing amounts of CO_2 burdened with environmental loads from the source process;

   i.e. this principle is directly linked to the following:
3. Severity of the environmental burden of the CO_2 source process
4. Avoidance of risk of lock-in effects (related to the condition demanding the exclusion of fossil CO_2 sources).

The principles are interrelated and must therefore be analysed for all sources – with the exception of the fossil character in case of biogenic sources.

5.2.1.1 Fundamental exclusion of fossil CO_2

The first and comparatively clear principle poses the question of the fossil or regenerative character of CO_2. It is indisputable that sources of fossil CO_2 cannot be considered sustainable in principle, since the goal of climate protection policy is ultimately to phase out the use of all fossil raw materials. Regarding the argument that it should be in the interest of climate protection to equip fossil sources with *carbon capture and utilisation* (CCU), it is often overlooked that the considered fossil CO_2 will be emitted after the second use as PtL. These emissions would have to be allocated to the two uses (e.g. a natural gas power plant with CCU and the use of the PtL as kerosene). If the emissions are split evenly (see also Fehrenbach et al. 2017), half of the fossil CO_2 emissions would have to be credited to the PtL, which would definitely rule out a positive sustainability certification.

Fossil sources are thus generally excluded, while leaving room for certain exceptions. Conditions for exceptions are defined via the principles of the residual character issue (see the following point 2) and the lock-in effects (see point 4).

5.2.1.2 Residual character of the CO_2

Basically, direct environmental effects cannot be attributed to the production and use of biogenic CO_2, since the CO_2 can be considered a waste product in virtually all cases. None of these processes was designed to produce CO_2. Accordingly, the CO_2 can consistently be labelled a *residual substance* as defined in RED II:[1] "*'Residue' means a substance that is not the end product that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it.*" (Article 2, No. 43). This applies to fossil CO_2 (e.g. coal combustion, hydrogen reforming, etc.) as well as biogenic CO_2 (e.g. biogas, bioethanol).

The residual character consequently changes when the process is modified accordingly, e.g. when a cement plant or biomass CHP plant is equipped with CCU technology. Then the character changes from a waste (CO_2 diffusely diluted in the flue gas stream) to a co-product or by-product.

In principle, the more pronounced the residual character of the CO_2 emission is, the less the environmental impacts associated with its source process are to be attributed to it. Rather, burdens are to be attributed to the same extent to which the CO_2 becomes a targeted product or a waste product accumulated without major additional expenditure.

5.2.1.3 Severity of the environmental burden of the CO_2 origin process

As explained above, CO_2 can be considered a residual substance unless it is extracted directly from the air. The environmental impacts of the source processes are therefore only indirectly attributable to it. Nevertheless, the severity of the associated environmental burdens must be considered as a principle within the framework of a demanding sustainability certification.

A distinction must be made between direct and indirect impacts. Direct impacts are impacts of the production chain, such as the impacts of maize cultivation (see below). Indirect impacts, on the other hand, are those that do not arise in the production chain itself, but are related to the industrial sector for which the production chain produces. An example would be ammonia production, which, apart from the fact that it is based on the fossil raw material natural gas, has little environmental impact. However, the massive use of synthetic fertilisers (the target application of > 80 % of the

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[1] DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)

ammonia produced)[1] lead to a wide overshoot of planetary boundaries on a global scale (Rockström et al. 2009).

Essentially, the present principle aims at the evaluation of biogenic sources. As the long-standing debate on the sustainability of bioenergy shows, biogenic sources cannot be considered environmentally or climate-friendly per se. Renewable energy sources, e.g. biogas from maize or ethanol from grain, require land and thus compete with food production. Moreover, agricultural production is associated with numerous harmful environmental impacts (nitrate input, loss of biodiversity). Not only agricultural products but also biogenic residues can be directly or indirectly associated with major ecological burdens, e.g. manure, linked to the overproduction and consumption of meat and other animal products.

The criteria of this principle therefore differentiate according to the severity of the environmental burden, but also according to the directness or indirectness explained above. The severity is measured by the environmental impacts of the production process, aiming at the effects of land and the multiple burdens caused by livestock farming. In both cases, good practice can reduce severity, e.g. through certified cultivation on farms either according to an organic farming standard or the RED sustainability regulation. The former could also be considered for livestock farming. However, an elimination of all environmental burdens is not possible, as some environmental impacts remain even with good practice.

5.2.1.4 Risk of lock-in effects

The so-called lock-in effect is understood as the creation of a dependency with respect to a technology that in general is to be avoided. E.g., fossil power plants need to be shut down in accordance with the overarching goal, but currently they are still needed as a source of concentrated CO_2.

Therefore, the lock-in effect is a comparatively important component of the criteria to be developed. However, the question of assessing the future prospects of the respective technologies must be considered in detail. This applies in particular to the variety of industrial CO_2 sources beyond fossil power plants. A central example is the cement industry. CO_2 emissions (especially from the burning of lime) cannot be avoided here, even with modern technology and the use of biogenic waste as fuel. Assuming that cement will continue to be an indispensable building material in the future, the use of the CO_2 emissions captured from the respective plants represents an effective contribution to overall emission reduction – at least for a transitional period.

In this respect, exceptions to the basic exclusion of fossil CO_2 mentioned under point 1 can be justified based on the condition that the emissions occur in the future not due to lock-in effects, but rather because

the technology or the products cannot be dispensed with, and

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[1] Ullmann's Encyclopedia of Industrial Chemistry (2011): Ammonia; https://doi.org/10.1002/14356007.a02_143.pub3

the technology has no other option for zero CO_2 emissions.

However, such an exception has to be reassessed after a defined time period and cannot be applied in general and for all time.

The issue of lock-in effects is relevant not only for fossil but also for biogenic sources, although a rather indirect connection can be found here: For CO_2 from biogas via manure fermentation, a lock-in effect for industrial livestock farming can be assumed. However, compared to the strong and complex drivers behind livestock farming, the actual burdens of industrial livestock farming are likely to a be far more significant issue than the detail of CO_2 use via manure biogas.

5.2.2 Criteria grid for CO_2 sources

The criteria to be applied to specific CO_2 sources are formulated in the following, subdivided according to the discussed four principles. The criteria are summarised in Table 11. Each criterion exhibits three stages of fulfilment (1: fulfilled, 2: partially or conditionally fulfilled; 3: not fulfilled), additionally illustrated with colours for further presentation according to the traffic light principle (green, orange, red, 1 2 3) (see also Table 12).

The criteria are often interrelated or presuppose premises when applied to an individual case. For example, for the source "CO_2 from direct capture from air", it must be assumed in principle that the considerable energy demand for the DAC process is covered by 100 % additional renewable energy sources (see criteria for renewable electricity).

Table 11: Criteria for the assessment of specific CO_2 sources.

Principle / Criterion	CO_2 source	Explanation / Justification	Score
Principle 1: Fundamental exclusion of fossil CO_2			
Criterion 1: The source of CO_2 is biogenic or the atmosphere.	Direct separation from the air	Fulfilled	1
	Natural outgassing (e.g. mofettes)	Fulfilled, provided that no active deep groundwater wells are drilled into (if the latter is the case: not fulfilled)[1]	1 3
	Biogenic CO_2 source	Biogas, bioethanol, any type of biomass (according to biomass regulations)	1
	Waste gas from gas, oil and coal-fired power plants, combined heat and power plants or heating plants	The national climate protection targets demand the rapid phase-out of all forms of fossil energy production. The certifiability of CO_2 from these plants for sustainable PtL increases the risk of a lock-in effect. (principle 4)	3

[1] Assessment cannot yet be fully made; this requires more detailed investigations into the question of whether all or part of the CO_2 would also be released without human intervention.

