Facilitating a sustainable future

CARBON SOURCES IN THE CONTEXT OF POWER-TO-X

- Scaling up the global capacity to source carbon is essential to satisfy growing demand for Power-to-X (PtX) products. However, lock-in effects leading to prolonged usage of technologies that should be phased out must be avoided
- To achieve the production of sustainable PtX products, it is imperative to establish a closed carbon cycle
- Carbon removal and capturing technologies are highly energy intensive processes and depend on additional renewable energy to be sustainable
- While carbon removal/capturing technologies are essential to reach net zero scenarios, reducing the overall CO_2 emissions remains more effective

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Developments and chances

Carbon, commonly in the form of carbon dioxide (CO_2), functions as a feedstock in certain PtX processes. The utilisation of CO_2 is required in a wide variety of use cases such as chemicals, polymers, pharmaceuticals and synthetic fuels. In the chemical sector and derived materials, projections indicate a substantial increase in carbon demand, expected to surpass a twofold rise by the year 2050. The total demand in these sectors is estimated at 1,000 Mt by 2050 (Kähler, 2021). Similarly, the growing demand for synthetic fuels in the transport sector is leading to an increasing carbon demand. The CO_2 demand varies in the literature, ranging from 0.7 to 3.1 t CO_2/t synthetic fuel (Koj et. al., 2019; Bazzanella & Ausfelder, 2017).

According to predictions of the International Renewable Energy Agency (IRENA), by 2050 electric vehicles will constitute over 80 % of all road transport activities. Meanwhile, the marine and aviation industry, while aiming to reach decarbonisation, still faces major challenges. Consequently, synthetic fuels are expected to be utilised in the transport sector and, thus, provide a missing link. Supporting policies and regulations bring forward the future growth of the PtX market and the related carbon demand. By 2050, the global CO_2 demand will reach an estimated of 6,076 Mt, with approximately 2,179 Mt allocated to produce synthetic fuel (Galimova et. al., 2022). Ammonia can be an alternative fuel in the shipping industry that does not require carbon. For synthetic hydrocarbons, the question arises as to which carbon sources can be used to meet the demand for a growing global PtX economy. This briefing paper examines Direct Air Capture (DAC), Carbon Capture and Utilisation (CCU), biogenic sources and their associated concerns and potentials to supply carbon for the PtX production.

Direct Air Capture

DAC is a technology that removes CO_2 from the ambient air based on chemical reactions. With 417 parts per million (0,04 %) the atmospheric concentration is 50 % higher compared to pre-industrial levels, which shows the importance of carbon removal measures (NOAA a, 2023). While various technical solutions for DAC exist, the globally most common method are solid DAC (S-DAC) and liquid DAC (L-DAC) (Saenz Cavazos et. al., 2023). In order to operate DAC plants, heat, electricity and water are needed. With a temperature demand of 80-120 °C S-DAC can be considered as a low temperature system (An et. al., 2023). In contrast, L-DAC as a high temperature system requires up to 900°C (IEA, 2022). While consequently L-DAC requires more energy for the CO_2 capturing process, both technologies remain highly energy intensive. On average they require an electrical energy equivalent between 1.4 and up to 2.8 MWh/t CO_2 (McQueen et. al., 2021; Geoengineering Monitor, 2021). The water consumption varies depending on the technology utilised. L-DAC requires 1-7 t H2O/t CO_2 while S-DAC requires 0.8-2 t H_2O/t CO_2 (Liebling et. al., 2022). Currently, 27 DAC plants are operating globally with a combined capacity of 10,000t CO_2 annually. Additionally, 130 further DAC facilities are in the planning or construction stage (IEA, 2023).

Carbon Capture and Utilisation

CCU refers to the process of capturing and reusing CO_2 to produce, for example, synthetic fuels. In contrast to DAC where the CO_2 is obtained from the ambient air, CCU requires CO_2 point sources, e.g., flue gases of industrial process (Zimmermann et. al., 2022). Table 1 shows possible CO_2 point sources and the CO_2 concentration of the emerging flue gas.

