Global Alliance
POWERFUELS

Carbon Sources for Powerfuels Production

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Content

Executive Summary

Powerfuels will have an indispensable role in advancing the energy transition and achieving climate neutrality by 2050. This includes carbon-based powerfuels such as synthetic kerosene, methanol or diesel, which are necessary for far-reaching emission reductions in sectors and applications that are difficult to electrify directly or decarbonise using carbon-free powerfuels. As demand for powerfuels is projected to increase significantly in the next decades, future global CO_2 demand for carbon-neutral powerfuels production could potentially amount to approximately 6,000 Mt CO_2 in 2050. It is therefore vital to define which carbon sources are eligible for use in powerfuels production by systematically assessing available sources based on economic, geographic, and sustainability criteria. With regard to the regulatory environment, time is pressing as uncertainty about how emission reductions through the capture and re-use of CO_2 are to be credited is currently undermining the planning and investment security that would enable the market ramp-up of powerfuels.

This paper aims to give an overview of possible carbon sources and provide a basis for further discussion on the topic. It differentiates between industrial CO_2 point sources, biogenic CO_2 sources and CO_2 from ambient air, and analyses them under the criteria of cost, scalability/ expected long-term availability, regional availability, greenhouse gas intensity of the capture process, unavoidability, and verifiability/certifiability. The results indicate that considerations of costs and energy intensity of the capture process currently favour industrial and biogenic point sources with a high CO_2 purity and concentration. However, carbon captured from ambient air using Direct Air Capture (DAC) technologies will dominate the provision of CO_2 for powerfuels in a future low-carbon energy system due to its long-term and location-independent availability at large scale, its independence of industrial carbon-emitting processes and the anticipated cost degression of DAC technologies.

This paper further offers an analysis of the regulatory framework and possible approaches to regulating carbon sources and carbon-based powerfuels, focusing on the EU Emissions Trading System and the Renewable Energy Directive II. Carbon captured and used for the production of powerfuels is effectively 'recycled' and emission reductions that are achieved when powerfuels replace fossil-based energy carriers should thus be accounted for. At the same time, double-counting of emission reductions needs to be avoided. One possible provision could be to count emissions that occur during the end-use of powerfuels at the capture stage and make emission reductions creditable at the usage stage, which would allow to classify all powerfuels as carbon-neutral in the end-use sector. The technicalities of the accounting of emissions from carbon used in powerfuels production will have to be addressed in the delegated act of Article 28 of the RED II, due in December 2021. This will be complemented by provisions for industrial sources under the delegated act of Article 25, due in January 2021, on the minimum threshold for emissions reductions of Recycled Carbon Fuels. Generally, a fundamental requirement for any crediting mechanism, in particular when CO_2 is provided from industrial point sources, is that it does not incentivise industry sectors to uphold or even augment carbon-emitting processes. As carbon captured from ambient air will constitute the main input source for powerfuels production in the long-term, a well-designed and effective policy support that induces the necessary cost degression of DAC technologies should be put in place.

1 Introduction

Powerfuels can be used in a variety of applications in virtually all sectors of the economy. As they are based on renewable electricity and can be produced to be chemically identical to their fossil counterparts, they are a versatile green substitute for fossil energy carriers and will therefore play a key role in the energy transition and in achieving the European Union's target of climate neutrality by 2050.[1]

Our definition of powerfuels embraces a broad range of technologies and encompasses not only hydrogen but other synthetic gases and synthetic liquid fuels as well.[2] This includes several hydrocarbon powerfuels, particularly synthetic methanol, diesel, kerosene, and others, which will be essential for the envisioned far-reaching defossilisation in hard-to-abate sectors such as industry and heavy-duty transport. For their production, carbon dioxide (CO_2) is required as a feedstock material. This use of carbon in the production of powerfuels is a form of Carbon Capture and Utilisation (CCU), a term that refers to a variety different technologies and processes that use CO_2.

In line with the long-term goal of reducing greenhouse gas (GHG) emissions, it is a fundamental requirement that the use of carbon in the production of these powerfuels should not cause any significant additional net emissions. This includes the effects of the carbon capture process itself. The carbon needed for the production of hydrocarbons can originate from different sources, namely the capture of carbon from existing industrial emission streams and biogenic sources or from direct air capture technologies that draw carbon dioxide from ambient air.

This utilisation of CO_2 as a raw material is still a novel idea and so far, there is no common understanding among stakeholders on which carbon sources to use for powerfuels production. In addition, the current European regulatory framework offers little indication regarding which type of carbon sources are eligible in order for the produced powerfuels to be considered as renewable. Furthermore, there is uncertainty about how the utilised carbon is to be counted, and emission reductions are to be credited, over the lifecycle of these carbon-based powerfuels. From investors' and project developers' perspective, the existing uncertainty around the regulation of carbon sources creates investment risks and thus inhibits the market development of powerfuels. In addition, carbon as a coupled product is dependent on the development in other industries and related regulations, e. g. regarding powerfuels, carbon emitting industries, and carbon pricing, which are equally associated with regulatory uncertainty. At the same time, there is an urgent need to scale up the market for powerfuels and the carbon capture technologies necessary for their production to ensure the future availability of these much-needed green energy carriers.

With legislative processes underway as part of the actions proposed in the EU Green Deal and the upcoming revision of significant policy packages, i.e. the Renewable Energy Directive and the Emissions Trading System, more clarity and certainty is within reach. To add to the pan-European multi-stakeholder discussion on this issue, this paper provides an analysis of future powerfuels-related demand for carbon and the available technologies to capture carbon from the various potential sources. In order to account for the complexity of the issue, the different carbon sources and related capture technologies are evaluated based on certain pre-defined criteria, in coherence with the overall goals of scaling up powerfuels production and reaching climate goals. This thorough assessment will allow a better understanding towards determining suitable carbon sources for powerfuels production.

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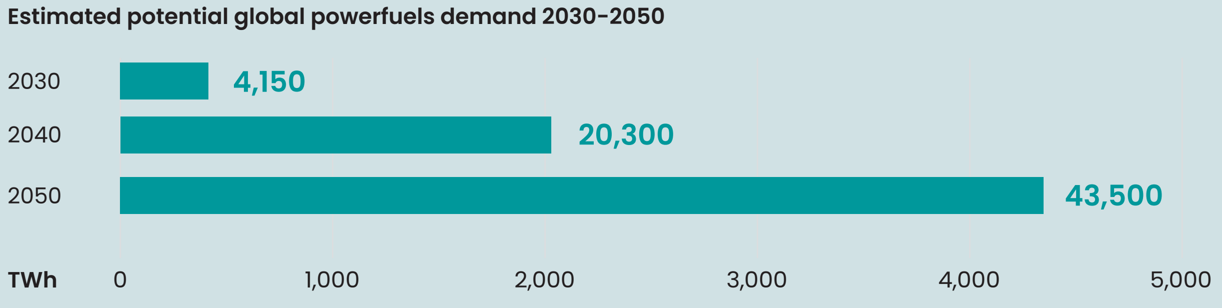
[1] European Commission, 'EU 2050 Long-Term Climate Strategy', 2020, https://ec.europa.eu/clima/policies/strategies/2050_en.
[2] Global Alliance Powerfuels, 'What Are Powerfuels?', 2018, https://www.powerfuels.org/powerfuels/.

2 Future CO_2 demand

The future global CO_2 demand for powerfuels production, as depicted in Figure 1, could amount to approximately 6,000 Mt CO_2 in 2050, an almost tenfold increase compared to the expected CO_2 demand in 2030. As defossilisation across all sectors and applications becomes necessary, the demand for powerfuels, and, subsequently, the demand for CO_2 could accelerate.

The data on demand quantities presented below originates from an upcoming energy system modeling study which was developed by LUT University and commissioned by the Global Alliance Powerfuels[3]. The study quantifies the global CO_2 demand in 2030, 2040, and 2050 in relation to the foreseen powerfuels demand (if a global energy system completely based on renewable energy sources were to be established

The values depicted in Figure 1 are estimations for future powerfuels demand and powerfuels-related carbon demand in a global energy system that is fully based on renewable energy sources by 2050. Independent of absolute values, it can be derived that demand for carbon-based powerfuels is likely to increase similar to the growth seen in total powerfuels demand.


Estimated potential global powerfuels demand 2030-2050

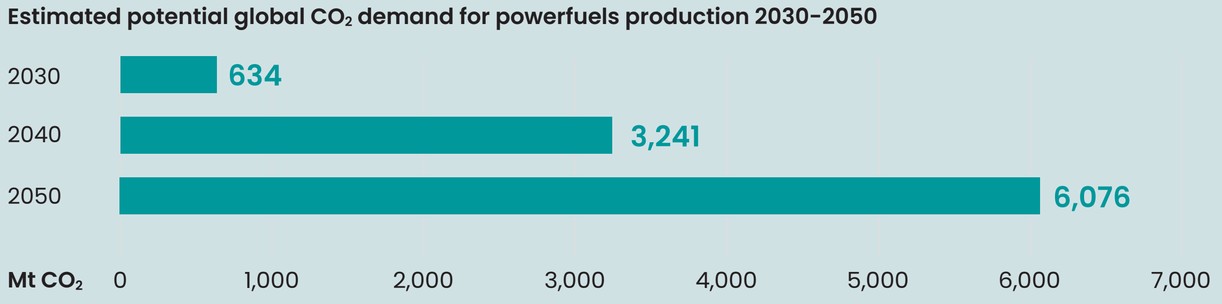

Estimated potential global CO_2 demand for powerfuels production 2030-2050

Figure 1: Global powerfuels demand and global CO_2 demand for powerfuels production [based on[3]]

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[3] LUT University, Powerfuels in a renewable Energy World, 2020, publication pending.

[4] Ram M, Bogdanov D, Aghahosseini A, Oyewo AS, Gulagi A, Child M, Fell H-J, Breyer C. Global Energy System Based on 100 % Renewable Energy -Power Sector. Study by Lappeenranta University of Technology and Energy Watch Group. Lappeenranta, Berlin; 2017. https://goo.gl/NjDbck.

by 2050, and assuming strong levels of electrification of the transport and heat sectors as well as a cap on the global amount of final energy consumption from biofuels at 2020 levels to maximise the energetic use efficiency of land areas)[4].

Beyond the global CO_2 demand for powerfuels production in the above-mentioned scenario, the specific CO_2 demand of selected powerfuels is depicted in Figure 2. Demand for CO_2 across different liquid carbon-based powerfuels such as e-Diesel or e-Jet A (synthetic kerosene) will likely be approximately even, ranging from 82.2 g per MJ for e-Gasoline to 87.8 g per MJ for e-Diesel.