Principle / Criterion	CO_2 source	Explanation / Justification	Score
	Waste gas from waste incineration plants	The ratio of fossil to biogenic C content in the waste incineration input is 40 % to 60 % (Hoffmann et al. 2011).	2
	Waste gas from RDF plants	The ratio of fossil to biogenic C content in the waste incineration input is 60 % to 40 % (Schwarzböck et al. 2018).	3
	Waste gas from municipal sewage sludge incineration plants	The ratio of fossil to biogenic C content in the input is 20% to 80%.	1
	Waste gas from industrial sewage sludge incineration plants	The ratio of fossil to biogenic C content in the input 50 % to 50 %.	2
	Waste gas from cement, lime, ceramics, glass works	These products will also be needed in a material-efficient materials economy of the future, but there are also increasingly low-carbon alternatives. [CO_2 from the calcination of limestone is not fossil in the strict sense, but mineral. However, it shows the same character as fossil CO_2 in the context of anthropogenic greenhouse gas emissions.]	3
	Steel, aluminium	Steel and aluminium will be needed in the future; however, scenarios for a resource-conserving and greenhouse gas-neutral Germany show technical solutions for an elimination of all CO_2 emissions by 2050.	3
	Chemical industry (hydrogen for ammonia production)	For ammonia, scenarios for a resource-conserving and greenhouse gas-neutral Germany show technical solutions for an elimination of all CO_2 emissions by 2050. For other process emissions, sourcing must be examined on a case-by-case basis	3
	Mineral oil sector (hydrogen for hydrogenation)	The use of hydrogen serves the production of fossil fuels, the certifiability of CO_2 from these plants for sustainable PtL is therefore excluded according to Criterion 1.	3
Principle 2: Residual character of the CO_2		**The more pronounced the residual character, the more favourable the rating; rating 1 also for CO_2 from the air.**	
Criterion 1: The CO_2 is extracted from the air; the electricity used for this purpose fulfils the criteria for additional renewable electricity as defined in the catalogue *Valuation of Electricity* (see chapter 6.3).	DAC, Direct separation from the air	Withdrawal from the atmosphere indicates climate neutrality and – with the exception of the current high specific energy demand and a certain land requirement – has no environmental burdens or lock-in effects.	1
Criterion 2: The CO_2 accumulates in a process in a highly enriched	Biomethane or bioethanol plant that involuntarily	In this case, CO_2 is in full sense a residual substance as defined in Directive (EU) 2018/2001	1

Principle / Criterion	CO_2 source	Explanation / Justification	Score
form (degree of purity > 80 % CO_2) without the process being aimed at or modified for the production of CO_2.	produces a highly enriched CO_2 fraction when separating CH_4 and CO_2 in the biogas.	(RED II), to which no burdens from preceding processes are to be credited in accordance with the allocation rule.	
	Steam reforming of methane to hydrogen	Analogous to CO_2 from the biomethane or bioethanol plant	1
	CO_2 separation (CCU) from combustion exhaust gases	The CO_2 is produced in a process that is operated specifically to capture it from an upstream process.	2
	purposefully produced CO_2	Such CO_2 is by definition a product.	3
Principle3: Severity of the environmental impact of the CO_2 origin process			
Criterion 1: The CO_2 source is unburdened by a preliminary process.	DAC, Direct separation from the air	The technology removes CO_2 from the atmosphere and thus mitigates the greenhouse effect, as long as the energy used originates 100 % from additional renewable energy sources.	1
	For all other sources, the classification according to Principle 2 Criterion 2 applies.	Preliminary process burdens are more or less credited in connection with the residual material character.	**see Principle 2 Criterion 2**
Criterion 2: The upstream process is not associated with land use and resulting environmental impacts.	Biomethane upgrading from biogas or CO_2 from bioethanol based on renewable raw materials (e.g. maize), conventional agriculture	Sustainability conflicts occur due to cultivated biomass for energy.	3
	Biomethane upgrading from biogas or CO_2 from bioethanol based on renewable raw materials (e.g. maize); organic farming	Mitigating environmental conflicts through ecological practice	2
	Biomethane upgrading from biogas based on liquid manure	Manure production as a result of excessive livestock farming with significant consequences for the nitrogen balance, climate protection, land use	3
	Biomethane upgrading from biogas based on biowaste	No relevant space occupancy	1
	Biomethane processing of sewage gas [a)]	No relevant space occupancy	1
	Biomethane upgrading from biogas on the basis of other organic residues	No relevant space occupancy	1
	CCU Biomass CHP cultivated biomass	Sustainability conflicts due to cultivated biomass for energy, for woody biomass generally less than for agricultural products; the following classification apply:	
		Agricultural biomass (land use)	3

Principle / Criterion	CO_2 source	Explanation / Justification	Score
		Forest biomass (without certificate)	2
		Forest biomass (with high-quality sustainability certificate, e.g. *Naturland*)	1
	CCU Biomass CHP biogenic residues	No relevant space occupancy	1
	CCU waste incineration	No relevant space occupancy	1
	CCU RDF cogeneration plant	No relevant space occupancy	1
	Sewage sludge incineration plant, municipal	No relevant space occupancy	1
	Sewage sludge incineration plant, industrial	No relevant space occupancy	1
	CCU fossil power, CHP heating plants	already excluded via Principle 1 Criterion 1	3
	Industrial CO_2 sources	No relevant space occupancy	1

Principle / Criterion	CO_2 source	Explanation / Justification	Score
Criterion 3: The preliminary process is generally not associated with significant environmental burdens, except via land use.	Waste gas from cement, lime, ceramics, glass works	No process is without environmental burden; the industrial processes listed here can be optimised from an environmental point of view and are not associated with significant environmental burdens as a result of the use of the products.	1
	Process gases from steel, aluminium plants	See waste gas from cement, lime, ceramics, glass works	1
	Steam reforming for ammonia production	80 % ammonia use for fertiliser production; the extent of nitrogen fertiliser use is one of the key global environmental problems.	3
	CCU fossil power, CHP heating plants	already excluded via Principle 1 Criterion 1; significant environmental impacts otherwise due to power plant emissions and extraction of energy sources.	3
	Steam reforming for hydrogen in the mineral oil sector	Already excluded via Principle 1 Criterion 1	3
	Biogenic source, plant-based	Disadvantages via land use (Criterion 3) considered	1
	Biogenic source, livestock farming	Already considered major disadvantages via land use (Criterion 3); aspect of global limits for the consumption of animal products scored again here.	2
	Biogenic waste/residual material as a source for biomethane production	**Differentiation according to Annex A**	
	Biogenic waste/residue as source via biomass CHP with CCU	**Differentiation according to Annex B**	

Principle / Criterion	CO_2 source	Explanation / Justification	Score
Principle 4: Risk of lock-in effects			
Criterion 1: The CO_2 source technology or the products are not dispensable or substitutable even in the longer term.	Biomethane upgrading from biogas or CO_2 from bioethanol based on renewable raw materials	Bioenergy can be replaced by other renewable energies, but can make a transitional contribution.	3
	Biomethane upgrading from biogas based on liquid manure	Bioenergy can be replaced by other renewable energies, as manure will be produced in the long term, it is necessary to use it in an environmentally friendly way (→ fermentation is necessary).	2
	Biomethane upgrading from biogas based on biowaste and other organic residues	It is sensible to use this unavoidable waste efficiently via biogas and biomethane utilisation.	1
	CCU biomass CHP cultivated biomass	Bioenergy can be replaced by other renewable energies, but can make a transitional contribution.	2
	CCU biomass CHP biogenic residues	Use of residual materials can make a meaningful contribution within the scope of the available potentials.	1
	CCU waste incineration	In the longer term, waste incineration will be the decisive measure for environmentally sound waste disposal.	1
	CCU RDF cogeneration plant	Energy recovery will be a key measure for environmentally sound waste management in the longer term; (on the other hand, the policy objective is to increase the recycling rate and waste prevention rate – especially for mass flows from the packaging sector and plastics as a whole).	1
	CCU sewage sludge incineration plant	Sewage sludge incineration is, with the sewage sludge ordinance, the decisive measure for the environmentally sound disposal of this waste stream.	1
	CCU RDF cogeneration plant; sewage sludge incineration plant		1
	Waste gas from cement, lime, ceramics, glass works	The products are not dispensable or only partially substitutable, even in the longer term.	1
	Process gases from steel, aluminium plants	The products are not dispensable or only partially substitutable, even in the longer term.	1
	Steam reforming for ammonia production	Ammonia will continue to be needed in the future; it is questionable whether it makes sense for sustainable development on this scale.	2
	CCU fossil-fuel power and heating plants	already excluded via Principle 1 Criterion 1	3

Principle / Criterion	CO_2 source	Explanation / Justification	Score
Criterion 2: The technology has no other possibility for zero CO_2 emissions.	Biomethane upgrading from biogas or CO_2 from bioethanol	It is sensible to use the CO_2 that has already been captured.	1
	CCU biomass CHP	No other avoidance options	1
	Waste gas from cement, lime, ceramics, glass works	Only very limited other avoidance options	1 2-3
	Process gases from steel, aluminium plants	In the long term, there are other ways to reduce CO_2 emissions.	3
	Steam reforming for ammonia production	In the long term, there are other ways to reduce CO_2 emissions.	3

a) In principle, landfill gas would also have to be considered, however, it is of decreasing importance in Germany, as it is prohibited to landfill organic waste since 2005. The volume of landfill gas is about a quarter compared to sewage gas (UBA 2019a). However, landfill gas can play a significant role for the application of the criteria countries other than Germany.

