LIFE CYCLE ASSESSMENT

DIRECT AIR CAPTURE

PHLAIR™

As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology are published for maximum transparency.

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Terminology, units and abbreviations

CCS	Carbon capture and Storage
CDR	Carbon Direct Removal
CO_2	Carbon dioxide
CO_2-EOR	Carbon dioxide enhanced oil recovery
DAC	Direct air capture
EF	Emission factor
EHLC	Electrochemical hydrogen looping cell
EOR	Enhanced Oil Recovery
g	Gram
t/year	Tonne per year
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kg CO_2-eq.	Kilogram carbon dioxide equivalent
LCA	Life Cycle Assessment
Mt/year	Million tonne per year
PEM	Proton exchange membrane
WMO	World Meteorological Organization

About Phlair

Phlair offers modular Direct Air Capture (DAC) technology to remove unavoidable CO_2 emissions. The captured CO_2 can be used as feedstocks in e-fuels like methanol, methane and sustainable aviation fuels to replace fossil-based CO_2. Their system promises one of the lowest energy consumption per ton of CO_2 currently removed and offers flexibility in managing energy usage to align with renewable energy generation.

Version 1.0 - September 12, 2024

Summary

The 2023 AR6 Synthesis report by the Intergovernmental Panel on Climate Change (IPCC), which synthesised nearly a decade of research findings, notes that Carbon Dioxide (CO_2) removal will be needed to counterbalance "hard-to-abate residual greenhouse gas emissions" to reach net-zero CO_2 emissions.

Carbon dioxide removal (CDR) – also referred to as "negative emissions" – defines a range of methods by which humans can either directly remove CO_2 from the atmosphere using technology or influence its removal via natural systems like forests. One technological option for removing CO_2 from the atmosphere is Direct Air Capture (DAC).

Phlair develops modular, flexible, and energy-efficient DAC systems to sequester CO_2 from the air and achieve rapid decarbonisation.

Direct Air Capture technologies extract CO_2 directly from the atmosphere, unlike carbon capture which is generally carried out at the point of emissions, such as a steel plant. The CO_2 can be permanently stored in deep geological formations or used for a variety of applications.

In this study, we assessed the environmental impact of Phlair's DAC systems. We calculate the reduction in net CO_2 emissions, evaluate its sensitivity to the electricity mix and compare the performance compared to other technologies.

The results in brief are:

- Phlair's 260t/year pilot plant leads to a net reduction of 679 kg CO_2 per ton of CO_2 sequestered from the air and the 1Mt/year scaled-modular plant will have a net reduction of 934 kg CO_2 per ton of CO_2 sequestered from the air.
- Embodied emissions of the electricity used to operate the plant and recycling precious metals like titanium and platinum used in the electrolyser and copper in the cables are the biggest levers in maintaining the high carbon removal efficiency of Phlair's DAC plants.
- Phlair's 260t/year pilot system performs better than the average technology currently available in terms of energy efficiency and the 1Mt/year scaled-modular system is at par with the best available technologies with a significant potential for further development and second-order impact creation by reducing renewable energy curtailment.

This demonstrates that Phlair`s DAC technology has the potential to be one of the key technological solutions to mitigate climate change.

The study concludes by providing downstream options for captured CO_2 including permanent storage and use in different fuels and chemicals.

About this study

This study first provides insights into the necessity of reducing the carbon concentration in our atmosphere (currently at 422ppm) and different types of direct air capture (DAC) technologies. Later, it provides insights into Phlair's modular DAC system and its advantages. Finally, a consequential life cycle analysis (LCA) study shows the energy consumption of Phlair's technology compared to other DAC technologies and Phlair's potential for a net reduction in CO_2.

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1. Global warming, environmental crisis and the need for CO_2 capture

1.1. Global warming and carbon removal

Human-induced climate change has accelerated at an alarming rate, with the past decade witnessing an unprecedented increase in global temperatures (IPCC 2023). June 2023 -June 2024 was the hottest year on record, with global temperatures 1.64°C above the 1850-1900 pre-industrial average (WMO 2024).

Global warming is primarily attributed to persistent high levels of greenhouse gas emissions, which have averaged 53±5.4 Gt CO_2-eq. per year over the last decade (Forster et al. 2024). The emissions have risen consistently since the industrial era, with a rapid increase in CO_2 emissions in recent decades (see Figure 2).