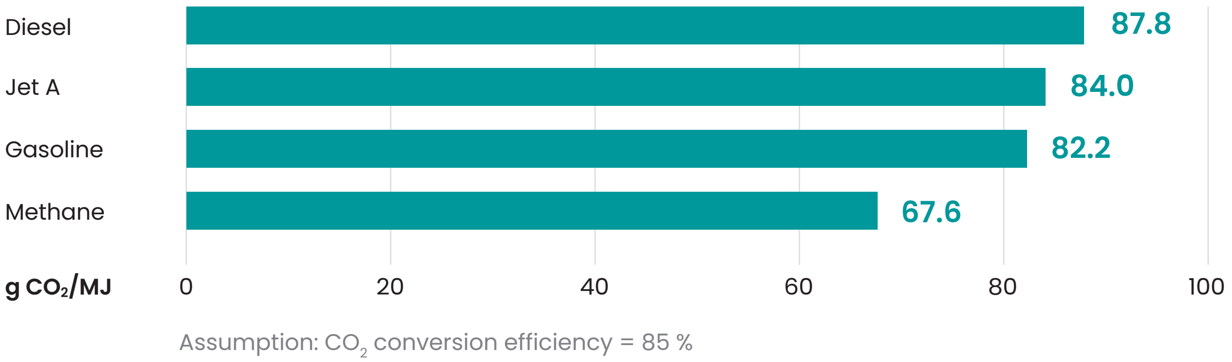

Figure 2: Specific feedstock CO_2 demand of selected powerfuels [own depiction]

3 Definition of carbon sources and evaluation on the basis of pre-defined assessment criteria

Carbon Capture and Utilisation (CCU), the recycling of CO_2 into products, is already commonly used at industrial scale in the chemical industry, such as in fertiliser, plastic and rubber production, and in food and beverages, e. g. to carbonate soft drinks.[5]

The different carbon sources available to provide CO_2 as a feedstock for the production of powerfuels can be categorised by differentiating between industrial CO_2 point sources, biogenic CO_2 sources and CO_2 from ambient air.

Industrial CO_2 point sources

Industrial CO_2 point sources are localised industrial emitters, including, e.g. fossil fuel power plants, industrial process plants, oil refineries or other heavy industrial sources[6]. One defining characteristic is that industrial point sources are stationary as opposed to other mobile CO_2 point sources such as road and maritime vehicles.

Several technologies can be applied to capture carbon from point sources, e. g. absorption, meaning that CO_2 is brought into contact with and dissolves into a sorbent material, adsorption, a process in which CO_2 molecules adhere to the sorbent material's surface, cryogenic separation, or membranes[7].

Biogenic CO_2 sources

The term biogenic carbon sources refers to processes during which CO_2 stored in biologically based materials is released, e. g. through their combustion, fermentation, decomposition or processing. The main biogenic carbon sources are biogas upgrading to biomethane, combustion of biomass, and industrial fermentation processes, e. g. in the food and beverage industry[8]. Like the industrial carbon sources described above, they are stationary point sources of CO_2.

There is a high concentration of biogenic CO_2 sources in some countries: Germany, the United Kingdom and Italy, for example, currently produce the largest amounts of biogas in Europe and could therefore also potentially provide the largest amount of CO_2 from biogenic sources for powerfuels production. Comparable to the available capture technologies for industrial point sources, multiple capture technologies – at varying stages of commercial viability – also exist for providing carbon from biogenic sources.

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[5] http://www.uigi.com/carbondioxide.html.

[6] Zero Emission Resource Organization, 'Stationary Point Sources of CO_2', 2010, http://www.zeroco2.no/capture/sources-of-co2.

[7] Heleen de Coninck and Sally M. Benson, 'Carbon Dioxide Capture and Storage: Issues and Prospects', Annual Review of Environment and Resources 39, no. 1 (17 October 2014): 243–70, https://doi.org/10.1146/annurev-environ-032112-095222.

[8] Valerie Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2', Journal of CO_2 Utilization 41 (1 October 2020), https://doi.org/10.1016/j.jcou.2020.101219.

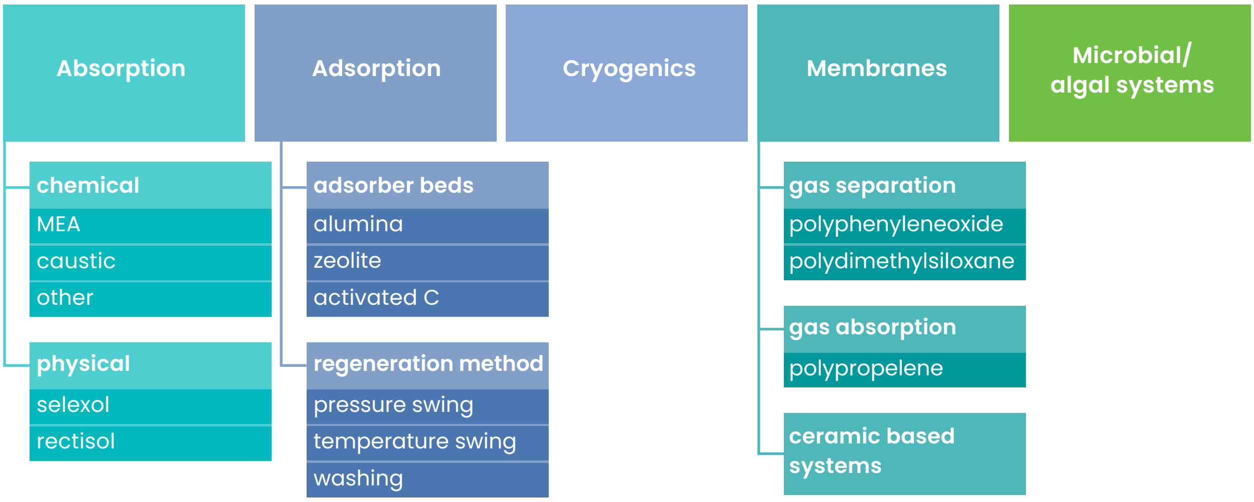

Figure 3: Schematic overview of CO_2 separation technologies, retrieved from: Gerda Reiter and Johannes Lindorfer, 'Evaluating CO_2 Sources for Power-to-Gas Applications – A Case Study for Austria', Journal of CO_2 Utilization 10 (1 June 2015).

CO_2 from ambient air

The term Direct Air Capture (DAC) refers to technologies for capturing CO_2 from the atmosphere. These are relatively new and innovative technologies, which are still in their early commercial stages[9]. Even though the CO_2 concentration in ambient air is rather low at just over 400 parts per million by volume (ppmv), it can be removed from the atmosphere by bringing large volumes of air into contact with sorbents[10].

Sorbent materials can work either by the process of absorption or by adsorption, as described above. Regardless of which of the two processes is chosen, sorbents are subsequently treated to release the CO_2, which can then be used in the production of carbon-based powerfuels[11]. An overview of the different capture technologies available for carbon sources subsumed under the three categories is given in Figure 3.

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[9] Mahdi Fasihi, Olga Efimova, and Christian Breyer, 'Techno-Economic Assessment of CO_2 Direct Air Capture Plants', Journal of Cleaner Production 224 (1 July 2019): 957–80, https://doi.org/10.1016/j.jclepro.2019.03.086.

[10] Ajay Gambhir and Massimo Tavoni, 'Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation', One Earth 1, no. 4 (20 December 2019): 405–9, https://doi.org/10.1016/j.oneear.2019.11.006.

[11] Gambhir and Tavoni.

As outlined above, both industrial and biogenic point sources encompass a variety of combustion and industrial production processes, while ambient air can be captured using different DAC technologies. Figure 4 gives an overview of exemplary carbon sources subsumed under each of the three categories.

While carbon capture from all of these sources is technologically feasible, the selection and eligibility of carbon sources for the production of powerfuels depends on a number of criteria, including economic, geographical, and sustainability-related considerations. This paper establishes five distinct criteria under which potential carbon sources are to be assessed.

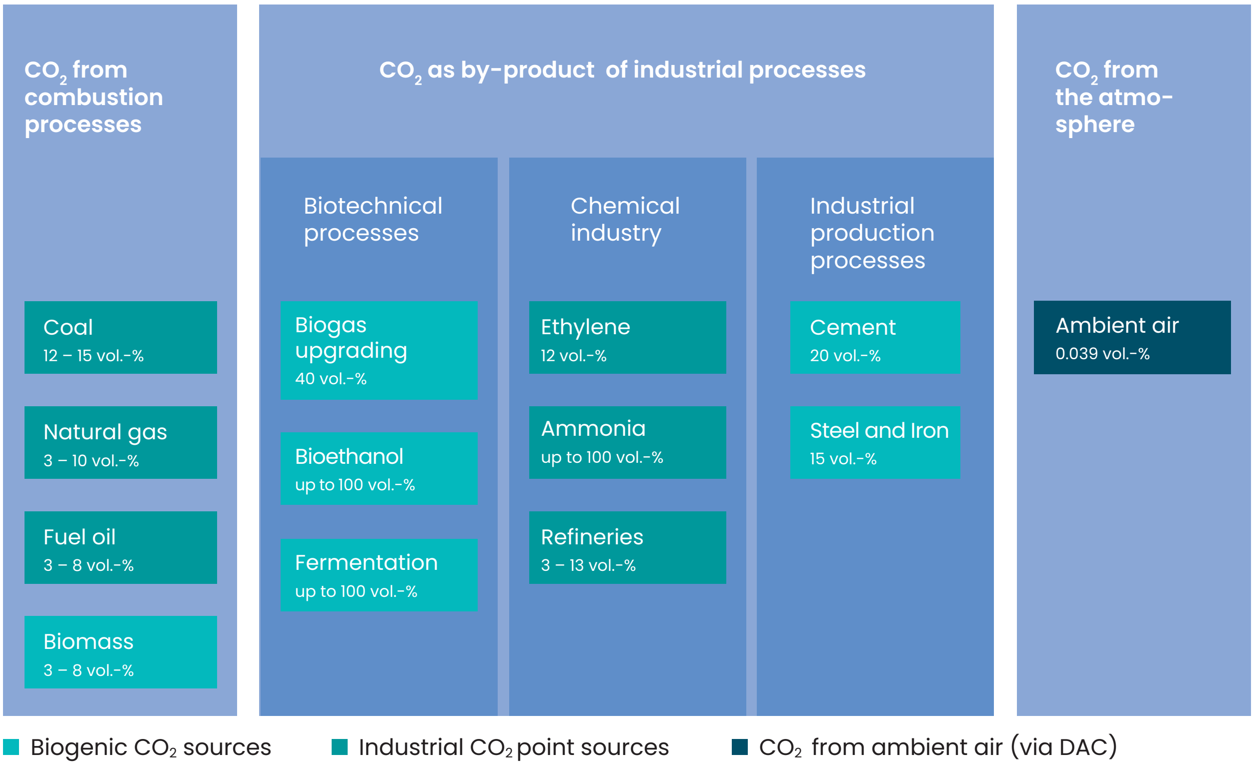

Figure 4: Classification of potential carbon sources, adapted from: Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2', Journal of CO_2 Utilization 41 (2020).