5.2.3 Consolidation and overall ranking

Procedure

Table 12 compiles the ratings for all CO_2 sources considered according to all criteria. As a last step, the ratings of all criteria are combined into one result; the six criteria are weighted evenly. The overall rating determines which CO_2 source

1. is assessed positively overall, i.e. the use of the CO_2 can be unrestrictedly certified as sustainable.
2. is assessed predominantly positive, but can only be certified as sustainable provisionally, i.e. for a limited period of time, due to individual adverse aspects.
3. has too many disadvantages to be certified as sustainable.

The procedure for a summarized assessment is as follows:

positive overall means*:*
In a maximum of two criteria the rating is 2, all others are rated 1.

predominantly positive means*:*

In a maximum of one criterion the rating is 3 and all others are rated 1, or

In none of the criteria the score is 3, and more than two criteria are scored 2.

All other scoring results mean: *too many disadvantages*.

Result

Overall, the following five CO_2 sources are rated positively:

Direct separation from the air

Biomethane processing from biowaste

Biomethane upgrading from biogas from other organic residues (see Annex A, List 1, e.g. from biowaste or sewage gas).

CCU from waste gas of biomass CHP fired with biogenic residues (see Appendix B, List 1, e.g. black liquor)

CCU from waste gas from waste incineration plant

Predominantly positively assessed, and thus provisionally classified as sustainable for a limited period of time, are the following three CO_2 sources:

Biomethane upgrading from biogas from other organic residues (see Annex A, List 2)

CCU from flue gas of biomass CHP fired with cultivated biomass (see Appendix B, List 2)

CCU from waste gas from cement, lime, ceramics, glass works

Table 12: Evaluation of CO_2 sources according to the principles and criteria in detail.

Source	Principle / Criterion	**Fossil CO_2** P1 C1	Residual substance P2 C1 + C2	P3 C1	Severity of the environmental impact of the CO_2 production process P3 C2	P3 C3	P4 C1	Risk of lock-in effects P4 C2	Overall ranking
Direct separation from the air		1	1	1	1	2	1	1	1
Biomethane plant	Renewable raw materials (conv.)	1	1	1	3	1	2	1	3
	Renewable raw materials (org. farming)	1	1	1	2	1	2	1	1
	Liquid manure / slurry	1	1	1	3	2	2	1	3
	Organic waste	1	1	1	1	1	1	1	1
	Other organic residues	1	1	1	1	see Appendix A	1	1	1 2
Bioethanol plant	Renewable raw materials (conv.)	1	1	1	3	1	2	1	3
	Renewable raw materials (org. farming)	1	1	1	2	1	2	1	1
	Agricultural residues	1	1	1	1	1	2	1	1
BECCU plant	Cultivated biomass	1	2	2	1 2 3	1	2	1	2 3
BECCU plant	Biogenic residues	1	1	1	1	see Appendix B	1	1	1 2
Waste incineration plant with CCU		2	1	1	1	1	1	1	1
RDF (heating) power plant with CCU		3	2	2	1	1	1	1	2 (3)
Municipal sewage sludge incineration with CCU		1	2	2	1	1	1	1	1
Industrial sewage sludge incineration with CCU		2	2	2	1	1	1	1	1 (2)
Fossil-fuelled power plants, combined heat and power plants with CCU		3	2	2	1	3	3	3	3

	Fossil CO_2	Residual substance	Severity of the environmental impact of the CO_2 production process			Risk of lock-in effects		Overall ranking
Waste gas from cement, lime, ceramics, glass works	3	2	2	1	1	1	1	2
Steel, aluminium	3	2	2	1	1	1	3	3
Chemical industry (hydrogen for ammonia production)	3	2	2	1	3	2	3	3
Mineral oil sector (hydrogen for hydrogenation)	3	2	2	1	3	3	3	3

Table 13 summarises the overall results from Table 12 with an assessment of the availability of the respective CO_2 sources and the volume potentials (from chapter 5.1). The following graphic symbols are used in the assessment of availability:

- → Source is available with existing technologies.
- ↗ Source will be available as the technology evolves.
- ↘ source will no longer be available in the future due to the development of technical alternatives.

Combined or intermediate assessments are created, as →↗ in the case of direct capture from air, where functioning pilot plants exist but large-scale implementation is still pending. Examples would be the biomass CHP with CCU based on biogenic residues or cultivated biomass (energy crops); the technology is available but cost-intensive, so that plants have not yet been implemented due to a lack of incentives.

Table 13: Overall result of the assessment of CO_2 sources in Germany, their long-term availability and potential quantities.

Source	Overall ranking	Availability	Volume potential [Mt CO_2/a]
Direct separation from the air	1	→ ↗	unlimited
Biomethane plant, renewable raw materials (conv.)	3	→	7.7
Biomethane plant, renewable raw materials (organic farming)	3	→	(1.5) [a]
Biomethane plant, liquid/solid manure	3	→ ↗	3.3
Biomethane processing, biowaste, green waste	1	→	approx. 1
Biomethane processing, other organic resi-dues	1 2	→	1.4
Bioethanol plant, renewable raw materials (conv.)	3	→	0.7
Bioethanol plant, renewable raw materials (organic farming)	3	→	(0.14) [a]
Biomass CHP with CCU cultivated biomass (energy crops)	2 3	→ ↗	2
Biomass CHP with CCU biogenic residues	1 2	→ ↗	73.8
Waste incineration plant with CCU	1	→ ↗	8.0
RDF (heating) power plant with CCU	2	→ ↗	14
Municipal sewage sludge incineration with CCU	1	→ ↗	2
Industrial sewage sludge incineration with CCU	1	→ ↗	1.6
Fossil-fuelled power plants, combined heat and power plants with CCU	3	↘	313 [b]
Waste gas from cement, lime, ceramics, glass works	2	↗	32
Steel, aluminium	3	↘	29
Chemical industry (hydrogen for ammonia production)	3	↘	7.4
Mineral oil sector (hydrogen for hydrogena-tion)	3	→ ↘	0.78

a) Rough estimate by assuming 20 % organic farming as a political target.
b) General assumption for energy industry according to UBA: https://www.umweltbundesamt.de/daten/energie/energiebedingte-emissionen#textpart-1

5.3 Recommendation

Based on the results of the preceding analysis and evaluation, the criteria allow a clear differentiation between CO_2 sources assessed as *positive overall, predominantly positive* and *detrimental* (see Table 13). An overall or predominantly positive evaluation applies to CO_2 from

biomethane upgrading of biogas based on

organic waste.

various biogenic residues (excluding residues from livestock farming).

biomass CHP with various biogenic residues with CCU.

thermal waste treatment plants with CCU (for the biogenic share of CO_2 in the flue gas).

cement, lime, ceramics, glass plants with CCU (for the process-related share of CO_2 in the waste gas).

These sources can be certified as sustainable without restrictions or for a limited period of time. Table 13 shows the available potentials of these sources for a ramp-up of PtL in the near future. These sources are summarised in Figure 7; in total, they comprise a potential of 117 million tonnes of CO_2 per year. The biggest portion is represented by the large variety of residual materials for biomass CHP plants, most of which, according to the lists in Annex B, lead to a *predominantly positive* assessment (wood, straw).

It can be assumed that with these potentials, sufficient CO_2 resources are available for the necessary ramp-up of PtL production for the aviation sector in Germany. The premises for this are the PtL demands shown in chapter 2.1 of around 520 PJ per year (= approx. 12 million tonnes) by 2050, with an initial 10 % by 2030 and an accelerated ramp-up between 2030 and 2050, both in terms of the share of PtL and the share of direct capture of CO_2 from air (DAC).

Accordingly, it is concluded that the PtL demand for CO_2 from non-DAC sources for German aviation will not exceed 10 million t CO_2 per year at any time (see in chapter 2.1, Table 1). As illustrated in Figure 7 this demand can be covered by the sources biomethane processing and residue-fired biomass CHP with CCU. Accordingly, fossil or other unfavourable CO_2 sources will not be needed for this ramp-up.