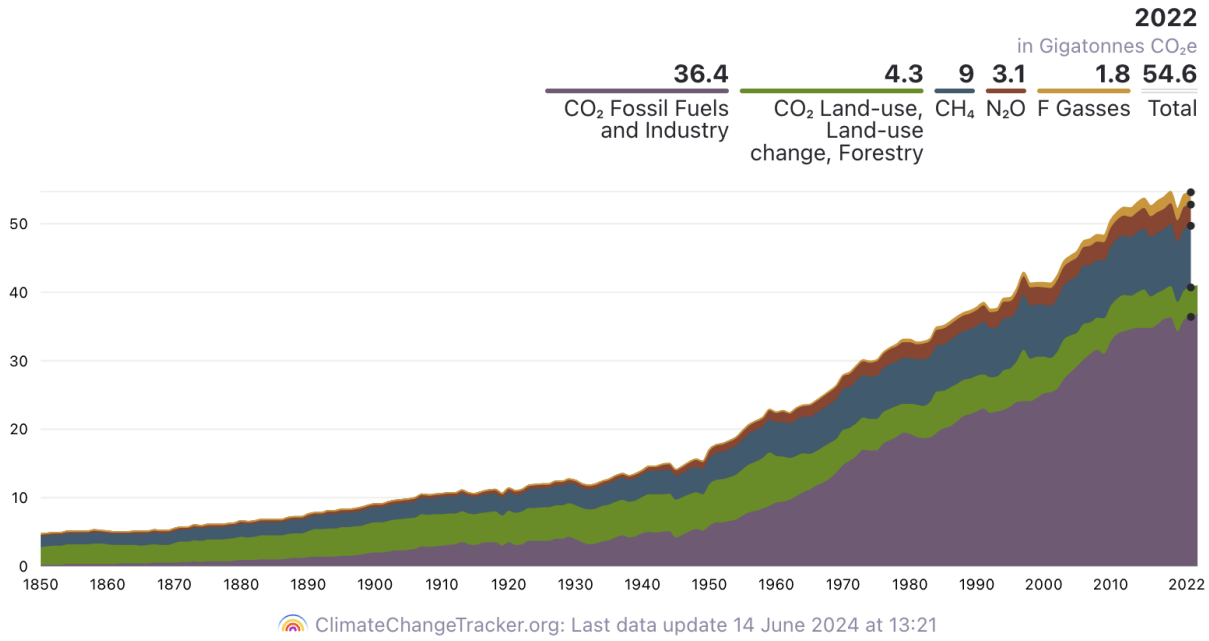

***Figure 2**: Yearly Human-Induced Greenhouse Gas Emissions. (Source: ClimateChangeTracker.org, 14th June 2024)*

As of July 2024, the remaining carbon budget for a 50% chance to limit global warming to 1.5°C has been reduced to 200 billion tonnes of CO_2 and at the 2023 emission levels, this budget will be used up in **five years** (ClimateCarbonTracker 2024; Friedlingstein et al. 2023). It is the first time that scientists have also factored in "carbon removal" in the carbon budget calculation. To reach the net-zero emissions targets massive efforts to reduce emissions are essential. To offset emissions that are hard to avoid, a strong expansion of carbon removal technologies will further be necessary (Global Carbon Budget report 2023).

The latest IPCC report underscores the critical role of carbon capture and storage (CCS) technologies. It highlights that CCS is central to most mitigation pathways that aim to keep global warming below 1.5ºC with limited overshoot, emphasising the necessity of capturing and storing a median average of 665 gigatonnes of CO_2 cumulatively by 2100 (IPCC 2022). Reaching net zero by 2050 would require around 6 gigatonnes per annum of CO_2 to be captured and stored by 2040 and over 8 Gt per annum by 2050, from a current rate of 0.04 Gt/ annum (IRENA 2024). Carbon Dioxide Removal (CDR) is essential to limit warming to 1.5°C or below 2°C by 2100, regardless of whether global emissions reach near zero, net zero or net negative levels (IPCC 2022) (see Figure 3).

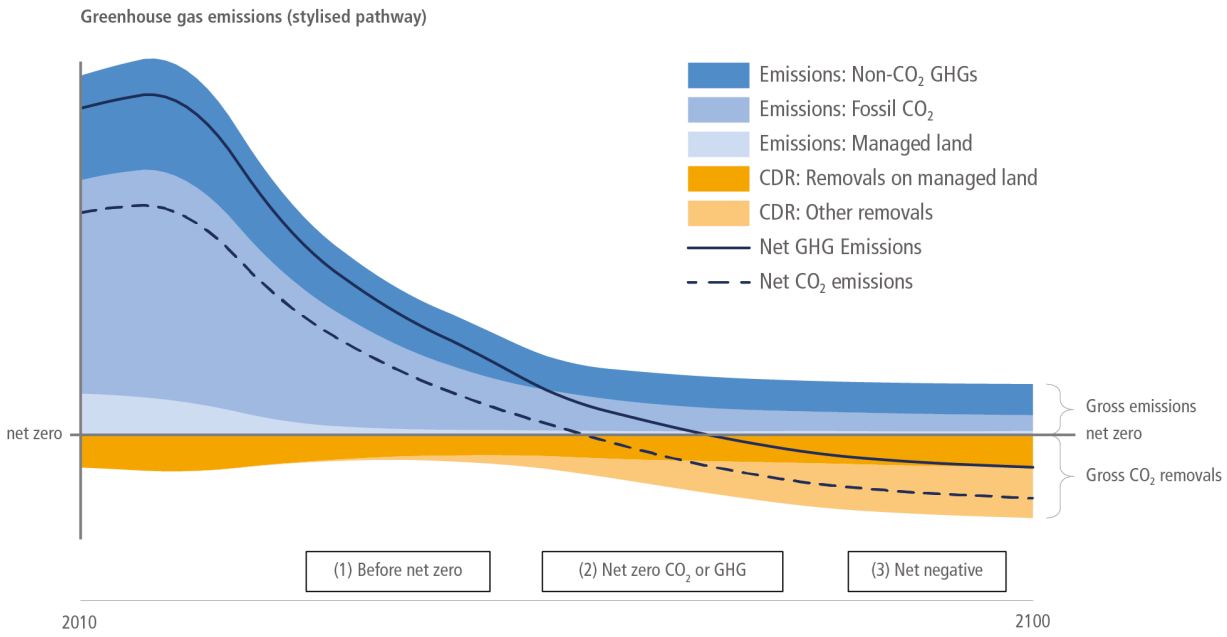

***Figure 3**: Stylised pathway representing the scaling of CDR even post-net zero to keep global warming below 1.5°C and limit the potential overshoot. (Source: IPCC AR6 WGIII report - Chapter 12)*