3.1 Costs

The cost of providing CO_2 for powerfuels production varies greatly across sources and technologies. Despite the fact that some capturing technologies can be used for both highly concentrated and diluted sources, costs greatly depend on the concentration of CO_2 as well as potential impurities

Industrial CO_2 point sources

Costs vary considerably across industrial point sources, and are influenced, amongst other factors, by the CO_2 concentration in the exhaust gas. For example, meeting CO_2 pipeline specifications through compression and cooling alone, without requiring separation of the CO_2, considerably reduces costs of capture. Costs for capturing carbon from diluted industrial flue gases (e. g. combustion of natural gas, refinery) range from € 50 – 100 per tonne. Substantially less effort is required for sources with a high CO_2 concentration (e.g. ammonia production.), which makes it possible to reduce the cost of capture to values well below € 50 per tonne[12].

Biogenic CO_2 sources

Similar to industrial point sources, costs of capturing CO_2 from biogenic sources vary considerably by carbon source due to variation in CO_2 concentration. In addition, required purification can be another cost factor: e. g., most CO_2 from upgrading plants needs to be purified further before it can be utilised for powerfuels production or other carbon capture and utilisation (CCU) pathways. While costs therefore vary by source and location, on average, cost capture of carbon from diluted industrial flue gases (e. g. solid biomass combustion) is estimated to be around € 50 –100 per tonne of CO_2. Due to the reasons outlined above, cost is lower for capturing carbon from highly concentrated sources, at less than €50 per tonne of CO_2, and values as low as 12 – 25 €/t CO_2 for some sources such as bioethanol plants[13]. For cost reasons, among others, bioethanol fermentation, a process characterised by high purity of exhaust CO_2, and biogas upgrading have been identified as "low hanging fruit" biogenic carbon sources[14].

CASE STUDY 1 ▶

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[12] Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2'.

[13] Praveen Bains, Peter Psarras, and Jennifer Wilcox, 'CO_2 Capture from the Industry Sector', Progress in Energy and Combustion Science 63 (1 November 2017): 146 – 72, https://doi.org/10.1016/j.pecs.2017.07.001.

[14] Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2'.

Falkenhagen STORE & GO demonstration site: Production of synthetic methane using CO_2 from a bioethanol plant as a feedstock

As one of three demonstration facilities that were part of the STORE&GO project, a multinational and interdisciplinary cooperation project funded under the European Union's Horizon 2020 research and innovation programme from 2016 to 2020, the Falkenhagen pilot plant in the German federal state of Brandenburg produced synthetic methane from green hydrogen and biogenic CO_2. For this process, a power-to-gas plant producing green hydrogen from wind power via electrolysis, which had been in operation since 2013, was extended with a methanation unit.

The STORE&GO project aimed to demonstrate the potential of various power-to-gas technologies in combination with various setups to demonstrate sector-coupling applications in the European energy grid.

Besides the renewable energy sources for green hydrogen production (different combinations of wind, solar, and hydropower were used at the three demonstration sites), the CO_2 sources used also varied across the three locations of the project. In the case of the demonstration site in Falkenhagen, a bioethanol plant in Zeitz (Saxony-Anhalt) was chosen as the source to provide carbon for various reasons. Firstly, the project partners opted for a biogenic carbon source in order to be able to produce synthetic methane from 'green' CO_2. Secondly, the high purity and concentration of the CO_2 produced during bioethanol fermentation lowered the energy intensity of the capture process as well as the costs of providing carbon for the synthetic methane production compared to other potential sources. Lastly, as the project in Falkenhagen aimed to demonstrate the feasibility of producing synthetic methane and feeding it into the natural gas grid at large scale, a carbon capture technology that was already marketable and enabled the provision of the required quantities of CO_2 was sought. The market-readiness of capturing, transporting and storing the CO_2 from the bioethanol plant thus also contributed to the choice of using it in the methanation unit.

The plant in Falkenhagen produced up to 1,400 cubic meters of synthetic methane (SNG) per day, corresponding to approximately 14,500 kWh of energy, which was fed into the natural gas grid. Over the course of its runtime, the methanation unit produced the equivalent of about 192,000 kWh of energy.

Carbon from ambient air

Due to the lower technology maturity level of DAC technologies and the low carbon concentration in ambient air, cost of DAC is considerably higher at present, at approximately 300 – 600 €/t[15]. However, a significant cost degression is expected, with long-term estimates of below € 100 per provided tonne of CO_2 (see Figure 5).

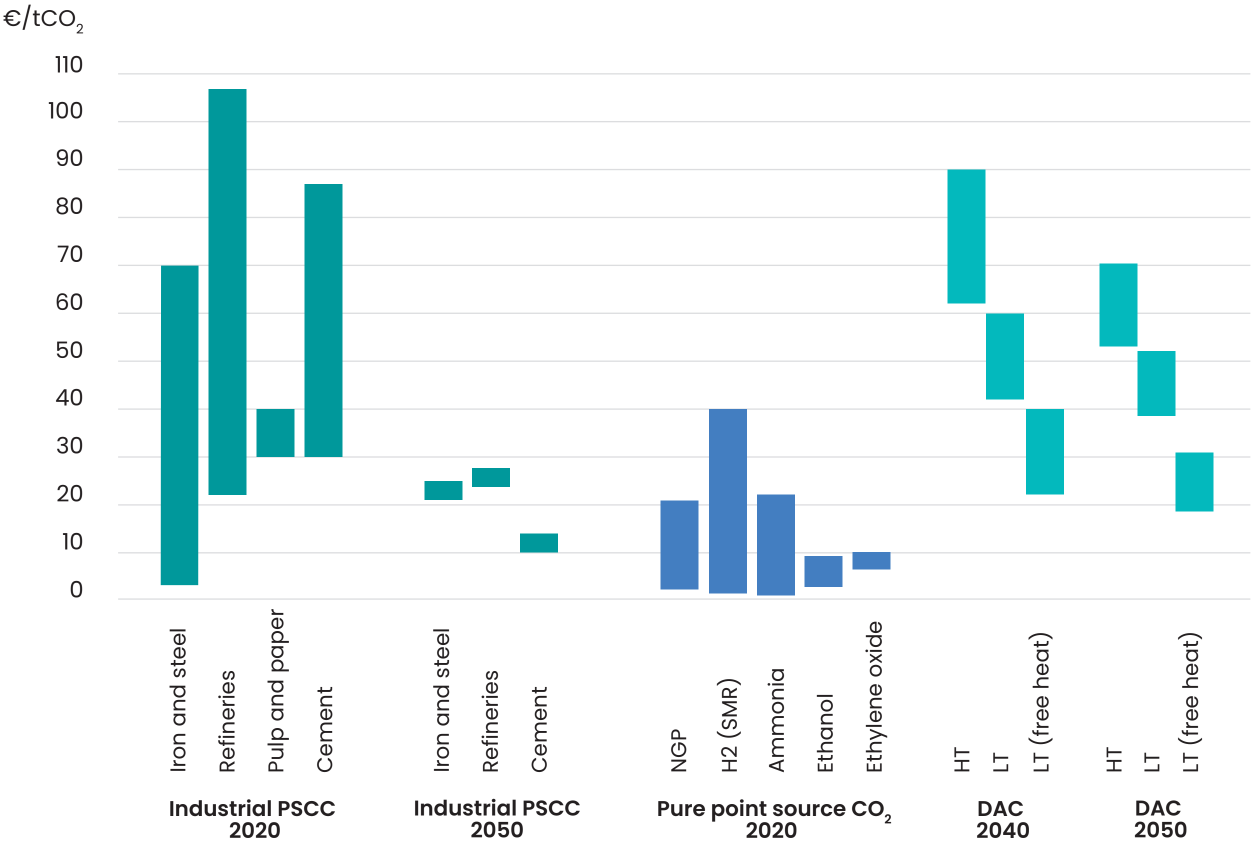

Figure 5: Projected range of costs of carbon capture from point sources (PSCC) for different industries and DAC. Retrieved from: Mahdi Fasihi, Olga Efimova, and Christian Breyer, 'Techno-Economic Assessment of CO_2 Direct Air Capture Plants', Journal of Cleaner Production 224 (1 July 2019).

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[15] Johannes Schaffert et al., 'Innovative Large-Scale Energy Storage Technologies and Power-to-Gas Concepts after Optimisation: Report on an EU-Wide Potential Analysis of Power-to-Gas Locations Coupled to Local CO_2 and Renewable Energy Sources', 2020; Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2'.

3.2 Scalability/expected long-term availability

Given the importance of powerfuels for the envisioned low-carbon economy, scalability of carbon capture technologies and long-term availability of selected carbon sources are vital to meet future demand. Mid- and long-term energy transition pathways to meeting climate and sustainability targets can thus guide and shape decisions about carbon sources to be made today.

Industrial CO_2 point sources

Industrial CO_2 point sources, and fossil fuel based power plants in particular, currently have a large share in global carbon emissions. However, given the increasing replacement of fossil-fuelled power plants with renewable energies, the potential CO_2 supply from power plants is expected to fall sharply over the next decades[16]. This will presumably result in larger shares of potential CO_2 supply by other industrial point sources, such as iron, steel or cement production plants, and chemical plants, e.g. for ammonia production. In addition, the total useable CO_2 potential from industrial sources in the EU is expected to decrease by approximately 75 %[17], assuming that CO_2 emissions from certain chemical reactions, which cannot be avoided by using renewable energy sources and/or alternative production processes, will remain the only carbon-emitting industrial processes in the long-term (see unavoidability criterion below).

To avoid so-called 'carbon lock-in' effects, describing inertia in carbon emission reductions due to mutually reinforcing economic, physical, and social constraints[18], it needs to be ensured that the utilisation of CO_2 from selected industrial point sources neither increases nor prolongs carbon emissions at these sites compared to a baseline of no carbon capture in place.

Biogenic CO_2 sources

Like carbon captured from ambient air via DAC technologies (see below), and in contrast to industrial point sources, carbon captured from biogenic sources and released during the 'use phase' of powerfuels does not contribute to the net release of CO_2 and is hence generally classified as a 'carbon-neutral' or 'sustainable' carbon source.