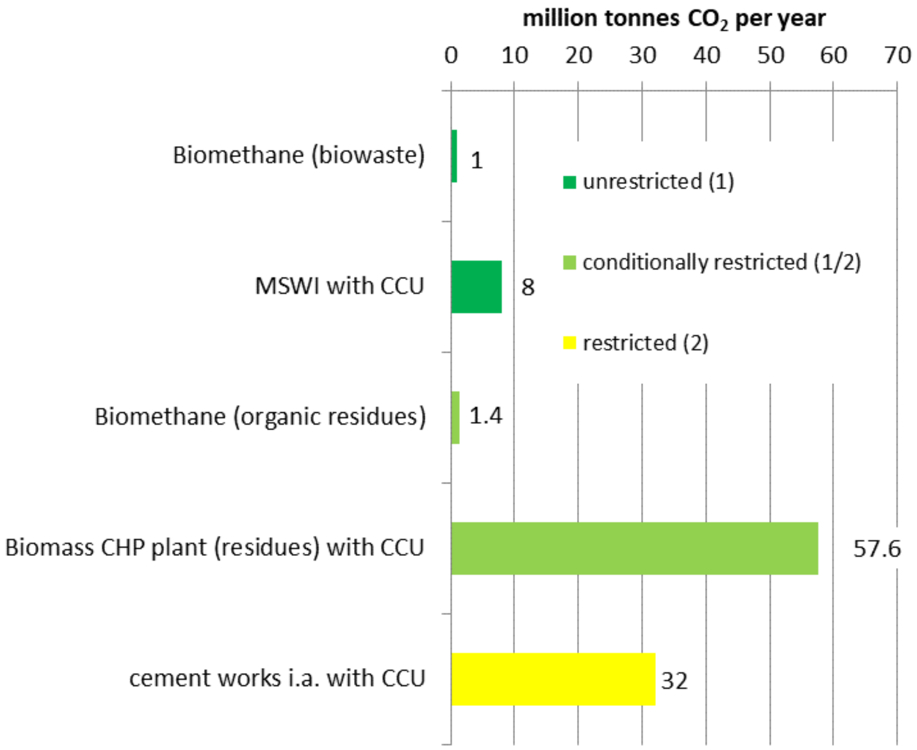


Figure 7: Potential CO_2 sources with unrestricted to restricted recommendations for use in terms of sustainability certification.

Transferability to international projects

As far as the principles and criteria are concerned, a basic applicability outside of Germany can be assumed. Depending on the situation, other sources may be available in other countries that would have to be evaluated according to the proposed catalogue.

Generally, the above conclusion that the potential of positively assessed sources is sufficient for the required ramp-up of PtL can also be applied to the majority of countries in the European Union, as the similar sets of CO_2 sources are available in these countries.

The situation in countries outside the EU must be analysed specifically, as the occurrence and availability of CO_2 sources can vary significantly. On the other hand, sources such as the WBGU prove that biomasses with a strong residual character provide several billion tonnes of CO_2 annually worldwide. Compared with the emission of 0.8 billion tonnes of CO_2 in 2017 from all air traffic worldwide, this suggests that – in terms of quantity – the demand for CO_2 for a 100 % PtL kerosene supply could be met by these residue biomasses for air traffic on a global scale.

In any case, the principles of the catalogue of criteria proposed here apply to the application in countries outside the EU, respectively emerging and developing countries, including the following guidelines:

Fossil CO_2 sources are excluded.

For DAC there is no restriction (as long as the power input meets the criteria).

Cement plants, lime, ceramics or glass plants are permissible using CCU from combustion flue gases, while the restrictions due to the substitutions as expected in industrialised countries would not be applied with the same stringency in emerging and developing countries.

For these countries, the main potential will lie in biomass, in biomass power plants and especially biogas plants. For both, the decisive question is the availability and origin of the biomass, where basically the same principles apply as described above. Regarding cultivated biomass and wood, the exclusion of competing uses, displacement in land use, deforestation and degradation is of particular importance.

It can be assumed that in the future biomass combustion for energy supply will be expanded in those emerging and developing countries with correspondingly high biomass potentials. However, additional equipment of these plants with CCU would mean significantly higher investment costs.

The expansion of biogas production and use is likely to be of greater importance for these countries than the capture of CO_2. There have been numerous investments in this technology in many developing countries for several years, supported by Clean Development Mechanism (CDM) measures, among others. Biogenic waste, crop residues and animal manure are common substrates facilitating an affordable energy supply. The standards applied above, according to which animal manure tends to be evaluated negatively, should also apply here; however, the conditions of local livestock farming (qualitatively and quantitatively) should be reflected. The processing of biogas into biomethane is not to be expected in many of these countries due to the lack of natural gas networks. However, the CCU process should be economically more reasonable for biogas combustion than the combustion of solid biomass, based on the significantly higher CO_2 content in the flue gas of the former.

6 Criteria for renewable electricity

6.1 Preliminary remark

For the production of sustainable PtL, the electricity must generally and undisputedly be provided from renewable energy sources. This requirement already results from the alternative production routes for synthetic aviation fuel: if the electricity demand for PtL production was to be covered by gas- or coal-fired power plants, a significantly more efficient production route for kerosene would be a direct synthesis from gas or coal gasification processes rather.

However, this raises the follow-up question of what requirements are to be placed on renewable electricity. If PtL plants were built in Germany and no "additional" renewable energy plants were built to supply their demand, a cannibalisation of renewable electricity quantities can be expected in the short term – in other words, any contribution to decarbonisation by aviation is cancelled out. This is true as long as the overall electricity supply is dominated by nuclear and fossil power generation.

In the long term, assuming an electricity supply completely covered by renewable energy, the criterion of additionality is overlaid by the requirement of system serviceability. Therefore, the PtL criteria must distinguish between the different **market phases of the electricity market.**

At the same time, it is equally necessary to differentiate according to the **maturity and system significance of the PtL plant.** In an initial stage, the innovation potential of PtL is high, and the electricity consumption of the individual plants is marginal compared to the overall energy consumption. During this time, the criteria for the quality of the electricity may be interpreted rather generously. The situation is different in the maturity phase of PtL, when the respective electricity consumption and the load profile are significant and PtL operates in a normal competitive environment with other (renewable) fuels.

Hereafter, we will address the question of what requirements are to be placed on the electricity for PtL plants in each of these market phases. In doing so, we narrow the horizon of investigation in this respect: we do not examine any benefits of green electricity products that go beyond the plant- and generation-side criteria used today to define green electricity. Additional benefits may be due to increases in energy efficiency, tightened environmental and location criteria, sufficiency, supplier-related features, simultaneous supply, carbon sinks (reforestation), or others. See Hauser et al. (2019) for more details.

Accordingly, the assessment of the additionality of renewable electricity is based on the current regulatory environment, in particular:

The expansion targets (§1) and the tender volumes of the Renewable Energy Sources Act (EEG);

The ban on double marketing according to §80 EEG;

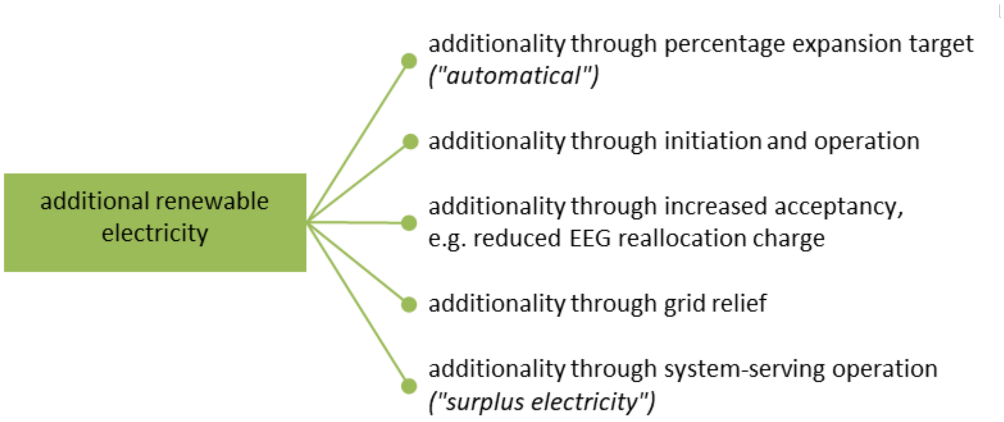
The rules of electricity labelling pursuant to § 42 EnWG;

The system of guarantees of origin under the European Energy Certificate System.