1.2. Direct air carbon capture

The latest IPCC report (table TS.7) sees massive potential for Direct Air Carbon Capture and Storage (DACCS) of 5–40 Gt CO_2/yr. Direct Air Capture (DAC) technologies extract CO_2 directly from the ambient air using chemical or physical processes. The captured CO_2 can then be sequestered underground or utilised in various industrial applications. DAC offers the advantage of being location-independent, meaning it can be deployed anywhere, and it can address dispersed and non-stationary sources of emissions. It is limited mainly by two factors: the requirement for low-carbon energy and cost (primarily related to energy and material consumption) (IPCC 2022).

Here is an overview of the different Direct Air capture technologies:

- **Solid DAC Technologies:** Use solid sorbents to capture CO_2 from the air. The sorbents typically consist of materials that chemically bind with CO_2. The captured CO_2 is then released through heating or applying a vacuum, allowing the sorbent to be reused. These systems can be modular (thus scalable), offer location flexibility and lower land use. However, their major drawbacks are the energy-intensive process of regenerating the sorbent and the high cost of CO_2 sequestration (Ozkan et al. 2022).
- **Liquid DAC Technologies:** Involves passing air through a liquid solution that absorbs CO_2. The CO_2 is then separated from the solution through a series of chemical reactions, typically involving high temperatures. These systems offer higher efficiency as compared to solid DAC but still have high energy demand and cost associated with CO_2 sequestration (Ozkan et al. 2022).

There are also a few **emerging DAC technologies** like :

- Electro Swing Adsorption (ESA): Uses an electrochemical cell where a solid electrode adsorbs CO_2 when negatively charged and releases it when a positive charge is applied. ESA-DAC aims to reduce energy consumption and improve efficiency (IEA 2024).
- Zeolite-Based DAC: Zeolites, with their porous structure, are being explored for their potential to adsorb CO_2 effectively. This technology is in the early stages but shows promise for scaling up (IEA 2024).

- Passive DAC: This approach accelerates the natural process of converting calcium hydroxide and atmospheric CO_2 into limestone, offering a potentially low-energy solution for carbon capture (IEA 2024).

2. Phlair's DAC technology and its advantages

Phlair is developing a modular and energy-efficient electrochemical DAC system with the potential to achieve a levelised cost of capture below \$100/t CO_2. Their systems have many advantages over a standard electrochemical DAC:

- *Electrochemical hydrogen looping cell (EHLC):* This is the novel element in Phlair's DAC system. The EHLC is a proton exchange membrane (PEM) electrolysis cell utilising the principle of pH swing, within which an electric current is used to split an electrolyte solution into acid and base solvents via a PEM. The design of the EHLC optimises the electrolysis process by looping hydrogen from the cathode to the anode. This lowers the energy requirement for sorbent regeneration by 33% and avoids the need for scarce catalysts such as Iridium.

- *Low liquid flow rate absorber packing:* This element has been developed in an exclusive partnership with a specialist company. It allows the design of the packing to be optimised for liquid-to-gas ratios, where conventional capture modules would normally fail i.e. low liquid flow rates and simultaneously high gas flow rates. This is an ideal specification for an efficient DAC absorption system, where high residence times, packing density and air volume flow rates are desired with minimal pressure drop.

- *Slurry system for extracting solid bicarbonates:* Stoichiometrically, releasing a CO_2 molecule from a bicarbonate ion requires an electron/CO_2 ratio of 1:1 instead of 2:1 from a carbonate solution. Thus, the application of this system provides a significant potential for energy saving in the CO_2 desorption process, further improving the energy efficiency of the DAC system.

- *Flexible chemical energy storage:* The acid/base configuration of the electrochemical system results in inherent chemical energy storage. In periods of renewable energy oversupply, the electrochemical cells can be operated at high current densities to over-produce acid/base solvents which can be stored for use in periods of under-supply. This enables potential secondary applications as a curtailment avoidance tool for renewables. It creates a second-order positive impact that is not being considered in this study.

- *Scalability:* Phlair's DAC systems are modular to facilitate easy scaling and capacity ramp-up and repowering. Furthermore, the modular systems use a mix of proven off-the-shelf components and proprietary elements facilitating easy scalability with minimum supply chain challenges.

3. Life Cycle Analysis

This subsection describes the LCA model, results (including sensitivity analysis) and limitations and uncertainties of the study.

3.1. System description

This LCA study aims to assess the efficiency of carbon capture using Phlair's DAC systems. A consequential LCA approach was applied to assess the impact on the environment.

Two different types of systems from Phlair were evaluated:

1. 260t/year (pilot): The plant is assumed to operate for 4 years at a 65% capacity factor.
2. 1Mt/year (scaled-modular): The plant is assumed to have a lifetime of 20 years with a 90% capacity factor.