Theoretically speaking, up to 500 Mt of biogenic CO_2 per year are currently available in Europe from biogas upgrading, biogas and solid biomass combustion, as well as bioethanol and other fermentation processes[19]. However, the actual utilisation potential for powerfuels production and attainable capture rates are only a fraction of these theoretical amounts.

This is not only because competing uses for biogenic CO_2 exist, e. g. in the beverages industry, but also due to the fact that the attainable capture rates depend, i. a., on the level of dilution of flue gases. Size is also a limiting factor, as the necessary capture efforts exclude small biogenic stationary carbon-emitting sites as potential sources of CO_2 for powerfuels production. Considering only solid biomass combustion and biogas upgrading plants larger than 1MW, the estimated annual useable CO_2 potential in Europe is estimated to amount to approximately 85 million tonnes[20]. In consequence, while biogenic carbon sources are generally classified as sustainable and a potential 'technology lock-in' is thus not a concern, the expected capture potential will not suffice to meet future demand for CO_2 as a feedstock for powerfuels production.

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[16] European Climate Foundation, 'Roadmap 2050 - Technical & Economic Analysis - Full Report', 2010, https://roadmap2050.eu/attachments/files/Volume1_fullreport_PressPack.pdf.

[17] German Energy Agency (dena) and LBST – Ludwig-Bölkow-Systemtechnik GmbH, '«E Fuels» Study - The Potential of Electricity Based Fuels for Low Emission Transport in the EU', November 2017.

[18] Karen C. Seto et al., 'Carbon Lock-In: Types, Causes, and Policy Implications', Annual Review of Environment and Resources 41, no. 1 (20 October 2016): 425 – 52, https://doi.org/10.1146/annurev-environ-110615-085934.

[19] Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2'.

[20] German Energy Agency (dena) and LBST – Ludwig-Bölkow-Systemtechnik GmbH, '«E Fuels» Study - The Potential of Electricity Based Fuels for Low Emission Transport in the EU'.

Carbon from ambient air

In contrast to carbon from industrial or biogenic sources, the application of DAC technologies is geographically independent from the availability of industrial plants or related infrastructure. In consequence, the DAC production potential is solely limited by its energy demand, as the capture process is energy-intensive (see below). Carbon from ambient air as a potential feedstock for powerfuels production will therefore be available in large quantities long-term, and DAC technologies are considerably less limited in their scalability.

3.3 Regional availability

Industrial CO_2 point sources

Industrial CO_2 point sources are currently geographically dispersed, yet concentrated in terms of their share in total emissions: The largest 1000 power plants are responsible for approximately 22 % of global fossil fuel CO_2 emissions[21]. The level of concentration, and hence emissions per industrial site, vary across different carbon sources. E. g., emissions from iron and steel and the refinery industry are highly centralised, while the cement industry is characterised by lower emissions per site but a higher number of sites in total[22]. Overall, the widespread and dispersed distribution of industrial carbon point sources (see Figure 6 for an exemplary illustration of dispersion and size of industrial sources in European countries), especially those often classified as the most 'unavoidable' emitters (see unavoidability criterion below), would allow a distributed or decentralised installation of CO_2 utilisation technologies.

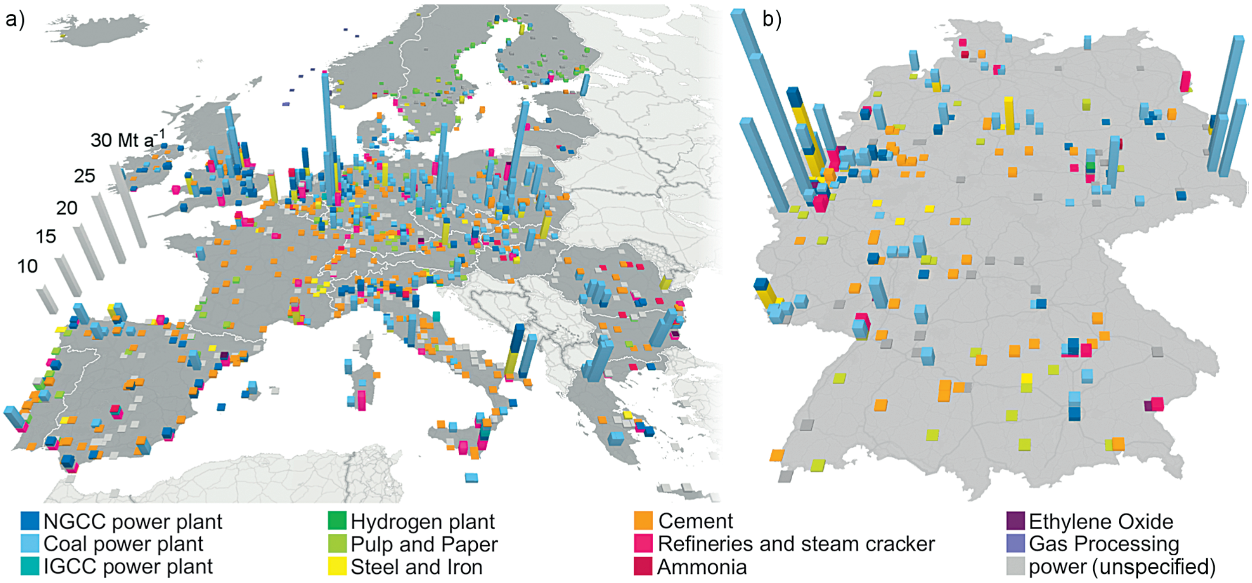

Figure 6: Distribution of industrial carbon point sources (>0.1 Mt a) in 2011 in a) Europe and b) Germany as exemplary country. Retrieved from: Niklas von der Assen et al., 'Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves', Environmental Science & Technology 50, no. 3 (2016).

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[21] Jocelyn Christine Turnbull et al., 'Independent Evaluation of Point Source Fossil Fuel CO_2 Emissions to Better than 10 %', Proceedings of the National Academy of Sciences 113, no. 37 (13 September 2016): 10287, https://doi.org/10.1073/pnas.1602824113.

[22] Rodin et al., 'Assessing the Potential of Carbon Dioxide Valorisation in Europe with Focus on Biogenic CO_2'.

Biogenic CO_2 sources

As mentioned above, the availability of biogenic CO_2 point sources is currently unevenly distributed as it is highly clustered in some countries, e. g. Germany. However, despite fewer sites for combustion of biomass or biotechnological industrial processes (e. g. fermentation) in other locations, most European countries engage in at least some level of biogas production, as shown in Figure 7. In addition, approximately 50 % of these plants are within proximity of up to 10 km to renewable energy sources (wind and utility-scale PV) and hence exhibit a potential for local energy coupling[23].

Per-site emissions from biogenic sources are rather low compared to fossil industrial emissions, especially for biogases. This points towards a more decentralised implementation of CCU activities, even though clusters within countries or regions with many biogenic carbon sources could emerge.

Carbon from ambient air

Concentration of carbon in ambient air shows little variation across regions. Whether DAC can be implemented in potential powerfuels producing and/or consuming locations is thus not primarily limited by the capture technology itself but rather the availability of renewable energy supply.

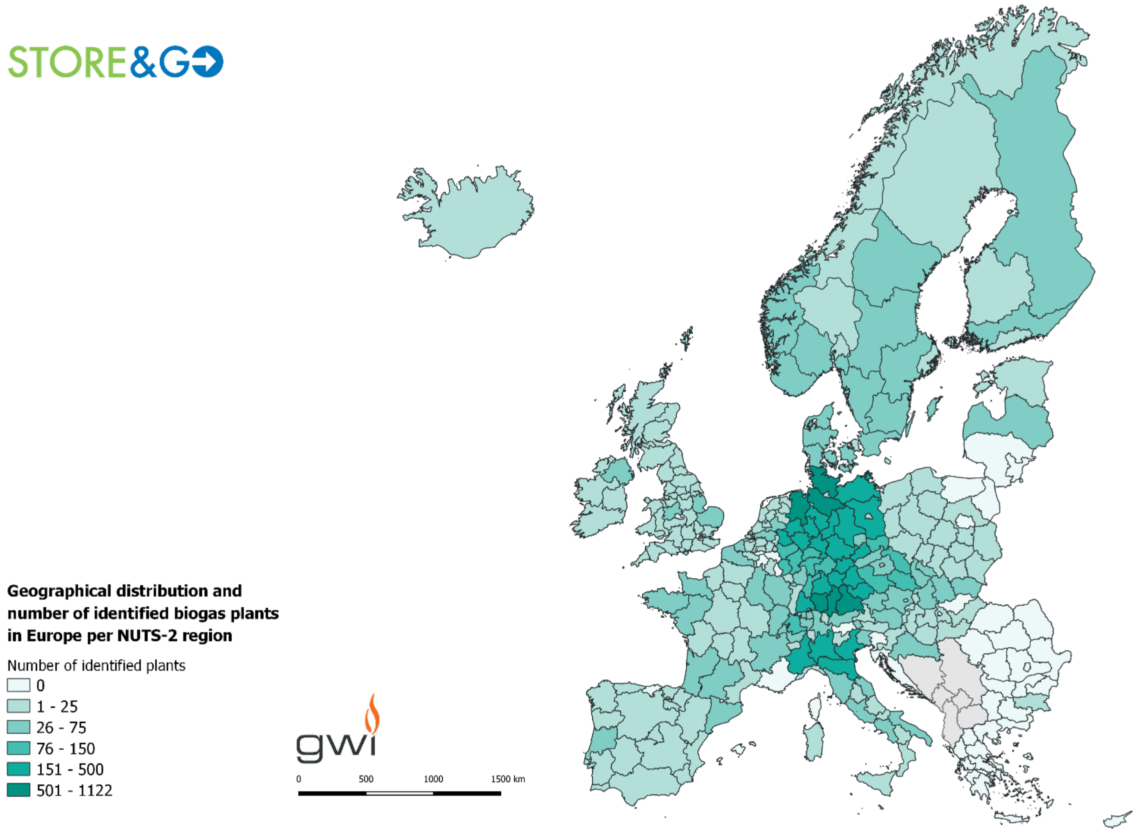

Figure 7: Geographical distribution and number of biogas plants across European countries. Retrieved from: Schaffert et al., 'Innovative Large-Scale Energy Storage Technologies and Power-to-Gas Concepts after Optimisation: Report on an EU-Wide Potential Analysis of Power-to-Gas Locations Coupled to Local CO_2 and Renewable Energy Sources', 2020.

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[23] Niklas von der Assen et al., 'Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves', Environmental Science & Technology 50, no. 3 (2016): 1093–1101, https://doi.org/10.1021/acs.est.5b03474.