For a detailed description of these framework conditions, see Seebach, Bracker, Pehnt (2019), among others.

6.2 Levels of additionality for the German market

The following section discusses the conceivable basic mechanisms for additionality. This relies on some current analyses of the green electricity market.[1]



Source: Illustration ifeu
Figure 8: Mechanisms of additionality.

6.2.1 Additionality through percentage expansion target, assuming a perfectly functioning market

Assuming that the Renewable Energy Sources Act (EEG) would work perfectly, 40-45 % of the additional electricity used for PtL production in Germany will be generated from renewable energy plants in 2025, and 55-60 % in 2035. The German government planned to raise the expansion target to 65 % in 2030, but this increase has not yet been implemented in law.

[1] Sources: Hamburg Institute (2019). Ökostrommarkt 2025. Wie eine intelligente Steuerung des Ökostrommarktes die Energiewende beschleunigt. Commissioned by Lichtblick SE. Öko-Institut, ifeu (2019): Ökologische Bewertung von Verkehrsarten: Strombilanzierung. Study commissioned by the Federal Environment Agency. IZES (2019): Marktanalyse Ökostrom und HKN, Weiterentwicklung des Herkunftsnachweisissystems und der Stromkennzeichnung. Study commissioned by the Federal Environment Agency. Öko-Institut (2019): Kein Selbstläufer: Klimaschutz und Nachhaltigkeit durch PtX. Impulse paper commissioned by BUND as part of the Copernicus project "P2X".

Accordingly, the additional electricity consumption for PtL would require the tender volume to be adjusted in such a way that this target is achieved. In 2025, PtL electricity would therefore be "automatically" 40-45 % additional, so to speak.

If operators of PtL plants plan to cover the remaining share of 55-60 % of non-renewable electricity in 2025 by installing their own renewable energy plants, this would count towards the achievement of the target according to §5 (5) EEG. Strictly interpreting the legislative, this means that for one self-initiated megawatt, one megawatt less must be put out to tender. From an economic perspective, this would result in a redistribution of costs, but no additional expansion.

In this perspective, it is not possible to supply PtL plants in Germany with more than 40-45 % additional renewable energy plants against the background of the tendering system.

Consider: It is quite conceivable that, within the framework of a legislative "real laboratory" or a further development of the EEG, the rules of the target crediting rules will be changed in the future in order to provide incentives for a market-based renewable energy expansion outside of the EEG. If self-initiated plants were not recognised under §1 and the resulting tender volumes, this would create an additional opportunity for market-driven renewable energy expansion.

6.2.2 Additionality through initiation and operation of new plants (initiation model)

In practice, the form of direct interaction described in the previous section will not come to pass, because the adjustments of the tender volumes will occur afterwards and with a corresponding time delay. This also presupposes that the tender volumes are actually successfully implemented. However, the numerous obstacles, especially in the area of wind projects, and the associated current problems due to low bid volumes in the tenders point to the fact that a higher electricity demand is not translated into a necessary renewable energy expansion instantaneously or 1:1 by the EEG. Rather, many studies assume that the energy policy targets will be undershot for the first time, at least by the middle of the decade, unless major changes are made to the policy instruments in the short term.

This suggests that installations not supported in the EEG should be recognised as renewable energy installations with an additional character, especially if they were initiated directly or indirectly by the PtL manufacturer. In the OK Power Label (as of 2018), this is called the "**initiation model**" (whereby an EEG remuneration is permitted in the OK Power Label, in deviation from the present proposal).[1] The effect of the OK Power Label is primarily that the plant initiators open up sites and thus narrow the expansion gap for achieving the target. In addition, the EEG reallocation charge is reduced, increasing the overall acceptance for the expansion of renewable energies.

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[1] In the current OK Power Label, the initiation model is designed differently as a "new plant model".

The term "initiation" must be defined accordingly. In the OK Power Label, initiation is understood as the project planning and structuring of the financing.

There are different variants for such an expansion of renewable energy that is not supported by the Renewable Energy Sources Act. Additional criteria can be defined for all of these variants; in accordance with Art. 27 of the European Renewable Energy Directive (RED II), it could be required that the plants are commissioned within a certain period of time from the installation of the PtL plant.[1]

Variant I. 1: Construction of renewable energy plants by the PtL manufacturer or a commissioned service provider, which are directly connected to the PtL plant without grid connection.

There is a direct coupling of expansion, location and consumer (PtL plant). In addition to the initiation effect by the PtL plant operator, the grid is not additionally burdened by the plants. There is a direct physical coupling. In this case, no time limit on the initiation power is required. This variant emphasises the direct spatial coupling; however, the question arises as to the significance of the grid relief function of the PtL plant in the first market phase. In this respect, this variant is sufficient for recognition, but not necessary.

Variant I. 2: Construction of renewable energy plants by the PtL manufacturer or a commissioned service provider, which are located in the spatial vicinity of the PtL plant but have grid connection, including corresponding guarantees of origin.

In this case, coupling takes place on site as for Variant I. 1. However, the grid relief only applies to a limited extent because the grid is additionally burdened to some extent. By obtaining guarantees of origin, it is ensured that the plants are not additionally remunerated under the EEG (ban on double marketing).

Under the OK Power Label, the initiation performance is not recognised indefinitely. Rather, after four years only 66 % and after 10 years 0 % of the electricity volume is counted as "initiated". This ensures that new construction impulses continue to be generated.

Variant I. 3: Construction of renewable energy plants by the PtL manufacturer or a commissioned service provider located in Germany, including the corresponding guarantees of origin.

This weakened variant only focuses on the initiation effect for plant construction itself, not on grid relief.

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[1] Art. 27(3): "However, electricity obtained from direct connection to an installation generating renewable electricity may be fully counted as renewable electricity where it is used for the production of renewable liquid and gaseous transport fuels of non-biological origin, provided that the installation: (a) comes into operation after, or at the same time as, the installation producing the renewable liquid and gaseous transport fuels of non-biological origin; and (b) is not connected to the grid or is connected to the grid but evidence can be provided that the electricity concerned has been supplied without taking electricity from the grid. "

6.2.3 Additionality through PPAs with renewable energy installations that meet certain criteria

While in chap. 6.2.2 an additional effect is ensured by the initiation of plants, it can also be argued that Power Purchase Agreements (PPA) with plant operators whose plants comply with specific conditions have an additional effect without the PtL actor being involved in the plant initiation.

Variant PPA.1: Power Purchase Agreements with additional requirements on the age of the plants and corresponding guarantees of origin

In principle, the plants may not be subsidised by the EEG. Plants that have not been awarded a contract under the EEG as part of a tendering process are permitted. The requirement of a certain proportion of new installations is intended to ensure an expansion impulse. This corresponds to the former trader model of the OK Power Label, which, however, was not granted for all installations that are in principle eligible for EEG subsidies. The new installation requirement also corresponds to the RED II requirement for the recognition of PtL as a renewable fuel (see above).[1]

OK Power currently (2019) requires that at least 33 % of the electricity supplied per year must be procured from additional new installations. Age limits apply to new plants (wind: 4 years; photovoltaic (PV): 5 years; biomass: 4 years; hydropower: 8 years). From the PtL project's perspective, this does not appear to be sufficient. In line with the requirement envisaged by the RED II, 100 % of the electricity supplied should come from new plants at the time of commissioning.

Variant PPA.2: Power Purchase Agreements for plants that are not eligible for EEG funding

There are only a few relevant examples for this category if hydropower is excluded as not eligible for EEG remuneration, as it does not contribute to additional use. It would be conceivable, for example, to allow PV systems that are not eligible for EEG remuneration due to the location requirements according to §37 EEG, for example PV systems on non-involved agricultural land or in the federal states that have not made use of an open space ordinance.

In principle, however, it should then be demanded that the PV open-ground systems do not have a strongly detrimental ecological impact. At the very least, PV installations in national parks, nature reserves, biosphere reserves and landscape conservation areas should be excluded and, in addition, an environmental report should be submitted that proves that no further negative environmental effects.[2]

Variant PPA.3: Power Purchase Agreements for post-EEG plants with corresponding guarantees of origin

Plants that will no longer be covered by the EEG in 2020 can continue to be directly marketed. Due to the different operating and maintenance costs, it is by no means self-evident that the plants will continue to be operated. However, a growing market

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[1] The question of how to treat installations that won a 0 Ct bid in the tender is left open here.
[2] These are the areas excluded in the OK Power Label.

is already developing due to the increasing number of plants that will gradually be phased out of the EEG from 2020.