Functional unit and indicators

The functional unit is **1 ton CO_2 sequestered using Phlair's DAC system**. Phlair's DAC systems are not in operation yet. The assessment considers a potential future system as it is planned at present. The system comprises (Figure 1):

- Electricity: grid mix in 260t/year (pilot) & renewable energy in 1Mt/year (scaled-modular) plant;
- Carbonation system (including vane-axial fans, absorber packaging, motors, pumps etc.);
- Electrolysis system (including electrodes, catalyst, electrolyte etc.);
- Degasification system (including motors and pumps etc.).

The system is assessed using the indicators **climate change** (Intergovernmental Panel on Climate Change (IPCC) 2014) and several indicators related to resource use, i.e. **abiotic resource depletion** (CML - Department of Industrial Ecology 2016), **cumulative fossil energy demand** - CED_f (Verein Deutscher Ingenieure (VDI) (ed.) 2012) and **water demand** - WSI (Pfister, Koehler, and Hellweg 2009), to calculate the net change in environmental impact.

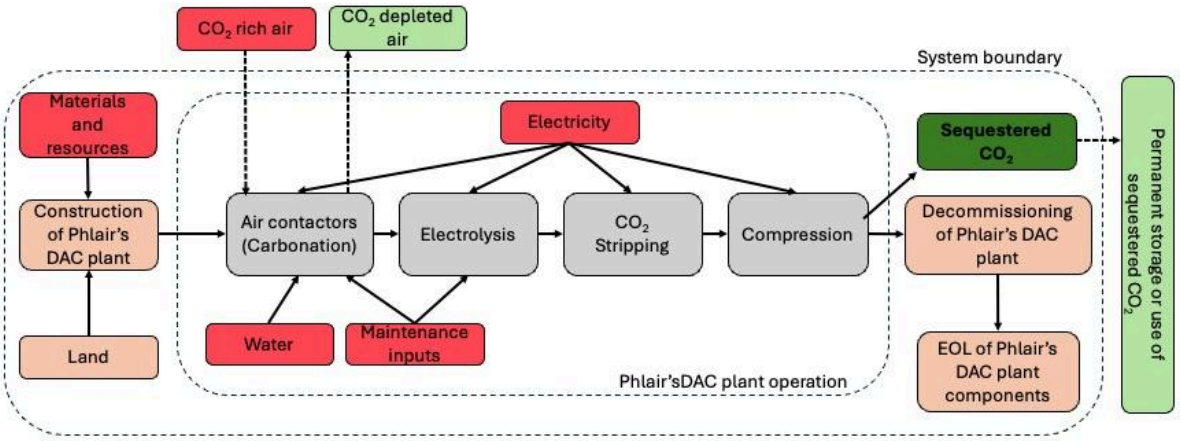

Figure 4 *Depiction of system boundaries. The grey processes represent the operational stages of the plant, whose output remains constant throughout the plant operation. The green processes will increase their output, while red processes are the inputs/ consumables. Additionally, the orange processes are necessary to realise the DAC systems and their outputs are changed only at the beginning or end of the plant's life cycle.*

Data Quality

The study is based on primary (prospective) data provided by Phlair, background data from consequential ecoinvent 3.10 (Moreno Ruiz et al 2024), and scientific literature.

3.2. Environmental impact of Phlair's plants

3.2.1 GHG emissions

The environmental impact of Phlair's two prospective DAC plants (see Figure 5) are:

1. **260t/year (pilot):** The CO_2 emissions of the plant components (including maintenance end-of-life of the components) and the electricity used (assuming Netherlands' electricity grid mix as Phlair is planning to set up their first plant in the Netherlands) levelised to the carbon captured over the plant's operating lifetime are 97 kg CO_2-eq./tonne carbon captured and 223 kg CO_2-eq./tonne carbon captured respectively. Thus, there is a net reduction of 679 kg CO_2 per tonne of CO_2 sequestered from the air. If the plant components are not recycled, the net reduction is reduced 635 kg CO_2 per tonne of CO_2 sequestered from the air.
2. **1Mt/year (scaled-modular):** The CO_2 emissions of the plant components (including maintenance end-of-life of the components) and the electricity used (assuming renewable electricity) levelised to the carbon captured over the plant's operating lifetime are 9.8 kg CO_2-eq. tonne carbon captured and 56 kg CO_2-eq./tonne carbon captured respectively. Thus, there is a net reduction of 934 kg CO_2 per tonne of CO_2 sequestered from the air. If the plant components are not recycled, the net reduction is slightly reduced to 933 kg CO_2 per tonne of CO_2 sequestered from the air.