Table 1: CO_2 concentration of flue gas (Wang & Song, 2020)

Flue gas source	CO_2 concentration (%)
Gas turbine	3-4
Fired boiler of oil refinery and petrochemical plant	8
Natural gas fired boilers	7-10
Oil-fired boilers	11-13
Coal- fired boilers	12-14
Steel production (blast furnace)	20-27
Aluminium production	1-2
Cement process	14-33

The higher the concentration of CO_2 in the flue gas stream, the simpler and more cost-effective the capturing process becomes (Lübbers et. al., 2021). In particular, the unavoidable process related CO_2 emissions of the cement production offer a high potential for CCU. Several technological pathways such as carbon capture from post-combustion, pre-combustion and oxy-combustion, are pursued (Wang & Song, 2020). Though CCU requires less energy than DAC, it remains an energy-intensive process. Besides the technology used, the heat and electricity demand of CCU can vary depending on factors such as, the size and the efficiency of the technology and the purity and concentration of CO_2 in the flue gas. Table 2 shows the thermal and electricity demand of CCU of carbon point sources. Oxyfuel combustion does not require thermal energy, but only electrical energy for the separation of oxygen from the air as well as for ventilation and pumps (Lübbers et. al., 2021).

Table 2: Energy demand of CCU of carbon point sources (Lübbers et. al., 2021)

	Electrical energy requirement in kWh/t CO_2		Thermal energy requirement in kWh/t CO_2	
	Min	Max	Min	Max
Post-Combustion Capture	129	410	920	1415
Oxyfuel Combustion Capture	180	360	-	-
Pre-Combustion Capture	324		1038	

In 2022, the operational capacity of carbon capture reached 45.9 Mt CO_2/year. Based on currently announced project of 'IEA CCUS project database' the carbon capture capacity will reach approximately 320 Mt CO_2/year by 2030 (IEA B, 2023).

Biogenic Sources

CO_2 from biogenic sources is produced from the decomposition, digestion or combustion of biomass. It can be obtained by e.g., biogas plants, bioethanol production or biomass (heating) power plants. The predominant method of obtaining CO_2 from biogenic origins typically centres around biogas power plants. Firstly, energy plants or organic waste is anaerobically fermented leading to the production of crude biogas. Secondly, crude biogas can be converted into electricity, heat, or bio-methane which can be further processed and fed into the natural gas grid. During this conversion process, the CO_2 can also be separated. Table 3 shows treatment processes that are used in practice to capture the CO_2 and their respective energy demand. The selection of the specific treatment process depends on factors such as the size of the biogas plant, the required feed-in pressure of the gas network or availability of waste heat (Fröhlich et. al., 2019). The current global capacity of carbon capture from biogenic sources reaches approximately 2 Mt CO_2 per year (IEA C, 2023).

Table 3: Energy demand of biogas processing for CO_2 capturing (per standard cubic meter (SCM)) (Fröhlich et. al., 2019)

	Pressure Swing Adsorption	Pressurized water washing	Physical absorption with organic solvents	Chemical absorption processes	Membrane process
Electrical energy demand (kWh/SCM)	0.20-0.25	0.20-0.30	0.23-0.33	0.06-0.15	0.18-0.25
Thermal energy demand (kWh/SCM)	-	-	0.3	0.5-0.8	-

Realising opportunities

PtX has emerged as a transformative solution for the transport and storage of energy sources. Nevertheless, alongside its numerous advantages, there are concerns pertaining to the carbon sources process for the PtX production. This chapter addresses the concerns associated with carbon removal and capturing technologies and provides possible improvements or solutions.