For this category of plants, additionality is more difficult to determine. There are plants, e.g. wind turbines, at favourable locations that can be operated economically even when maintenance costs are considered. Other plants, such as PV plants, may have very low maintenance costs and will therefore continue to be operated anyway, even if the revenues are low. Additionality also depends on whether other framework conditions are effective; if, for example, repowering of a wind farm is made impossible by distance regulations, the continued operation of the wind farm by the turbine operator is more "self-evident" than in the case of sites that can be repowered.

Other types of plants depend on additional market impulses to refinance the extra maintenance and possibly modernisation costs. Ultimately, it will be difficult to define a universally valid criterion. However, from a certification body's point of view it would be insufficient to recognise all post-EEG installations in general.

From a certification body's viewpoint, sufficient additionality would therefore be given if additional requirements were imposed, which might have to be examined individually. Such additional requirements could be that

- the corresponding sites cannot be repowered (**site additionality**) and
- a substantial modernisation/repair effort is necessary, precluding routine marketing by energy traders; this would rule out plants that could be operated based on attractive locations or high profitability (**economic viability**).

6.2.4 Additionality through system-serving operation, "surplus electricity"

Up to now, the additionality analysis has focused on individual plants. Another starting point are energy-economic situations where large amounts of electricity (especially from wind turbines) are fed into the grid due to temporary weather conditions. In these situations, which are also characterised by low stock market prices, the use of electricity is beneficial to the system.[1]

A starting point for a well-defined distinction of system-serving electricity quantities is offered by §13 (6a) EnWG (utilisation instead of shutdown, "Nutzen statt Abregeln", NsA), which promotes the installation of Power-to–Heat (PtH) in connection with a CHP plant (analogue: PtL). Based on a contract with the transmission system operator (TSO), the CHP operator is reimbursed for the investment costs for a PtH system if, in return, he is willing to hold the system available as a switchable load for utilisation in a redispatch situation. If the TSO gives the corresponding utilisation signal within the framework of grid congestion management, the CHP/PtL operator uses the corresponding amount of electricity. It can be assumed that this outage work will also occur in the next decade, considering the comparatively high quantities of electricity regulated in feed-in management (in 2016, the outage work amounted to around 3.7 TWh

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[1] For the following paragraph, see ifeu, Prognos, Ecofys, dena (2018): Untersuchung zu Primärenergiefaktoren. Study commissioned by the Federal Ministry of Economics and Technology.

(BNetzA 2017)), the continued ambitious expansion of renewable energies and the delays in grid expansion. Pursuant to §13 (6a) ENWG, the limit is 2 GW of capacity to be installed in the grid expansion area pursuant to §36c (1) EEG. Geographically, these effects will mainly occur in northern Germany. In 2016, around 89 % of the outage work was caused by bottlenecks in the transmission grid (BNetzA 2017). However, there are publications that assume a growing share of distribution grid congestion (KIT 2017).

Reliable figures on the expected use of NsA are not yet available; potential is seen in larger district heating networks in Hamburg, Rostock, Schwerin, Greifswald and Neubrandenburg, among others. Empirical evidence for plausible values will come from the SINTEG projects Windnode and NEW 4.0. With the voluntary commitment of the TSOs and the publication in the Official Gazette of the Federal Network Agency on 24.1.2018 (BK8-17-0009A), it is now possible to allocate the costs arising from this mechanism to the network charges.

However, this so-called "surplus electricity" is usually not relevant for PtL plants. Unlike PtH plants, which have very low investment costs and are therefore utilised as switchable loads in surplus situations, PtL plants will aim for the highest possible operating hours because of the high investment costs. A flexible mode of operation should therefore be ruled out in general.

If "surplus electricity" (for which there is still no recognised definition beyond §13 (6a) EnWG) were to be recognised, it should only be related to connectable, flexible power shares that are actually added in the surplus situations.

6.2.5 Summary of the additionality assessment

Table 14 summarises and qualitatively assesses the individual additionality models in terms of their impact on

1. the expansion/continuation of renewable electricity generation capacity;
2. an increased acceptance effect through a reduction of the EEG reallocation charge by removing financing for renewable energy expansion from the "EEG pot";
3. the contribution to grid relief and
4. the use of "surplus electricity" that would otherwise have been regulated.

Table 14: Value-added effect of the variants.

	Contribution to expansion/continuation operation	Reduction of EEG reallocation charge	Contribution to grid relief	Use of "surplus electricity"	Comments
Initiation model					
I.1 (without grid connection)	High additional impact	High additional impact	High additional impact		Additional requirement: Construction of the plant within a certain period of time after installation of the PtL plant.
I.2 (geographical proximity)	High additional impact	High additional impact	Additional effect		Additional requirements: Construction of the plant within a certain period after installation of the PtL plant and time limit of 4/10 years.
I.3 (Initiation without geographical proximity)	High additional impact	High additional impact			Additional requirement: Construction of the plant within a certain period of time after installation of the PtL plant.
PPAs outside the EEG with additional criteria					
PPA.1 (New plant share)	Additional effect	High additional impact			100 % new plant share
PPA.2 (not EEG reimbursable)	Additional effect	High additional impact			Additional requirement: Submission of an envi-ronmental report
PPA.3 (Post-EEG)	Additional effect	Additional effect			Additionality depends on location and modern-isation/operating costs
System-serving operation					
NsA			Additional effect	Additional effect	Strict definition of NsA electricity required, hardly rele-vant for PtL plants due to high targeted full load hours/low load flexibility

(dark green)	High additional impact
(light green)	Additional effect

6.3 Recommendation

Based on this qualitative additionality analysis, we derive a staggered approach to additionality requirements for the power supply of PtL plants.

6.3.1 Additionality criteria for the first PtL plants

In a generally valid definition of additionality criteria, we propose an increasing requirement for the plants, especially for the first generation of PtL plants, which considers that in the first years after commissioning, new renewable energy capacity cannot be added abruptly.

In addition, a restriction of the permitted energy sources to wind and PV power is made, based on the target image of a supply[1] predominantly based on PV and wind power.

"Surplus electricity" (utilisation instead of shutdown, NsA) as described in chap. 6.2.4 is generally not considered relevant for PtL plants. If, in deviation from this, concepts are submitted providing for (partial) flexibility of the PtL plant aiming at the use of "surplus electricity", a case-by-case assessment must be carried out.

Concretisation of the proposal

1. Electricity for the PtL plant must be acquired 100 % from wind energy and PV plants that are not remunerated according to the EEG. This proof must be provided through the invalidation of guarantees of origin.

2. In addition, by the fifth operating year at the latest, 100 % of the electricity for the PtL plant must be generated from plants that fulfil one of the following conditions:

    a. **New wind or PV plants initiated, installed and operated by the PtL plant operator or a service provider commissioned by the PtL plant operator after commissioning of the PtL plant,** complying with the condition according to No. 1. Installations that have not been awarded contracts in the context of EEG tenders may be recognised. Installations in areas not permitted under the EEG (e.g. PV installations in non-disadvantaged agricultural areas) may also be recognised if an environmental report proves that there are no significant negative environmental effects preventing installation. It should be noted that PV installations in national parks, nature reserves, biosphere reserves and landscape conservation areas are excluded and that the acceptance of the installation is ensured through participation of the local residents.

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[1] This is based on the assumption that a) ecologically exploitable hydropower potentials are largely developed; b) biomass and geothermal energy are ruled out due to the higher electricity production costs for PtL production and the system-serving possible/required contributions of these sectors are stimulated by the EEG.

b. **Wind turbines that are no longer covered by the Renewable Energy Sources Act (post-EEG turbines)**[1] are permitted if it is proven by a certification body that the corresponding sites cannot be repowered (additionality of location) and that a substantial effort must be made for modernisation/repair precluding routine marketing by energy traders (additionality of economic viability).
The share of these post-EEG installations is limited to 50 %.

6.3.2 Additionality criteria for the diffusion phase of PtL plants

In principle, these criteria are also suitable for a later phase characterised by higher market penetration. The gradual tightening of the additionality requirement after the fifth year of operation ensures the success of gradually "covering" the individual PtL plants with additional renewable energy capacity. Such a step-by-step approach will also make sense in a later development phase of PtL plants, considering that procurement contracts, plant expansion of renewable energy capacities, etc. require a lead time. The difference is that, during the diffusion phase, more PtL plants are added; however, the procedure described the previous chapter can be scaled up as needed.