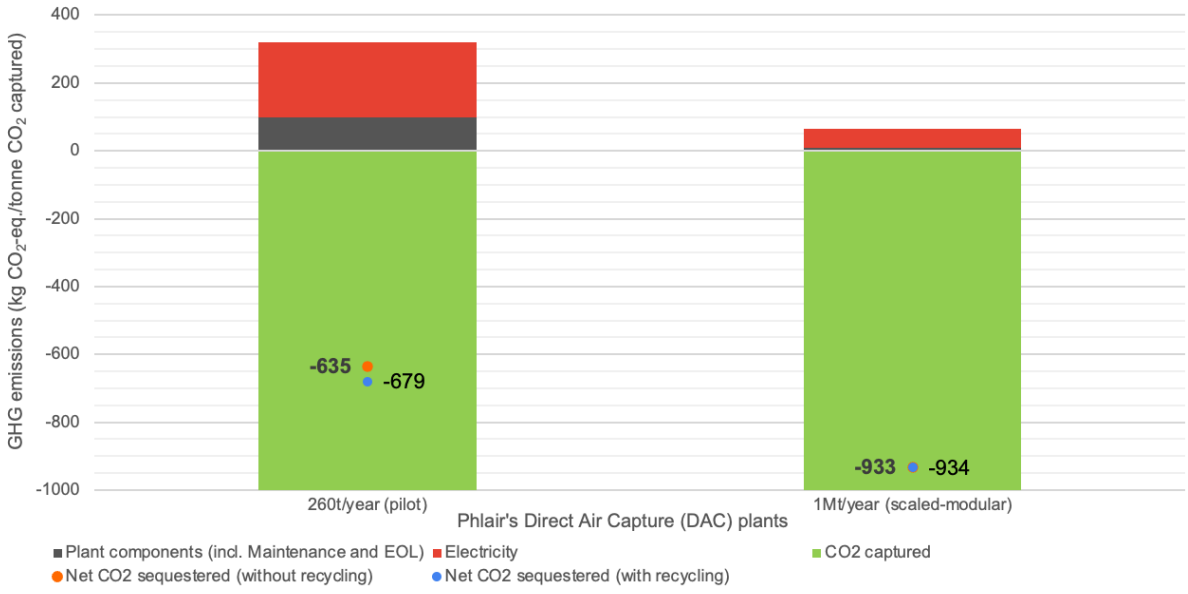

Figure 5: *GHG emissions from Phlair's plants in kg CO_2-eq./ tonne CO_2 captured.*

Please note the following three points that have a significant impact on results:

1. Electricity consumption (and its associated production emissions) have the largest impact on determining the DAC system's net CO_2 sequestration potential, i.e. its carbon removal efficiency.

2. The recycling of plant components, especially the titanium and platinum used in the electrolyser system, the copper in cables and plastic in pipes, tanks and absorber modules is essential to maintaining high carbon removal efficiency. Not recycling the plant components can increase the levelised CO_2 emissions per ton of CO_2 sequestered from the air and reduce the net impact by 3.5 percentage points for the 260t/year (pilot) plant and 1 percentage point for the 1Mt/year (scaled-modular) plant, thus reducing the carbon removal efficiency to 63.5% for the 260t/year (pilot) plant and 93.3% for the 1Mt/year (scaled-modular) plant.

3. This study has not considered the effect of bicarbonate removal using slurry and the second-order impact of avoiding renewable energy curtailment due to the lack of primary data. When these parameters are factored in (at a later stage in technological development), the overall positive impact of Phlair's DAC systems is bound to increase in terms of net CO_2 sequestration, resource demand and overall energy consumption.

3.2.2 Resource demand

i) Abiotic resource depletion

The capturing of CO_2 using Phlair's DAC plants (including end-of-life of plant components) results in an abiotic resource demand of 6.1 kg Sb-eq./ tonne CO_2 captured in 260t/year pilot plant and 3.5 kg Sb-eq. kg Sb-eq./ tonne CO_2 captured in 1Mt/year scaled-modular plant. If the end-of-life of plant components is excluded, the abiotic resource demand increases to 57.6 kg Sb-eq./ tonne CO_2 captured in 260t/year pilot plant and 4.4 kg Sb-eq. kg Sb-eq./ tonne CO_2 captured in 1Mt/year scaled-modular plant (Figure 6). The resource demand is dominated by materials used in the DAC facilities. The key contribution to abiotic resource demand is copper used in Phlair's DAC plants along with precious metals like platinum and titanium. Copper has one of the highest characterisation factors along with precious metals like platinum and titanium (signifying the high importance regarding abiotic resource use[1]). The negative values originate mainly from the recycling (end-of-life) of copper, platinum and titanium which reduces the need for primary metals production. Further, the use of certain metals in the supply chain of materials also has a minor contribution to the negative values (Wernet et al. 2016; Althaus et al. 2007). Metal mining and subsequent processing often produce a number of (companion) metals. If certain companion metals are co-mined or produced, this potentially results in a decreased abiotic resource depletion potential.

[1] Characterization factors are used in LCA to derive a single unit to compare impacts. The characterization factors express the contribution of a resource use or emission to a specific mechanism, e.g. climate change or abiotic resource demand. The total quantity of a resource use or an emission, e.g. copper or a GHG that is emitted, is multiplied by a characterization factor that expresses this contribution in relation to a reference substance, e.g. CO_2 in case of the global warming potential (climate change) and antimon in case of the CML abiotic depletion method. For instance, the characterization factor of methane expresses how much solar radiation methane absorbs over a specific period of time (e.g. 100 years) in relation to CO_2. Analogously, the resource demand in the CML abiotic depletion method expresses the resource use in relation to antimon (Sb). In the CML method, abiotic depletion potential of all resources (e.g. copper and the reference substance antimon) is calculated using the actual resource extraction rate of each divided by the ultimate reserve of each resource squared. The result of copper is then divided by the result of antimon, resulting in the desired unit kg Sb-eq. The abiotic resource depletion is therefore an expression of how much of the remaining reserve is annually extracted. More information and explanations on the global warming potential and the abiotic depletion can be found here, here and here.