3.4 Sustainability

a) GHG intensity of the capture process

The carbon capture process requires different forms of energy, mainly electricity and heat, to separate CO_2 from flue gas as well as to purify and compress it. The term 'CO_2 penalty' is therefore often used to specify the carbon emissions of the different energy inputs associated with the carbon capture process. Assuming that the captured carbon also needs to be transported to the utilisation site, resulting emissions also feature into the GHG intensity of the process.

Industrial CO_2 point sources
The GHG intensity of capturing carbon from industrial point sources varies depending on specific impact factors (e. g. source of electricity and heat supply as well as distance of transportation). Generally, however, the lowest emissions of providing CO_2, and thus largest total reductions in emissions from the sequestration, arise for CO_2 capture from the purest available sources, e. g. in ammonia production or natural gas processing. Capturing carbon from industrial sources with lower CO_2 concentration, e.g. cement production, is more energy intensive and is therefore associated with lower reductions in emissions, at approximately 0.6 t CO_2 saved per t CO_2 provided for utilisation[24].

Biogenic CO_2 sources
For carbon captured from the exhaust gases of biomass power plants at the post-combustion stage, the CO_2 penalty is estimated to be approximately 150 kg CO_2 per tonne of carbon captured. For pre-combustion capture, the value is approximately four times higher[25]. Carbon capture from other selected biogenic carbon sources, such as biogas upgrading or bioethanol production, requires lower energy input due to higher purity and concentration of CO_2 streams.

Carbon from ambient air
Capturing atmospheric carbon is generally more energy-intensive than carbon capture from industrial point sources, as CO_2 concentration in ambient air is between 100 and 300 times lower than, e. g., in the flue gases of coal- or gas-burning power stations[26]. Specific estimates of the GHG intensity of applying DAC technologies range around 0.5 t CO_2 per tonne of CO_2 provided[27]; this depends, however, on the specific DAC technology used and the selected energy sources for electricity and heat provision (see Case Study 1). A system fully powered by electricity and heat from renewable energy sources is technologically feasible[28].

CASE STUDY 2

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[24] von der Assen et al.

[25] Gerda Reiter and Johannes Lindorfer, 'Evaluating CO_2 Sources for Power-to-Gas Applications – A Case Study for Austria', Journal of CO_2 Utilization 10 (1 June 2015): 40 – 49, https://doi.org/10.1016/j.jcou.2015.03.003.

[26] Gambhir and Tavoni, 'Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation'.

[27] von der Assen et al., 'Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves'.

[28] Mahdi Fasihi, Olga Efimova, and Christian Breyer, 'Techno-Economic Assessment of CO_2 Direct Air Capture Plants', Journal of Cleaner Production 224 (1 July 2019): 957 – 80, https://doi.org/10.1016/j.jclepro.2019.03.086.

CASE
STUDY
2

Comparison of DAC technologies used by two leading suppliers: Climeworks and Carbon Engineering

While all DAC technologies are used to capture carbon from ambient air, which exhibits only small local variations in CO_2 concentration, differences in capture technologies and energy carriers used to power the system (e. g. provide heat and electricity) impact the GHG intensity of the process, and therefore the emissions associated with the captured CO_2. For example, Climeworks and Carbon Engineering, two leading suppliers of DAC technologies, have developed different processes to capture carbon from ambient air, which result in diverging energy input requirements.

Carbon Engineering, established in 2009 in Squamish, Canada, uses high temperature aqueous solution-based DAC. A so-called air contactor, which brings ambient air in contact with the aqueous sorbent, is at the core of Carbon Engineering’s air capture technology. The liquid solution binds the carbon molecules, and CO_2 contained in the solution is then filtered, purified, and compressed. In a central step of the process, small carbonate pellets, which are separated out from the liquid solution, are heated in a calciner to release the concentrated CO_2 for usage or storage, a process during which natural gas is used as an energy source. While natural gas as a fossil energy carrier thus provides the required heat, e.g., in the demonstration plant the company opened on the Squamish waterfront in 2015, resulting emissions from the natural gas combustion are also captured to prevent additional emissions. It should be noted, however, that the CO_2 captured from natural gas combustion is only stored temporarily. As for all carbon captured from industrial sources and used in powerfuels, the release of the CO_2 from natural gas combustion is thus only delayed, not fully avoided. Carbon Engineering states that it is developing an “all-electric variant of the calcium cycle that eliminates natural gas input”[a]. This would significantly lower the GHG intensity of the process, while energy demand remains high compared to technologies to capture carbon from other sources. According to the

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[a] David W. Keith et al., ‘A Process for Capturing CO_2 from the Atmosphere’, Joule 2, no. 8 (15 August 2018): 1573 – 94, https://doi.org/10.1016/j.joule.2018.05.006.

CASE STUDY

results of a simulation run by Fasihi et al. (2019), a fully electrified system based on the Carbon Engineering technology would require an energy input of approximately 1550 kWhel per captured tonne of CO_2. This compares to approximately 370 KWh_{el} for electricity provision and 1460 KWh_{th} for heat provision required to capture a tonne of CO_2 in an installation using both natural gas and electricity as energy carriers[b].

The Swiss company Climeworks, on the other hand, employs a low temperature solid sorbent-based DAC technology. It is operating multiple plants, e. g. a demonstration unit in Dresden, Germany to provide carbon as a feedstock for the production of synthetic diesel, and a plant in Switzerland to use the captured CO_2 in a nearby-located greenhouse. Climeworks' installations contain a single DAC unit where adsorption and desorption (regeneration) occur in succession. The key element of the company's capture process is a selective filter material made of cellulose fibre inside the CO_2 collectors, the surface of which the carbon adheres to. It is then released as purified gas by heating the system to 100 °C., cooled down, and collected. According to information provided by the company, the expected energy required for scaled-up systems amounts to approximately 2000 kWh_{th} and approx. 650 kWh_{el} per tonne of captured CO_2. The heat required in the regeneration stage can be supplied by waste heat recuperated from outside the DAC plant, as demonstrated by one of Climework's pilot plants.

As these two examples illustrate, electricity and heat demand of DAC plants per tonne of CO_2 produced vary across the available technologies, and the GHG intensity of the capture process also depends on the used energy carriers. Moving forward, high temperature aqueous solution and low temperature solid sorbent, which are the two main DAC technologies ready for implementation at commercial scale, could be fully supplied by electricity and heat from renewable energy sources. In particular, supplying the required electricity from fully renewable energy sources instead of using the current European electricity mix in the grid significantly lowers the GHG intensity of both technologies. The fossil fuels which are used to provide the required high-grade heat for most high temperature aqueous solution installations in operation at present significantly increase the 'CO_2 penalty' of the capture process and will have to be replaced by fully electrified systems in the mid- to long-term.

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[b] Mahdi Fasihi, Olga Efimova, and Christian Breyer, 'Techno-Economic Assessment of CO_2 Direct Air Capture Plants', Journal of Cleaner Production 224 (1 July 2019): 957 – 80, https://doi.org/10.1016/j.jclepro.2019.03.086.

b) Unavoidability

As illustrated by the projected demand for CO_2 in the previous chapter, carbon will become an increasingly important feedstock for the production of powerfuels to mitigate emissions in sectors that are hard to electrify directly. At the same time, the number of (in particular industrial) carbon sources and their contribution to global GHG emissions will have to be reduced drastically to reach climate targets at national, European and international level. It is therefore imperative that in the mid- to long-term, only unavoidable sources of CO_2 are eligible for the production of green powerfuels.

Industrial CO_2 point sources

Even if climate neutrality by 2050 is achieved, which is a goal the Global Alliance Powerfuels is strongly committed to, it is likely that some products will still be manufactured by means of carbon-emitting industrial processes. This is particularly true for industrial processes which, unlike electricity or heat generation, are not exclusively aimed at energy conversion. The carbon emitted during these processes can thus not simply be reduced or fully avoided by using a 'greener' energy carrier[29]. For example, in the production of cement, the second-most consumed product worldwide after drinking-water[30], carbon is released during the process of burning limestone to obtain calcium oxide, a key ingredient of the final product.

The unavoidability principle is explicitly referenced in the definition of Recycled Carbon Fuels (RCFs) in the RED II, which states that when they are produced from exhaust gas or waste processes of non-renewable energy, these need to be "an unavoidable and unintentional consequence of the production process in industrial installations".[31] However, no clear definition of 'unavoidable industrial carbon sources' exists as of date. It has been proposed that the classification should be guided by the possibility for substitution, both at the production stage and on the demand side, i.e. the question to which extent alternative production processes, resources, or substitute products for the same application are available[32]. Whether specific industrial carbon sources are considered to be 'unavoidable' is likely to change over time: As research and technological innovations advance, the set of industrial carbon-emitting processes defined as unavoidable is likely to become narrower in the future.

Biogenic CO_2 sources

Due to the closed carbon cycle of biomass combustion or biotechnological industrial processes, the question of unavoidable carbon emissions is less of a concern in the case of carbon captured from biogenic sources.

The GHG impact of CCU from biogenic sources in the production of biofuels is addressed in Annex V, C of the RED II. In its methodology of assessing the GHG impact of biofuels, biogenic carbon captured in the production of biofuels is counted as negative emissions in the calculation of the GHG emissions from the production and use of the fuels if replaces "fossil-derived CO_2" in the production process of commercial products and services.[33]

Carbon from ambient air

The process of capturing CO_2 from ambient air is decoupled from industrial carbon-emitting processes. Carbon captured via DAC technologies can therefore be considered fully unavoidable as no additional release of carbon is incentivised.

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[29] IN4climate.NRW, 'Unavoidable Production of CO_2 in a Climate-Neutral Primary Sector in North Rhine-Westphalia: Definition and Criteria', September 2020.

[30] Thomas Czigler et al., 'Laying the Foundation for Zero-Carbon Cement', May 2020, https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.

[31] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

[32] IN4climate.NRW, 'Unavoidable Production of CO_2 in a Climate-Neutral Primary Sector in North Rhine-Westphalia: Definition and Criteria', 4.

[33] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC.

3.5 Verifiability/creditability

The commercialisation of powerfuels and their recognition as renewable and climate-friendly energy carriers and feedstock requires that the renewable characteristics of the respective feedstock and energy sources used in their production, including electricity and carbon sources, are clearly defined and verifiable to allow for appropriate certification. Furthermore, it needs to be determined at which stage of the CO_2 capture or utilisation process the achieved emission reductions can be credited towards sector-specific mitigation targets.

Industrial CO_2 point sources

As CO_2 captured from industrial point sources and used in the production of powerfuels is eventually re-emitted once the powerfuels are used, carbon emissions are 'recycled' but not fully avoided in the process. Emissions thus need to be accounted for, and reductions ought to only be credited once to avoid 'double-counting'. What is more, it needs to be ensured that the captured carbon is not additional to avoid incentives for intensifying industrial carbon-emitting processes (see above). This requirement is in addition to other sustainability criteria that determine the eligibility for powerfuels production and apply for all carbon sources equally (e. g. threshold for GHG intensity of the capture process in relation to captured carbon).