On the other hand, a tightening of the criteria as defined for the first PtL plants does not seem appropriate, as sufficient additionality is already anchored in these criteria.

6.4 Transferability to international projects

The recommendations derived in chapter 6.3 can be applied in principle and mutatis mutandis to installations in an international context. A **case-by-case examination** must show to what extent the criteria are fulfilled. Under certain circumstances, a country-specific adaptation of the basic requirements may have to be made, as it is not possible to cover all countries in a generalised manner.

Regarding criterion 1

> *Electricity for the PtL plant must be procured 100 % from wind energy and PV plants that are not remunerated according to the EEG. This proof must be provided through the invalidation of guarantees of origin.*

Internationally, these requirements are to be interpreted in such a way that electricity is procured for installations from wind and PV plants that are **not remunerated by a feed-in charge model similar to the EEG.** Analogous to the register of guarantees of origin, there must be transparent proof, certified by an auditor or similar expert, that double marketing is avoided.

If the relevant country uses a quantity system instead of a price system, then it is required

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[1] PV systems are not included here, as it is assumed that they will continue to be operated anyway due to the low maintenance and operating costs.

that, in the case of regular **auctions**, the installations have not successfully participated in an auction and thus become eligible for a kWh or kW remuneration;

that the installations are not counted towards the fulfilment of the quota in a **quota system** or receive support under the quota for the considered production.

In many countries, these conditions are likely to be fulfilled if the PtL plant operator or a service provider on his behalf builds the power generation plant without subsidies and connects it directly and physically to the PtL plant.

Regarding criterion 2

Criterion 2 can be applied mutatis mutandis to other countries.

Other sustainability aspects

In addition to the product-oriented assessment for electricity, further regional or country-specific sustainability criteria should be examined in the course of a general sustainability assessment. From the viewpoint of electricity supply, these are, above all:

Local generation: An examination is required, investigating whether the available renewable energy potentials are limited to the extent that decarbonisation of the country's electricity supply **competes** with the electricity supply of the PtL plant. In principle, a direct competition for use can be ruled out if sufficient land or potential wind/solar sites are available. However, if profitable and attractive sites are scarce, they should first be used for local power supply, if a region does not already have high shares of renewable energy. This includes an analysis of whether adverse effects on the electricity costs of the local population can be expected.

Further overarching sustainability aspects are addressed in chapter 7.

7 Evaluation of other aspects

The criteria elaborated in this study are limited to an assessment framework, which

1. can be **applied in the short term** to the currently still very small quantities of PtL available on the market, and
2. is to be applied – for the time being – only to quantities of PtL produced **in Germany.**

The proposed criteria are thus intended for a first stage in the introduction of certified PtL and will need to be expanded as the market expands to include imported PtL. This expansion may also involve a revision of the criteria proposed here for CO_2 sources and electricity. Such an expansion will require additional criteria in any case.

7.1 Further sustainability criteria

Various studies have already addressed the question of fundamental sustainability criteria for PtX. These include Kasten & Heinemann (2019), Schmidt et al. (2016) and Siegemund et al. (2016). The latter essentially deal with CO_2 sources and deduce gradations ("shades of greenness") similar to those explained in chapter 5.2 of this study. The other authors list further criteria:

- Water demand
- Land use

The issue of **water demand** becomes particularly relevant if the production of the PtL is located in a region with a designated water scarcity. This criterion is of both ecological and social importance. Therefore, and from a sustainability perspective, it must be ensured that PtL production does restrict the local potable water supply (availability and costs) for agriculture and households (Kasten & Heinemann 2019).

According to Schmidt et al. (2016), approx. 1.4 litres of water are required purely stoichiometrically per litre of PtL fuel. In addition, there are demands for process water. However, the largest share of the overall water demand could be associated with regular cleaning of solar cells or solar mirrors. Malins (2017) estimates up to 70 litres of water per litre of PtX fuel for this.

As a solution for water supply issues, seawater desalination plants may be required. Their additional energy demand and other possible environmental interactions must be included in the sustainability assessment.

The largest main **land use** issue of PtX production is by far caused by the provision of renewable electricity, especially in the case of solar electricity generation (CSP or PV), which is assumed in most cases. Carbon capture from the air (DAC) is also comparatively land-intensive. The land issue is thus a decisive reason why an expansion of the technology is not considered a feasible scenario (UBA 2019) in a densely populated country like Germany, if the goal is a self-sufficient PtX supply. All the more reason to ensure that PtX projects are in line with sustainable land use by means of suitable criteria.

Another fundamental issue is the question of implementation of such an energy-intensive large-scale project in regions with a rather poor public energy supply. Investments in large-scale power generation plants can certainly improve access to energy for the local population. Conversely, serious disadvantages would be expected if access to energy were to become even more scarce as a result of a PtX project.

The sustainability of a project aiming at supplying an industrialised country such as Germany with PtX produced in areas such as the so-called MENA region therefore depends on the regional infrastructural development performance triggered by the project. This applies to water supply, land use as well as energy supply. Otherwise, the accusation of perpetuating *colonial* structures would be inevitable.

In addition to the above-mentioned work, there are currently no sustainability criteria for the production of PtX that have been agreed in a broad consensus. By 2022, the EU Commission is obliged by RED II to present such criteria via a delegated act, which will then be binding in the EU legal framework. It can be assumed that a certain reference standard will be formed by this act.

Existing reference standards are briefly described in the following chapter. However, they are not specifically aiming at PtX production but at large-scale projects of various kinds.

7.2 Practical standards for sustainability auditing

The international framework for setting objectives and the guard rails for assessing sustainability was presented in chapter 4. For concrete projects, the assessment of environmental and social compatibility is quite common practice and a prerequisite for funding e.g. by the major development banks such as the World Bank or the Kreditanstalt für Wiederaufbau (KfW). Essential standards are briefly described below.

World Bank Environmental and Social Framework (ESF)

An audit according to the EFS standards is an integral part of the World Bank's funding of emerging and developing countries. The framework contains ten standards to be audited[1]:

1. Assessment and Management of Environmental and Social Risks and Impacts
2. Labour and Working Conditions

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[1] https://www.worldbank.org/en/projects-operations/environmental-and-social-framework/brief/environmental-and-social-standards?cq_ck=1522164538151#ess1

3. Resource Efficiency and Pollution Prevention and Management
4. Community Health and Safety
5. Land Acquisition, Restrictions on Land Use and Involuntary Resettlement
6. Biodiversity Conservation and Sustainable Management of Living Natural Resources
7. Indigenous Peoples/Sub-Saharan African Historically Underserved Traditional Local Communities
8. Cultural Heritage
9. Financial Intermediaries
10. Stakeholder Engagement and Information Disclosure

Environmental, Health, and Safety Guidelines (EHS) of the International Finance Corporation (IFC)

The IFC, which is also part of the World Bank Group, applies more extensive guidelines for project financing. These guidelines are based on the World Bank's EFS framework, but formulate standards tailored to different industries and measures[1], such as for:

Chemical production plants

Facilities of the oil/gas industry (e.g. facilities for the production of LNG**)**

Infrastructure (terminals for oil or gas, gas pipelines)

Power plants (so far not covering solar power plants)

KfW Sustainability Guideline

The Environmental and Social Impact Assessment (ESIA) is an integral part of the approval of projects at the KfW bank group. The overarching standards of the World Bank and the IFC constitute the primary basis for this guideline.[2]

7.3 Outlook

There is sufficient basis for the further development of the proposed criteria for application at the international level. Initial approaches have been described partially in the chapters 5.3 and 6.4 and in particular in this chapter. The expansion of the approach should focus on the specific areas of conflict regarding PtL production and at the same time cover the framework of internationally customary standards.

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[1] https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/publications_policy_ehs-general

[2] https://www.kfw.de/nachhaltigkeit/KfW-Konzern/Nachhaltigkeit/Strategie-Management/Umwelt-Sozialvertr%C3%A4glichkeitspr%C3%BCfungen/
https://www.kfw.de/PDF/Download-Center/Konzernthemen/Nachhaltigkeit/FZ-Nachhaltigkeitsrichtlinie_D-3.pdf

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Annex A: Biogenic waste or residues for the production of biogas, which as CO_2 sources fulfil Principle 3, Criterion 3 fully (List 1), to a certain extent (List 2), or not at all (List 3).