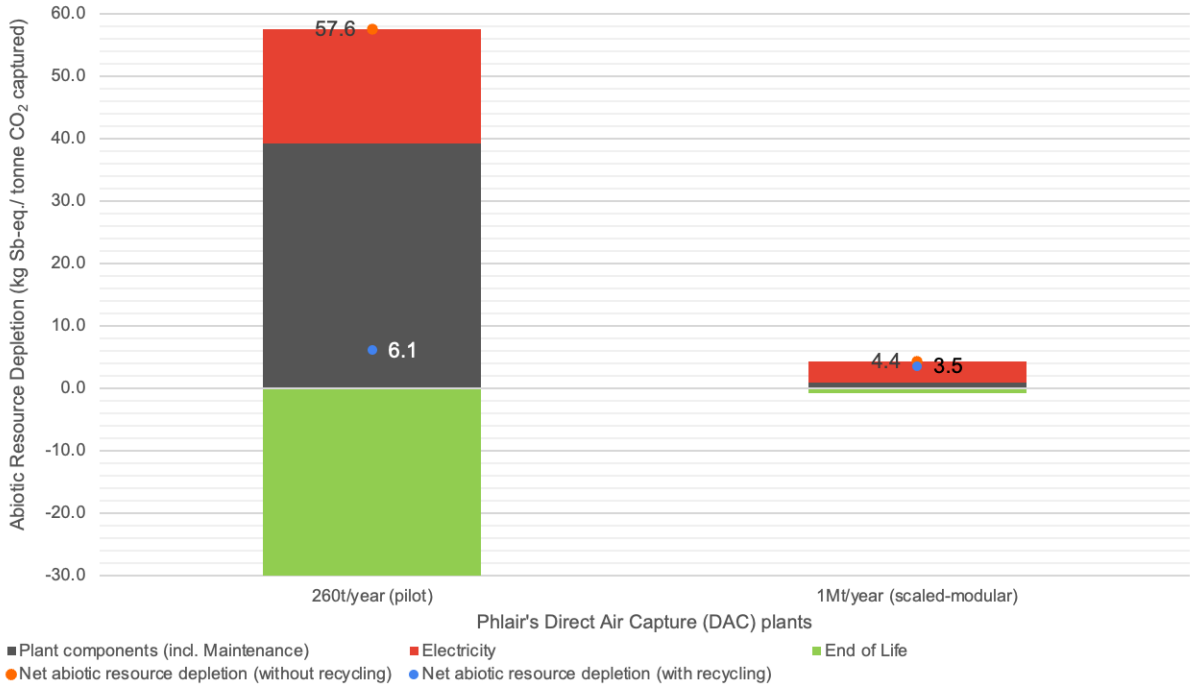

Figure 6: *Abiotic resource demand (abiotic resource depletion) of Phlair's plants in kg Sb-eq. per tonne CO_2 captured.*

ii) Cumulative fossil energy demand

The capturing of CO_2 using Phlair's DAC plants (including end-of-life of plant components) results in an overall demand for fossil energy resources of 4437 MJ/ tonne CO_2 captured in 260t/year pilot plant and 835 MJ/ tonne CO_2 captured in 1Mt/year scaled-modular plant. If the end-of-life of plant components is excluded, the overall demand for fossil energy resources increases to 4949 MJ/ tonne CO_2 captured in 260t/year pilot plant and 843 MJ/ tonne CO_2 captured in 1Mt/year scaled-modular plant (Figure 7). The major contributors to fossil energy demand are the electricity consumption in both DAC facilities followed by plant setup. The negative values are due to the recycling (end-of-life) of precious metals like platinum and titanium used in electrolyser modules along with copper from cables which reduces the need for primary metals production.