Biogenic CO_2 sources

CO_2 emitted during the combustion of powerfuels that are produced using carbon from biogenic sources is not additional as it is cycled from the atmosphere, through the growth of plants, and released again in the usage stage of the fuel. Full creditability is therefore expected as long as the above-mentioned additional sustainability criteria are met.

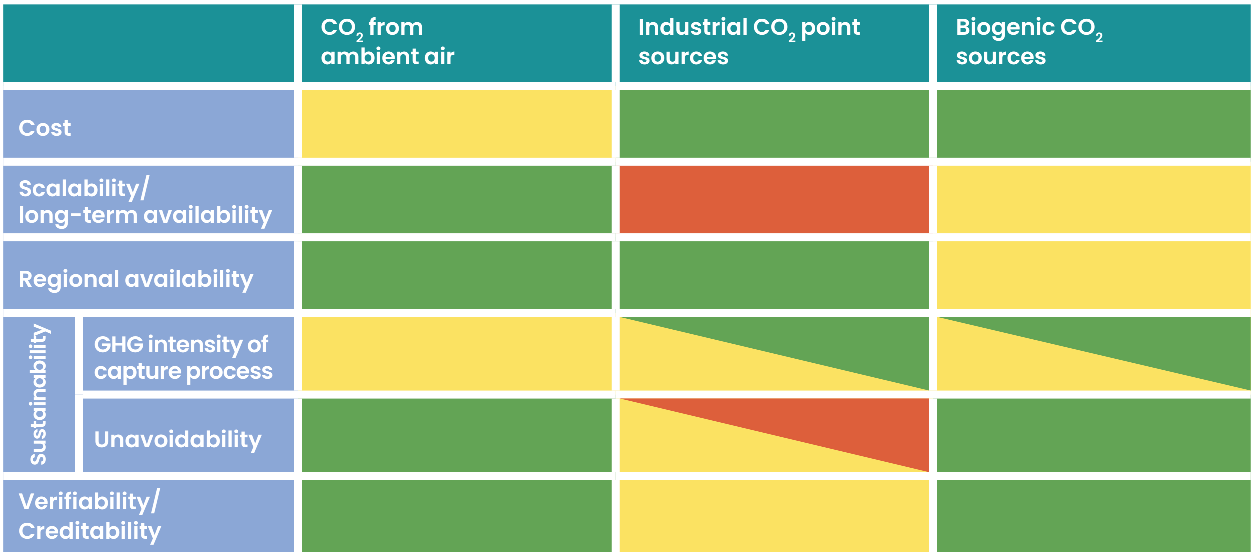
Carbon from ambient air

Carbon captured via DAC technologies is expected to be fully creditable as feedstock for powerfuels production as long as sustainability criteria which apply for all carbon sources equally are met.

Overview

The results of the assessment of the three categories of potential carbon sources for powerfuels production are summarised below based on a 'traffic light' colour-coded system. As outlined above, the heterogeneity of possible carbon sources within categories based on, e.g., the underlying carbon-emitting process, location, and capture technology employed, results in partially wide evaluatory ranges for the different criteria. The table below can thus only depict broad tendencies.

Table 1: Summary of assessment of categories of carbon sources under pre-defined economic, geographic, and sustainability criteria



		CO_2 from ambient air	Industrial CO_2 point sources	Biogenic CO_2 sources
Cost		🟨	🟩	🟩
Scalability/ long-term availability		🟩	🟥	🟨
Regional availability		🟩	🟩	🟨
Sustainability	GHG intensity of capture process	🟨	🟨🟩	🟨🟩
	Unavoidability	🟩	🟨🟥	🟩
Verifiability/ Creditability		🟩	🟨	🟩

Note: Selected colour codes follow a 'traffic light' system and depict broad tendencies for each of the three categories of carbon sources based on the evaluation above.

4 Market Integration

The necessary market integration of carbon capture technologies comprises targets and processes to commercialise its usage in the production of carbon-based powerfuels. As of today, no real market for carbon capture exists, and technologies are partially market-ready, but not yet widely commercialised. Political action is needed to make those carbon capture technologies that are not yet available at industrial scale, in particular DAC technologies, marketable.

First, it is important to create a **vision** for the application of carbon capture technologies for the different available sources of CO_2 that reflects long-term goals. Second, a **pathway** has to be developed which outlines how these long-term goals will be achieved. This requires a coordinated timeline for ramping up technologies and developing criteria for the usage of atmospheric, biogenic, and industrial carbon sources.

As illustrated in chapter 2, large-scale production of carbon-based powerfuels will be commercialised between 2030 and 2050.[34] With decreasing use of fossil energy carriers, the number of eligible industrial carbon point sources will reduce so that in the long term, only atmospheric and biogenic carbon sources will be available to supply carbon as a feedstock for powerfuels production. As shown in Figure 8, CO_2 captured from ambient air using DAC technologies will dominate carbon provision for powerfuels production in 2050. The absolute demand for CO_2 will increase significantly in the same time period, as also illustrated in Chapter 2.

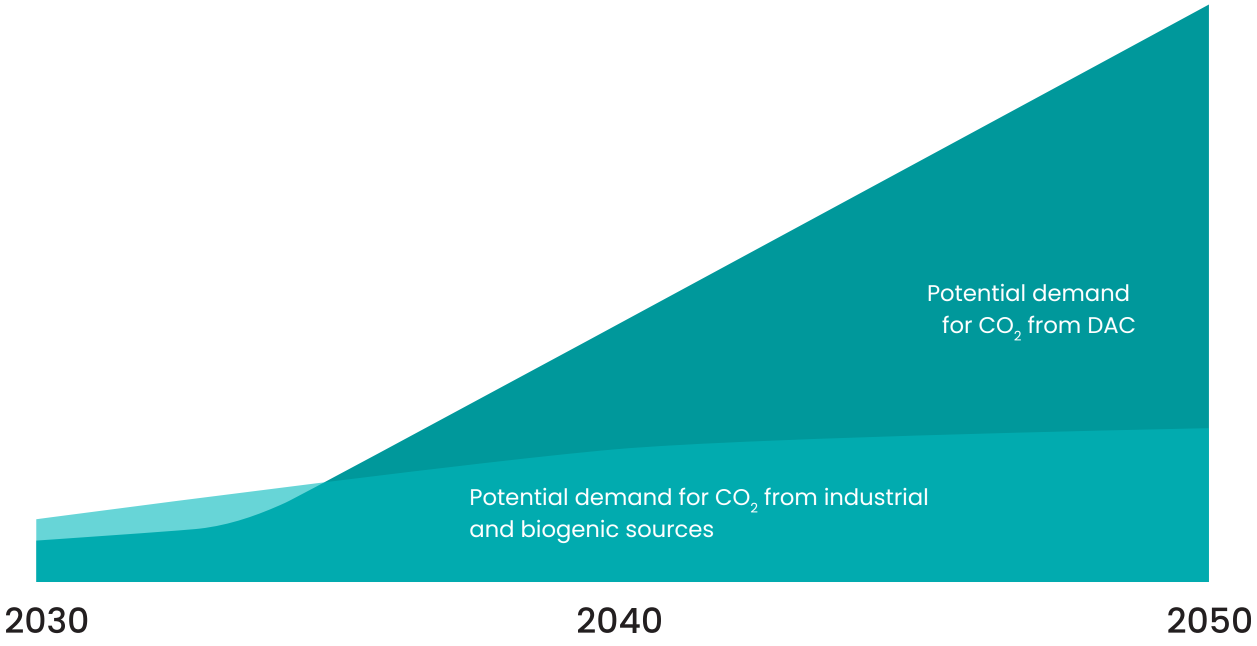


Figure 8: Schematic illustration of potential demand for CO_2 from point sources and DAC for powerfuels market ramp-up

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[34] LUT University, 'Powerfuels in a Renewable Energy World', 2020, publication pending.

Pathways

The design of market integration pathways has to consider the status quo of the energy system as well as the development of factors influencing the powerfuels and CCU market. Generally, the market integration of carbon capture technologies should serve the following three targets:

1. **Increasing Quantity**
   Carbon capture technologies have to be ramped up, meeting the demand of CO_2 for the increasing production of carbon-based powerfuels. For the timeline of this technology ramp-up, the expected availability of the respective carbon sources and the long-term goal of a carbon-neutral energy system should be taken into consideration.

2. **Decreasing Costs**
   The costs of carbon capture technologies need to decrease for powerfuels production to become economically viable and to make powerfuels as a product more competitive.

3. **Assuring Sustainability**
   Carbon capture technologies for powerfuels production have to contribute effectively to reaching emission reduction targets.

As analysed in the previous chapters, different industrial, biogenic and atmospheric carbon sources are available today, each of which come with both advantages and shortcomings. There are many factors influencing the performance of those sources towards fulfilling the above-defined targets.

The following factors are particularly influential for the market integration of carbon capture technologies, and will thus also shape decisions about eligibility and selection of specific carbon sources:

- **Powerfuels demand:** The demand for powerfuels determines the quantity of carbon feedstock needed. The transport sector is the largest potential demand market for carbon-based powerfuels. However, the future powerfuels demand in aviation, shipping and road transport is highly uncertain.

- **Carbon intensity of the energy system:** The carbon intensity within an energy sector describes the share of carbon-based energy carriers and their related GHG emissions. In the transport sector, e. g., a continuously high carbon intensity could indicate a potentially large demand for carbon-based powerfuels.

- **Cost degression of respective technologies:** The cost of capture technologies influences the cost per captured tonne of carbon and thereby the powerfuel production costs. Thus, the cost degression of capture technology increases the competitiveness of carbon-based powerfuels.

- **Development of CCS technologies:** The storage of carbon from industrial point sources using CCS technology is an alternative to the utilisation of captured carbon. While captured and stored carbon would be prevented from reaching the atmosphere, utilisation of carbon leads to the emission into the atmosphere at a later point in time. CCS and CCU could be either used complementary or exclusively.

- **Political targets for the decarbonisation of the industry sector, and openness to using industrial point sources over time:** As outlined above, availability of industrial point sources is expected to decrease significantly in the next decades, and only industrial carbon sources deemed unavoidable will presumably be available in the mid- to long-term. The pace of this transition, determined in part by political targets and decisions about the defossilisation of industry as well as the extent to which these are met, will thus also shape the market integration of technologies for capturing from the different sources presented in this paper.