One major concern regarding carbon sources for the PtX production is the high energy demand and the potential emerging CO_2 emissions during the carbon capturing process. If the carbon capturing process is powered by non-renewable energy sources the emissions emitted during the CO_2 capturing process could potentially exceed the emissions captured. While this is technically possible, the use of fossil power plants to capture CO_2 is counterproductive from a climate perspective. If more CO_2 is emitted than captured, the acceptance issue of that particular capturing process can arise. Therefore, the CO_2 emissions emitted during the CO_2 capturing process should never exceed the amount of CO_2 captured. In particular, the production of CO_2 from L-DAC relies due to its high energy demand on natural gas (Liebling et. al., 2022). Given that the energy mix in most countries still consists partly of fossil fuels, the aspect of additionality of renewable energy usage in producing carbon is essential. Simply shifting existing renewable energy would lead to a gap of renewable energy in other sectors. By satisfying the increasing energy demand of capturing CO_2 with additional renewable energy, the overall CO_2 emissions can be reduced. This leads to the conclusion that decision makers and planners should integrate renewable energy such as photovoltaic (PV) and/or wind in the planning phase of new carbon removal/capturing facilities.

Directly correlated with the high energy demand are the currently high cost for CO_2. With costs of US$250-$600/t CO_2, DAC is currently not economically competitive. Predictions which factor in the rate of development, supportive policies and market development estimate a price of US$150-$200/t CO_2 for the next 5-10 years and even predict a price of US$100/t CO_2 over the next decade if economies of scale can used by reaching a gigaton scale (Liebling et. al., 2022). Similar to DAC, the price of CCS varies. Prices range from US$27 up to US$161/t CO_2, while in the medium-term an average price of US$55/t CO_2 will likely be reached (Lübbers et. al., 2021). The separation of carbon from biogenic source in biogas power plants is compared to DAC and CCU with US$15-$25/t CO_2 more cost competitive (Baylin-Stern & Berghout (2021). Hence, an analysis focused solely on the cost per tonne of CO_2 may suggest the merit in pursuing the extraction of carbon from biogenic sources. Nevertheless, further factors have to be considered. The technology readiness level (TRL), in particular of DAC and CCU, has not reached full commercial deployment and further technological improvement could reduce the cost. Moreover, as discussed in the previous chapter the demand of carbon is increasing and all carbon sources are likely to be required to satisfy the increasing demand.

For PtX products to be sustainable a closed carbon cycle is necessary. According to NOAA b (2023), the carbon cycle 'describes the process in which carbon atoms continually travel from the atmosphere to the earth and then back into the atmosphere'. Within a closed carbon cycle, each carbon molecule emitted into the atmosphere undergoes sequestration or reabsorption back into the earth. Carbon sourced from DAC or biogenic sources can be integrated in a closed carbon cycle. However, this integration is not applicable to carbon obtained from CCU processes, due to its origin from fossil resources utilised in industrial processes. Furthermore, CCU poses the risk of look-in effects into technologies that ideally should be phased out. It could also generate price incentives that may favour fossil powered processes, potentially hindering the transition toward more sustainable alternatives (International PtX Hub, 2022). Hence, it is advisable to prioritise technologies that have the capability to establish a closed carbon cycle. CCU should primarily find application in industrial processes with unavoidable process-related carbon emissions, such as the cement industry. This approach ensures a strategic deployment of CCU where it can contribute most effectively to capture carbon in hard-to-decarbonise sectors.

In regions with abundant biomass resources, biomass plays a strategic role as a carbon source. To avoid acceptance issues, sustainability criteria such as the protection of the soil, water and air quality should be implemented. Additionally, the competition between the industrial use of biomass and food production should be resolved. However, the globally uneven distribution, the limited capacity of carbon from biogenic sources, and the high land use need to be addressed. A possible solution could be the integration of Agri-PV[1], which could increase the acceptance of CO_2 from biogenic sources by providing renewable energy and agricultural goods on the same area and therefore defusing land use conflicts.