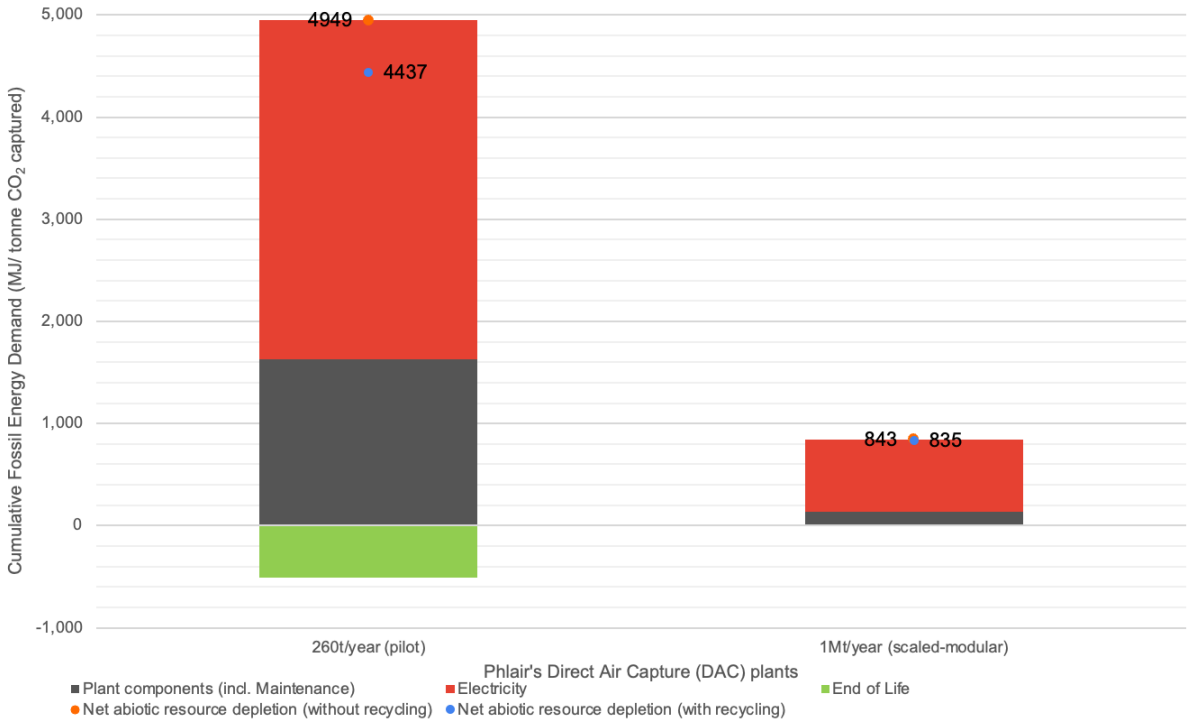

Figure 7: *Fossil energy demand of Phlair's plants in MJ per tonne CO_2 captured.*

iii) Water demand

The capturing of CO_2 using Phlair's DAC plants (including end-of-life of plant components) results in a water demand of 8.2 m^3/ tonne CO_2 captured in 260t/year pilot plant and 7.7 m^3/ tonne CO_2 captured in 1Mt/year scaled-modular plant. If the end-of-life of plant components is excluded, the water demand slightly increases to 8.4 m^3/ tonne CO_2 captured in 260t/year pilot plant but remains almost unchanged 1Mt/year scaled-modular plant (Figure 8). The water demand primarily arises from the water used as a maintenance input in the operational phase of the DAC facilities, with a small contribution from electricity consumption (i.e. the embodied water demand of production and transmission of the electricity) and the plants` components (i.e. the embodied water demand from production of the components). The negative values are due to the recycling (end-of-life) of precious metals like platinum and titanium used in electrolyser modules along with copper from cables which reduces the need for primary metals production.

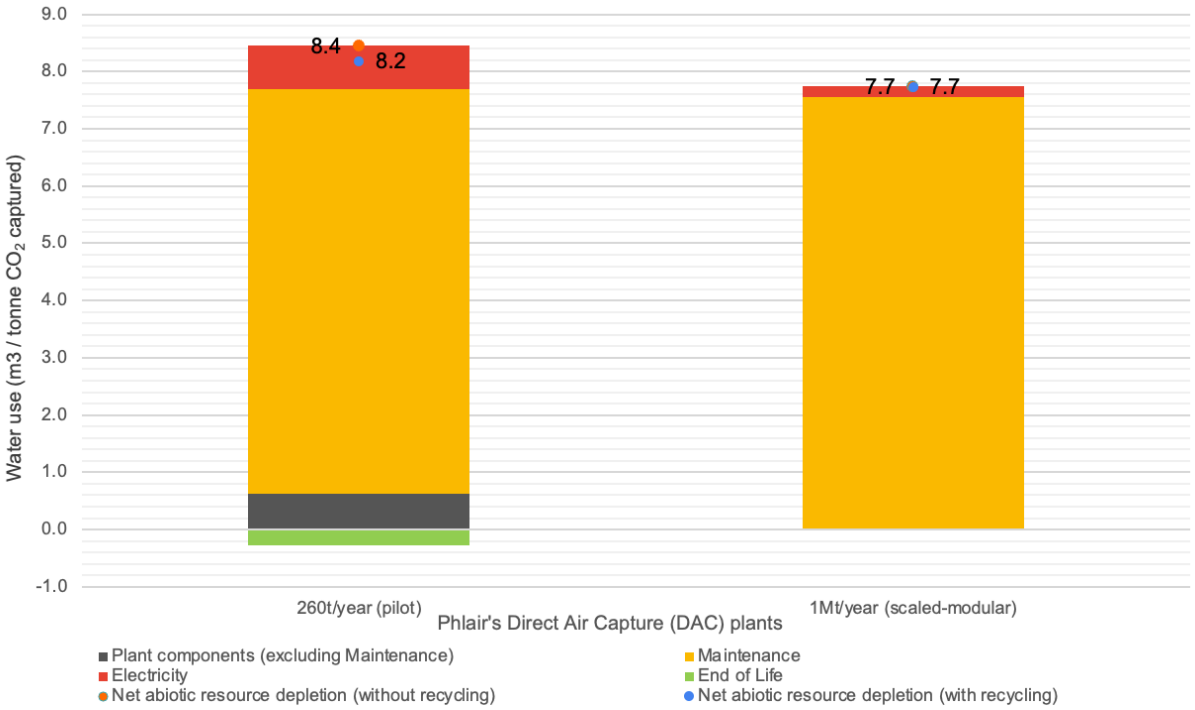

Figure 8: *Water use of Phlair's plants in m^3 per tonne CO_2 captured.*

3.3. Comparing Phlair's energy requirement to other technologies

The energy consumption of Phlair's 260t/year pilot plant is around 1400 kWh/ton CO_2 captured (i.e. 5 GJ/ton CO_2 captured) which is better than the average technology deployed today as per our findings based on primary data, research papers and various reports including but not limited to Lebling et al. 2022; Zeeshan et al. 2023; Heß et. al 2020 etc.