5 Discussion of Policy Measures

Despite the importance the EU attributes to powerfuels[35] in its Hydrogen Strategy, Energy System Integration Strategy, and the Renewable Energy Directive II (RED II), existing regulation offers neither a clear definition nor sufficient regulation for carbon sources and the carbon capture and utilisation technologies (CCU)[36] necessary to make carbon available as a feedstock for the production of powerfuels. The scope of the possible carbon sources introduced above and associated CCU technologies is not specified in EU terminology, and when they are mentioned, the definition is not sufficiently clear. Furthermore, CCU is currently not fully integrated into the policy framework despite the fact that powerfuels are a promising decarbonisation option and the production of many of them requires carbon as a resource.

This creates a major problem for investors, project developers, and potential consumers alike due to the uncertainty regarding future regulation on **which carbon sources are eligible** for the use in powerfuels production and which **sustainability criteria they need to satisfy**. This inhibits market development of both powerfuels and CCU technologies, as planning and investment security are negatively affected by the uncertainty surrounding regulation. Therefore, a clear definition needs to be adopted and clear rules for the re-use of carbon to be defined as soon as possible. It is crucial that these elaborations are also compatible with existing regulation on Carbon Capture and Storage (CCS) and powerfuels. In order to stimulate the discourse on this matter, possible policy scenarios will be discussed in the following.

Industrial CO_2 point sources

Carbon captured from industrial point sources originates from burning of fossil fuels in stationary industrial plants. After the carbon is captured and used in the production of powerfuels, it is eventually re-emitted once the powerfuels are being burned[37]. In view of the EU goal of carbon neutrality, this carbon release needs to be accounted for. However, as carbon is recycled in the process, emissions only occur once, raising the question of how and at what stage this CO_2 is to be counted.

For carbon captured from industrial installations covered under the EU Emissions Trding System (ETS), Article 12 (3a) of the ETS Directive states that *"An obligation to surrender allowances shall not arise in respect of emissions verified as captured and transported for permanent storage to a facility for which a permit is in force in accordance with Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide"*. According to this provision, installations that capture and transport emissions for permanent storage are not required to surrender ETS allowances. There is, however, no similar exemption for installations that capture emissions intended for temporary storage or utilisation, e.g. in powerfuels production. It therefore needs to be defined whether this principle ought to be extended to carbon captured for utilisation pathways and at what stages emissions are to be credited.

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[35] Termed 'Renewable Fuels of Non-Biological Origin' (RFNBO).

[36] The term CCU as we understand it comprises all possible carbon sources, including ambient, biogenic and industrial sources.

[37] Not all powerfuels are necessarily being burned when used. E.g., powerfuels can replace fossil fuels as feedstock in the chemical industry to produce every-day goods such as plastics, tyres and detergents.

End-use of powerfuel in non-ETS sector: If the powerfuel is used in a non-ETS sector (e. g. as fuel in road transport), no emission allowances currently have to be surrendered for the resulting emissions. One potential provision could therefore be that the carbon capture installation providing the carbon should continue to have to surrender allowances to ensure that emissions allowances are not bypassed. This potential mechanism is illustrated in Figure 9. Alternatively, emissions would have to be accounted for in the end-use sector, meaning that the carbon content of the powerfuels would have to be acknowledged accordingly.

In both cases, should the energy sources used to provide electricity and heat for the capture process itself not be 100 % renewable, the associated emissions are covered under the EU ETS but could potentially also be counted at the end-use stage.

End-use of powerfuel in ETS sector: The problem of 'bypassed' emissions allowances does not arise if the powerfuel is used in a sector covered by the ETS. In this case, the end-use emissions are accounted for under the ETS. An issue that arises in this case, however, is the risk of double counting: Each unit of CO_2 and its 'recycled quality' could potentially be counted twice (at the capture installation and at the end-use combustion). It therefore needs to be ensured that the emittance of CO_2 is only credited at one of these stages. The same needs to be considered for the crediting of CO_2 reductions.

In order to find a provision that works for both application cases (usage in- and outside the ETS), it could be stipulated that the usage of powerfuels in the end-use application, and release of carbon that goes along with it, should generally not require the surrendering of allowances. In this case, any type of powerfuel could be treated as carbon-neutral under the condition that emissions associated with its use are accounted for at the CO_2 capture stage, e. g. if the industrial installation is part of the ETS.

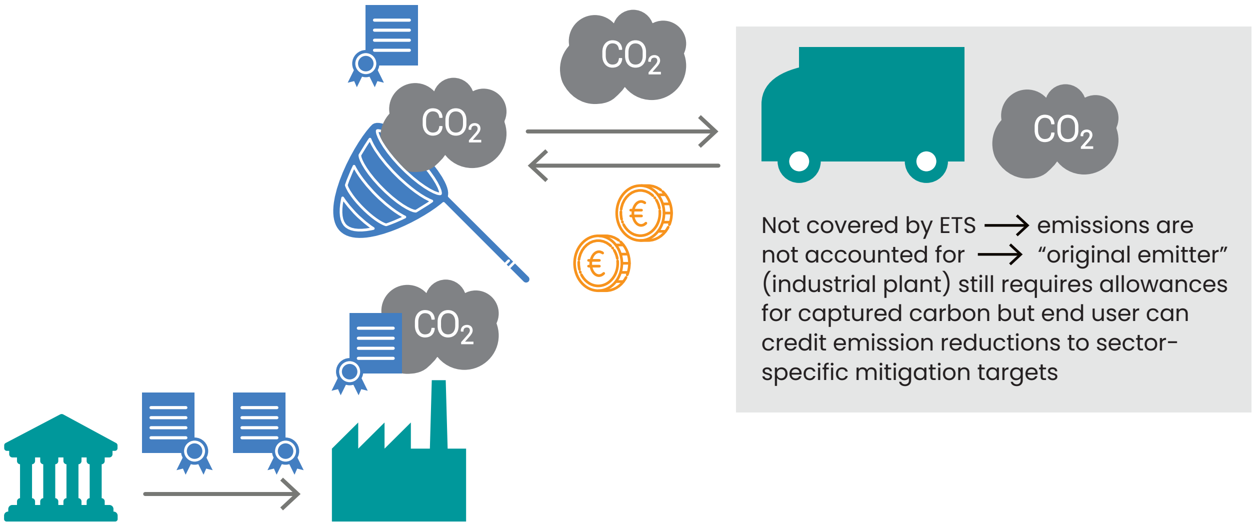
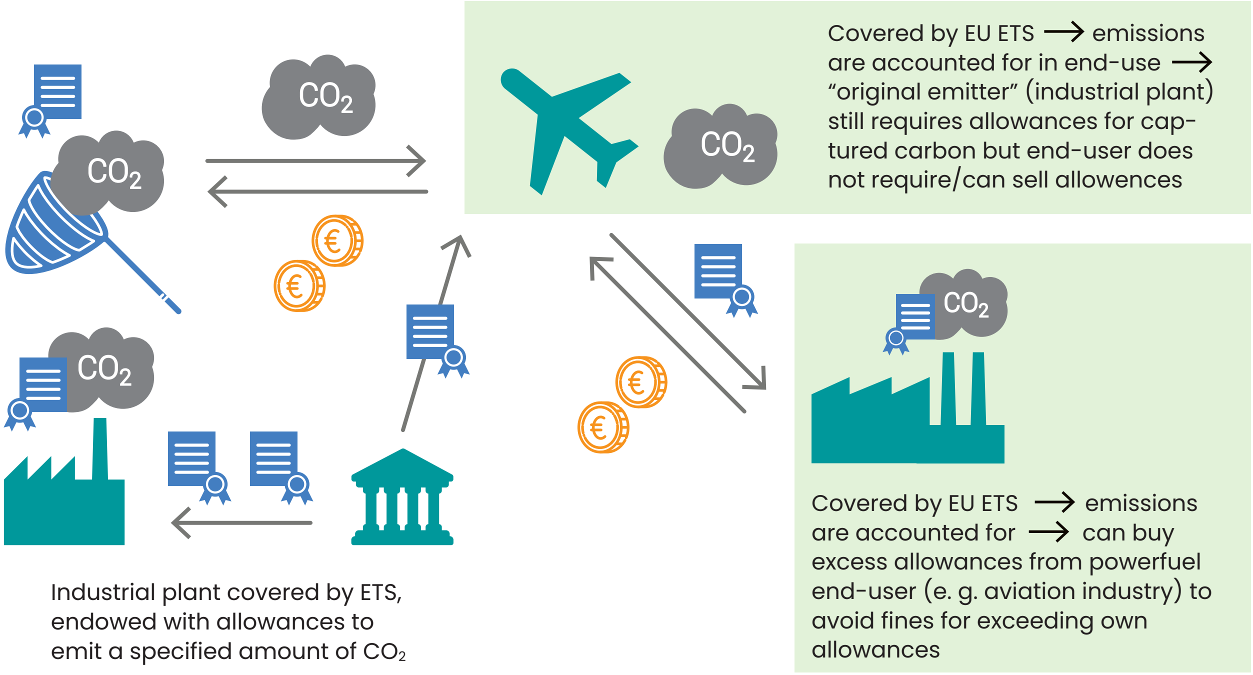


Figure 9: Illustration of potential mechanism for carbon captured from industrial point sources which are part of the EU ETS and used in a non-ETS sector

This would require industrial carbon capture installations to use allowances for each unit of carbon that they provide for powerfuels production. An amendment to the ETS Directive that exempts carbon capture for utilisation installations from the obligation to surrender allowances would be an alternative, but might be a less practicable approach as it would have to be ensured that the emitted carbon is counted at the point of usage.

The first option would imply that the carbon emitted over the entire lifecycle of powerfuels is counted at the point of capture and should thus not be counted at another point of the lifecycle. Accordingly, if the carbon source is covered by the ETS and was accounted for by surrendered allowances, emissions should not be counted again when the powerfuel is burned – even if it is used in a sector that is also under the ETS. An example of the functioning of this mechanism is provided in Figure 10.