An overarching concern inherent to the discussed carbon removal/capturing technologies is the currently missing or underdeveloped infrastructure in contrast to the predicted future demand of CO_2 for PtX production. The relevant infrastructure includes the treatment, transport, storage capacity and in some cases compressor booster stations. The combined cost related to the transport and storage of CO_2 are frequently estimated at US$10/t CO_2. The cost my vary due to regional specific factors. Smith and colleagues have determined the transport and storge cost of CO_2 in on-shore pipelines at US$4-45/t CO_2. While the transport for small scales can be realised by tanks and trucks, the large-scale transport relies on pipelines and ships. Investments in the transport and storage infrastructure are essential to address this issue.

[1] Agricultural Photovoltaics (Agri-PV) combines agricultural activities with solar energy production on the same area.

Ways forward

While carbon removal technologies are still under development, many institutions such as the Intergovernmental Panel on Climate Change (IPCC) consider carbon removals as one essential technology to reach carbon neutrality. As discussed in the previous chapter, the integration of additional renewable energies is essential. Decision makers, project managers and planners should integrate renewable energy such as PV and/or wind in the planning phase of new DAC/CCU plants. Existing facilities can be complemented by the installation of PV-systems or wind turbines. If safety or regulatory constraints do not impede the installation of rooftop PV systems, these available surfaces can be effectively utilised. Many roof areas have unused surfaces to add PV-panels and with the high energy demand of the DAC/CCU facilities the payback period of these investments is short and will generate future savings over the utilisation period.

While the transport of carbon has a high TRL, the transport is associated with further costs, energy demand or additional CO_2 emissions. Locally sourced carbon can pose an alternative (Dziejarski et. al., 2023). The determination of the most advantageous carbon capturing/removal technology (DAC, CCU, or biogenic sources) within a specific use case involves multifaceted considerations. Local contextual factors should invariably be taken into account to make informed decisions in each instance. An example of how local factors can be utilised is the bush biomass case in Namibia (International PtX Hub, 2023). If biogenic sources are not available and extensive land use is an issue, DAC can pose an option. Due to the high energy demand of DAC, the required renewable energy infrastructure leads to high land use. However, in comparison to biogenic sources, DAC facilities have comparatively little special requirements[2]. As DAC does not depend on carbon point sources, is offers greater flexibility in terms of siting (Liebling et. Al, 2022). If carbon point sources are locally available, CCU can pose an option. Considering that 27 % (9.15 Gt CO_2) of the global annual CO_2 emissions are emitted in the industry sector, this sector offers high potential for CCU (IEA D, 2023). However, lock-in effects need to be avoided, therefore investments in CCU technology, for example in the petrochemical or steel industry, should be avoided. In the steel industry, investments in green hydrogen and direct reduced iron (DRI) offer greater environmental and socio-economic benefits. Investments in CCU technology should ideally be limited to industry process with unavoidable process related carbon emissions.

Given that carbon removal/capturing technologies necessitate heat, planners, investors and project managers are advised to assess the accessibility and availability of geothermal resources and waste heat for optimal deployment and operational efficiency. Further considering that carbon capture and removal technologies have yet to attain technological maturity despite their recognition as essential components for achieving carbon neutrality, there is a critical need for policy makers to implement supportive policies for funding, research, and development initiatives in these domains. Under any circumstance, the continued expansion of renewable energy sources is imperative to meet the escalating energy requirements associated with carbon removal and capturing technologies. Lastly, only carbon from DAC or biogenic sources can be utilised to convert a linear process to close the carbon cycle (Zimmermann et. al., 2022).

[2] Approximately 862 km^2/million t CO_2 are required for Biogenic sources (forest) (Cook-Patton et. al., 2020)

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→ Briefing #1: Carbon Sources

→ Briefing #4: Benefits for local communities

→ Briefing #2: Desalination

→ Briefing #5: Skills & Jobs

→ Briefing #3: Land use

→ Briefing #6: Stakeholder participation

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