Origin	Species/substrate [a)]	List 1	List 2	List 3	Justification for this classification
Agriculture	Crop residues	X			no significant environmental impacts are to be assumed beyond the land requirements (criterion 2).
	Fodder residues, mashed grain, passed silage		X		is associated with livestock farming, but is plant-based
	Cereal straw		X		For sustainability reasons, the usable portion is limited; the limits must be observed. [b)]
Landscape	Green waste from private and public garden and park maintenance	X			No significant environmental impact to be assumed through use.
	Roadside grass	X			
Food, plant-based	Baking waste	X			as (predominantly) vegetable food waste, no significant environmental burdens beyond the land requirement (criterion 2) can be assumed.
	Brewer's grains (fresh/pressed)	X			
	Vegetables (rejected)	X			
	Vegetable cleaning residues	X			
	Cereals (rejected)	X			
	Grain stillage	X			
	Grain stillage from alcohol production	X			
	Grain dust	X			
	Glycerine	X			
	Medicinal and aromatic plants (rejected)	X			
	Potato fruit water from starch production	X			
	Potatoes (rejected)	X			
	Potatoes (mashed, medium starch content; not or no longer suitable for consumption)	X			
	Potato process water from starch production	X			
	Potato pulp from starch production	X			
	Potato peelings	X			
	Potato stillage	X			
	Potato stillage from alcohol production	X			
	Bran	X			
	Molasses from beet sugar production	X			
	Fruit pomace and grape pomace (fresh/untreated)	X			
	Beet pulp (from sugar processing)	X			

Origin	Species/substrate [a)]	List 1	List 2	List 3	Justification for this classification
	Rapeseed cake		X		Primary use here is as animal feed, question of possible competition for use
	Rapeseed extraction meal		X		
	Sugar beet press cake from sugar production		X		
	Sugar beet pulp		X		
Food, animal	Buttermilk fresh (not / no longer suitable for consumption)			X	Analogous to the evaluation of liquid and solid manure, all waste associated with livestock farming is associated with significant consequences for the nitrogen balance, climate protection, land use
	Casein			X	
	Grease separator contents			X	
	Flotation fats			X	
	Flotation sludge			X	
	Deep-frying fats			X	
	Rennet whey, thickened			X	
	Rennet whey, fresh			X	
	Stomach contents (pig)			X	
	Skimmed milk, fresh			X	
	Skimmed milk, dry product			X	
	Milk (not /no longer suitable for consumption)			X	
	Lactose			X	
	Milk sugar molasses			X	
	Low-protein milk sugar molasses			X	
	Rumen contents			X	
	Curd cheese (not /no longer suitable for consumption)			X	
	Sour whey, thickened			X	
	Sour whey, fresh			X	
	Animal blood			X	
Other vegetable waste	Cut flowers (rejected)		X		Plant-based, but associated with environmental burdens
Other waste	Old bread	X			Comparable with biowaste
	Leftovers	X			

a) Source for the listing: Bayerische Landesanstalt für Landwirtschaft (LfL) and Fachverband Biogas e.V. (2011): EEG 2012 - Feedstocks according to the Biomass Ordinance http://www.lfl.bayern.de/mam/cms07/iba/dateien/einsatzstoffe_eeg_2012.pdf

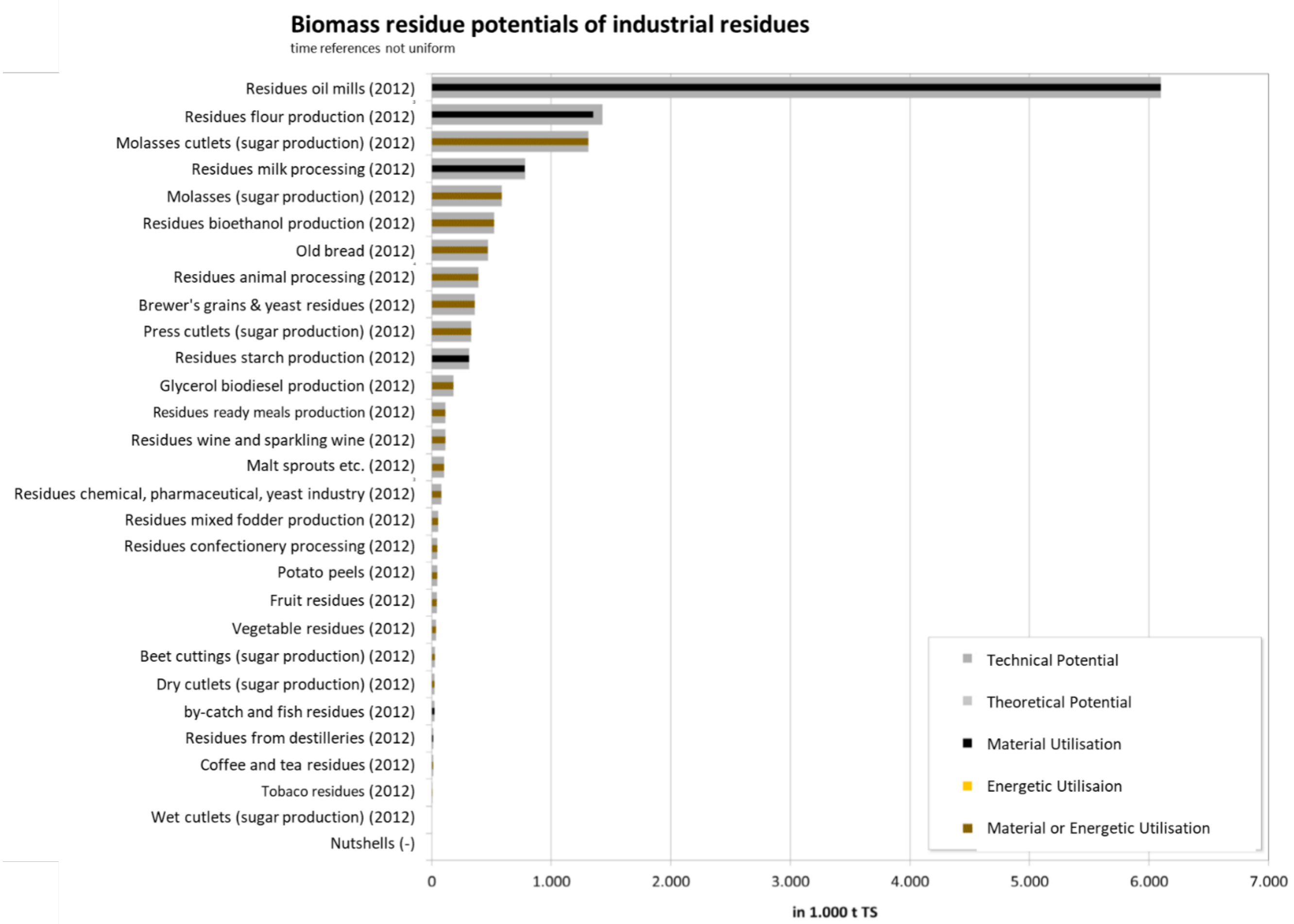
b) Justification based on the study by Fehrenbach et al. (2019)

Annex B: Biogenic waste or residues for use in biomass (CHP) plants (with CCU), which as CO_2 sources fulfil Principle 3, Criterion 3 fully (List 1), to a certain extent (List 2), or not at all (List 3).

Origin	Species/substrate	List 1	List 2	List 3	Justification for this classification
Forestry	Forest wood		X		For sustainability reasons, the potential that can be used for energy is limited; the limits must be observed [a)]
Agriculture	Cereal straw		X		
Landscape	Landscaping wood	X			Energetic use of the potential makes sense overall [a)]
	Woody green waste	X			
Municipal waste	Sewage sludge	X			
	Waste wood		X		In competition with material use, the potential for energetic use is limited; the limits must be observed. [a)]
Industrial refuse	Industrial waste wood		X		
	Solid industrial substrates	X			Energetic use of the potential is reasonable overall [a)]
	Black liquor	X			
	Various wastewater sludges, e. g. paper sludge	X			
	Animal meal			X	Analogous to the valuation of liquid and solid manure, all waste associated with livestock farming is associated with signif-icant consequences for the ni-trogen balance, climate protec-tion, land use

a) Justification based on the study by Fehrenbach et al. (2019)

Annex C: Volume potentials for various biogenic wastes or residues.



Source: (Brosowski et al. 2015), Fehrenbach et al. (2019)