Covered by EU ETS → emissions are accounted for in end-use → “original emitter” (industrial plant) still requires allowances for captured carbon but end-user does not require/can sell allowences

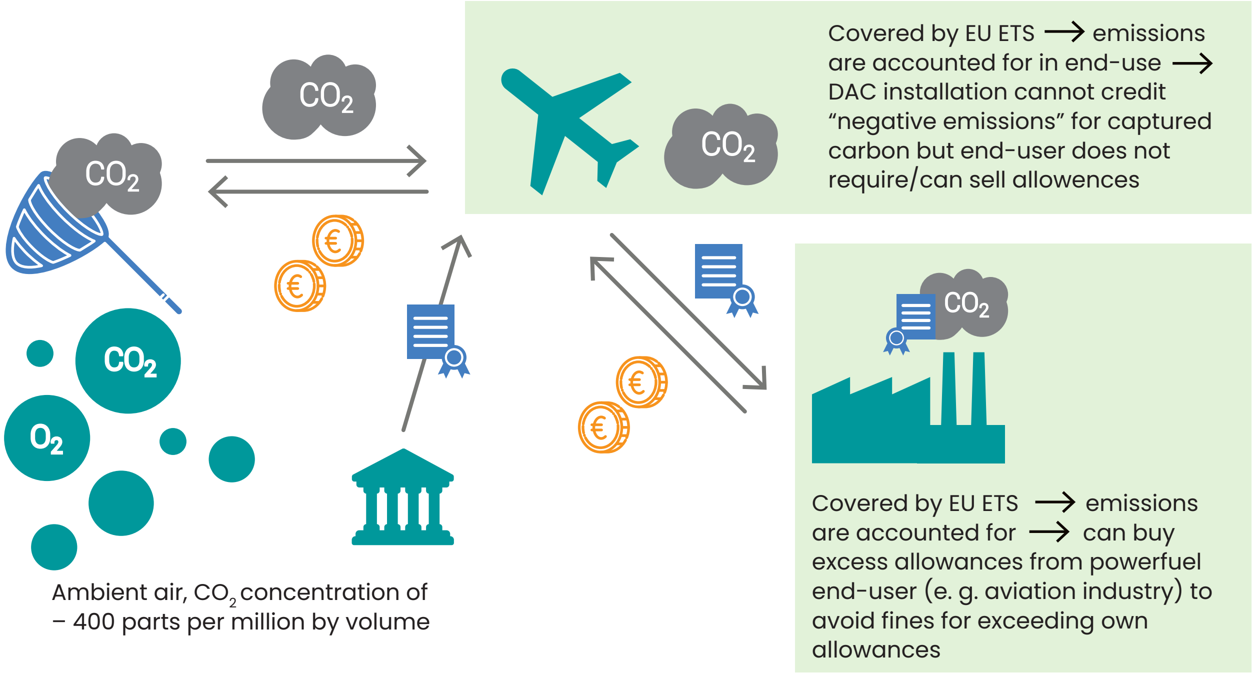
Covered by EU ETS → emissions are accounted for → can buy excess allowances from powerfuel end-user (e. g. aviation industry) to avoid fines for exceeding own allowances

Industrial plant covered by ETS, endowed with allowances to emit a specified amount of CO_2

Figure 10: Illustration of potential mechanism for carbon captured from industrial point sources and used in an ETS sector

Carbon from ambient air

If the carbon is captured from ambient air using DAC technologies, the carbon cycle is neutral and net emissions are zero. The DAC installation could thus either be credited with negative emissions, or the carbon emitted during end-use could be exempted from the ETS (or the emission reduction could be credited via other sector-specific mechanism if the end-use occurred outside the ETS). In this case, as in the case of powerfuels produced using carbon from industrial point sources which is counted at the capture stage described above, powerfuels could therefore be acknowledged as carbon-neutral. The operators of DAC installations should, however, need to provide certification that the energy used in the energy-intensive capture process itself is of renewable origin to avoid any additional emissions. An example of how this mechanism could function in practice is given in Figure 11.



Covered by EU ETS → emissions are accounted for in end-use → DAC installation cannot credit “negative emissions” for captured carbon but end-user does not require/can sell allowences

Covered by EU ETS → emissions are accounted for → can buy excess allowances from powerfuel end-user (e. g. aviation industry) to avoid fines for exceeding own allowances

Ambient air, CO_2 concentration of – 400 parts per million by volume

Figure 11: Illustration of potential mechanism for carbon captured from ambient air using DAC, and used in an ETS sector

Challenges associated with the outlined potential crediting mechanisms

As noted above, a clear definition of eligible carbon sources and integration of carbon capture technologies to provide CO_2 for temporary storage or utilisation in powerfuels are needed to provide planning and investment security. At the same time, it has to be ensured that a crediting mechanism for achieved emission reductions, in particular when CO_2 is provided from industrial point sources, does not incentivise industry sectors to uphold or even intensify carbon-emitting processes. The outlined possibility to count emissions at the stage of capture, and credit of reductions at the end-use stage therefore appears to be practicable to avoid double-counting of emissions or emission reductions; however, the following challenges need to be taken into consideration and addressed when a crediting mechanism is developed:

- The EU ETS and sector-specific regulations for GHG mitigation, e.g. in transport, are based on different approaches: The ETS is a system which sets a cap on the total number of units of greenhouse gases that can be emitted by participating installations; in transport, on the other hand, concrete GHG emission reductions compared to a fossil equivalent have to be demonstrated. Coupling the crediting systems could prove to be challenging, i.a., because of the large difference in cost for carbon (avoidance) between sectors, which could bear the risk of market distortion.
- Projections indicate that a significant share of carbon-based powerfuels will be produced in regions outside the EU and industry in these markets often does not face emission caps comparable to the ETS. Emissions that are associated with the used carbon captured from industrial sources, including those that result from the capture process itself, thus need to be accounted for to avoid that emission reductions are credited in the end-use sector but emissions are not accounted for. Furthermore, missing GHG reduction targets or caps in powerfuels producing markets could incentivise the intensification of carbon production.
- Fully counting emissions at the stage of capture, and crediting reductions at the end-use stage, would result in all powerfuels being treated equally at the usage stage in terms of their GHG reduction potential, and would hence render differentiation between carbon-based and carbon-free powerfuels, as well as between carbon-based powerfuels produced using biogenic, industrial, or atmospheric CO_2, difficult.

Discussion with regard to the RED II

The RED II is a major piece of EU legislation regulating the use and production of powerfuels. While providing no criteria for carbon sources, the RED II Article 27 offers certain sustainability criteria for electricity sources used in powerfuels production that producers need to comply with for the resulting fuel to be counted as renewable (renewability, temporal correlation, geographical correlation, additionality). In line with this provision, the electricity used during the carbon capture process would be required to comply with the same criteria, regardless of the type of carbon source.

The RED II does provide some indication regarding industrial point sources in its definition of RCFs. In Article 2, it states that " 'recycled carbon fuels' means liquid and gaseous fuels that are produced from (…) or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations". According to this definition, recycled carbon needs to come from **unavoidable waste streams**. In view of the delegated act of Article 25, due in January 2021, that will establish minimum thresholds for GHG emissions savings of RCFs through life cycle analysis, carbon emissions from industrial point sources not only have to comply with the unavoidability principle but will also have to lead to a yet-to-be-determined overall GHG emissions reduction threshold. As outlined above, industrial point sources should therefore be eligible for powerfuels production when complying with these criteria. However, what exactly counts as "unavoidable" is not clear and therefore needs to be defined in upcoming amendments.

As elaborated on earlier, both double counting of emissions and of emissions savings should be avoided. This should particularly be reflected in the upcoming delegated act of Article 28 of the RED II, due in December 2021, which will provide details on *"specifying the methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels, which shall ensure that credit for avoided emissions is not given for* CO_2 *the capture of which has already received an emission credit under other provisions of law."* As laid out in Article 27, powerfuels must provide at least a 70 % reduction in GHG emissions compared to fossil counterparts in order for them to be creditable towards CO_2 reduction targets in the transport sector. The upcoming elaboration of Article 28 will have to clarify how the carbon used in powerfuels production will be methodologically assessed in this context.

General policy recommendations

Despite the complexity of the issue and the challenges regarding the crediting of carbon emissions, the following general recommendations can serve as guiding principles for any upcoming regulation on the use of CO_2 for powerfuels:

1. A clear **definition of CCU technologies** should be provided. Existing definitions of CO_2 capture in the Commission implementing regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions, Article 3 (54), and the Commission Regulation (EU) 601/2012 0f 21 June 2012, Article 3 (51), state that *"'CO_2 capture' means the activity of capturing from gas streams carbon dioxide (CO_2), which would otherwise be emitted, for the purposes of transport and geological storage in a storage site permitted under Directive 2009/31/EC"*. This definition could be extended by the mention of CCU and the purpose of "permanent or temporary utilisation to reduce total GHG emissions across economic sectors or applications" and a clear definition of CCU should be added.

2. A fundamental requirement for all carbon sources used in powerfuels production should be that **their use shall not cause any significant additional net emissions in the system**, including through the capture process itself. This implies that **no new carbon streams** can be used and emission streams from existing industrial installations cannot be intensified. Therefore, only recycling of existing industrial emission streams as well as capture from biogenic sources and DAC are eligible. With regard to industrial sources, any regulatory changes and additions should ensure that all emissions are accounted for. For all sources, any emissions caused through the energy used during capture or transport must be considered in the GHG assessment methodology of powerfuels, which should be defined in the upcoming delegated act of Article 28 of the RED II.

3. Multiple fulfilment options should be allowed as such a pathway is cost-efficient and more robust against volatilities of parallel developments such as the ramp-up of related technologies. A narrow pre-selection of eligible carbon sources could thus inhibit the market ramp-up of powerfuels. For the market integration and cost-efficient deployment of CCU technologies, this should be translated into a technology-neutral approach towards available carbon sources, coupled with strict sustainability criteria.

4. Any provision to be put in place should avoid the double-counting of carbon emissions from industrial sources under the ETS. Whether emissions are counted at the industrial source/ the point of capture or at the usage stage remains to be determined.

5. In the **long-term, biogenic carbon sources and DAC should be favoured** over industrial point sources. In order to induce the necessary cost degression of DAC technologies, which is still in early commercial stages, a well-designed and effective policy support should be put in place.

    a) The **EU carbon price** is currently lower than the costs of capturing carbon, offering little market incentive. Therefore, a possible measure could be to raise the carbon price progressively. This will render DAC more competitive vis-à-vis currently cheaper capturing technologies from industrial sources, provided that these are not allocated free allowances.

    b) In terms of project financing, DAC projects should become a priority for the **EU Innovation Fund**, which already funds CCU technologies, the **Important Project of Common European Interest (IPCEI)** and the **InvestEU** mechanisms. This should serve to increase funding and leverage private investment into DAC demonstration projects.

    c) In order to reduce production costs, the electricity used for DAC, when originating from renewable energy sources, should be exempted from levies and taxes. This should especially be considered in the context of national regulatory frameworks of Member States.

    d) In addition, a financial support mechanism should be put in place, e. g. an innovation bonus for DAC technologies, that bridges the existing difference in costs.

    e) Support for Research & Development in DAC technologies could also help to bring down costs and develop the technology further. State finance complementing initial investment into this technology also plays a role. In particular, mechanisms like the **Clean Hydrogen Partnership** under Horizon Europe, as announced in the European Hydrogen Strategy in July 2020, should be used to promote the development of DAC technology.

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