Whereas, the energy consumption of Phlair's 1Mt/year (scaled-modular) plant is around 1127 kWh/ton CO_2 captured (i.e. 4GJ/ton CO_2 captured) which is at par with the best available technology as per our findings. Figure 9 shows Phlair's energy requirement compared to other DAC technologies.

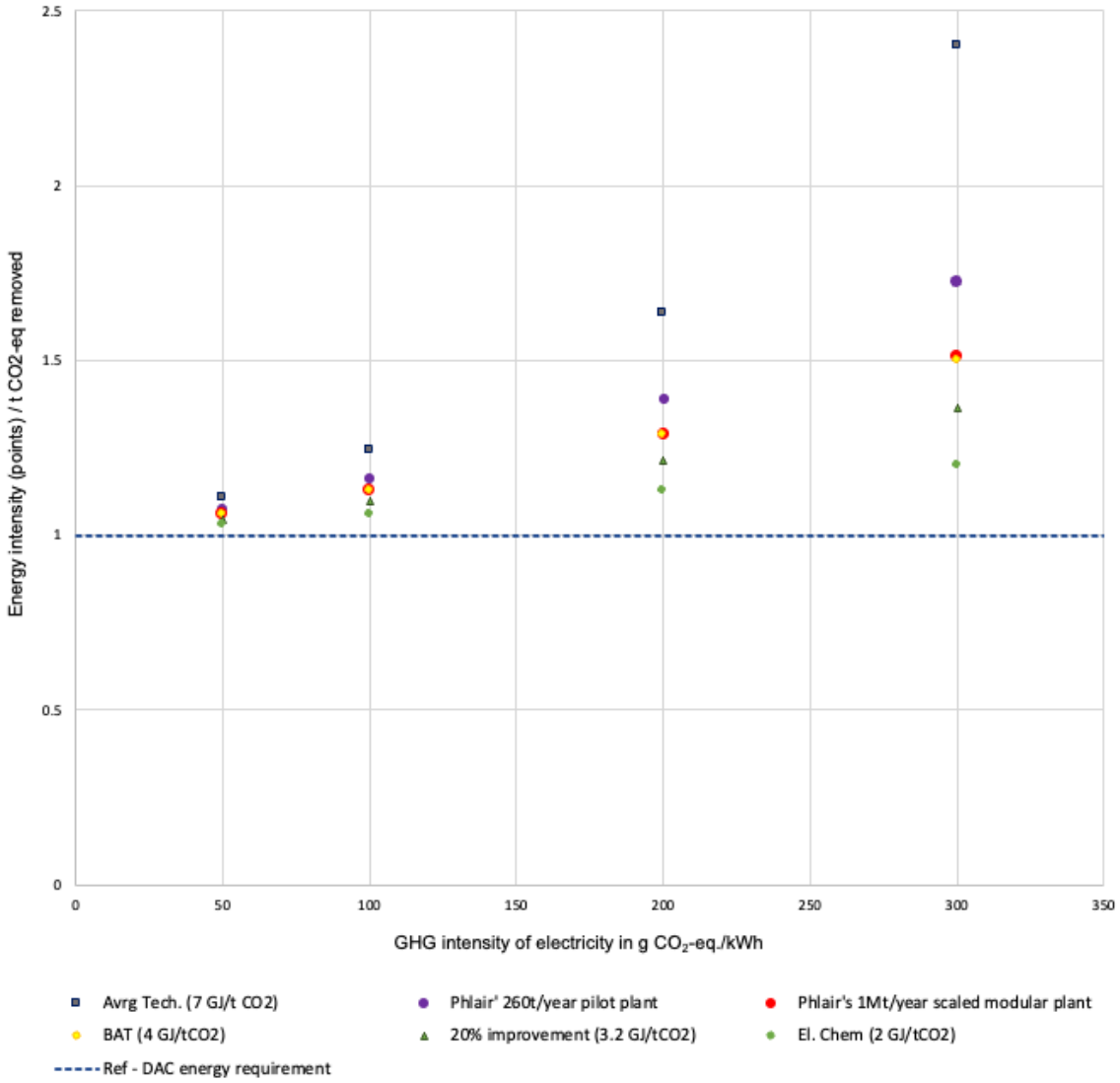

Figure 9: *Energy requirements of Phlair's systems vs other DAC systems. (Source: Own calculations based on primary data, scientific literature and confidential information)*

It is important to note that scientific literature (Seo et al. 2023; Achrai 2024; Jin et al. 2024) suggests that electrochemical DAC technology can achieve an energy efficiency of around 2GJ/tCO_2 (marked with yellow dots in Figure 9). This signifies Phlair's future development potential to reduce energy consumption to almost half of their planned 1Mt/year (scaled-modular) plant.

3.4. Sensitivity analysis: Using different energy sources for DAC system operation

As observed from the results presented in section 3.2. of this report, electricity consumption (and its associated production emissions) is the most important factor in determining the overall carbon removal efficiency of the DAC plant. A sensitivity analysis compares the carbon removal efficiency of Phlair's DAC system with different energy sources and electricity grid mixes (European countries' grid mix in 2022, EU mix average 2022 and projected EU mixes in 2030) (Figure 10).

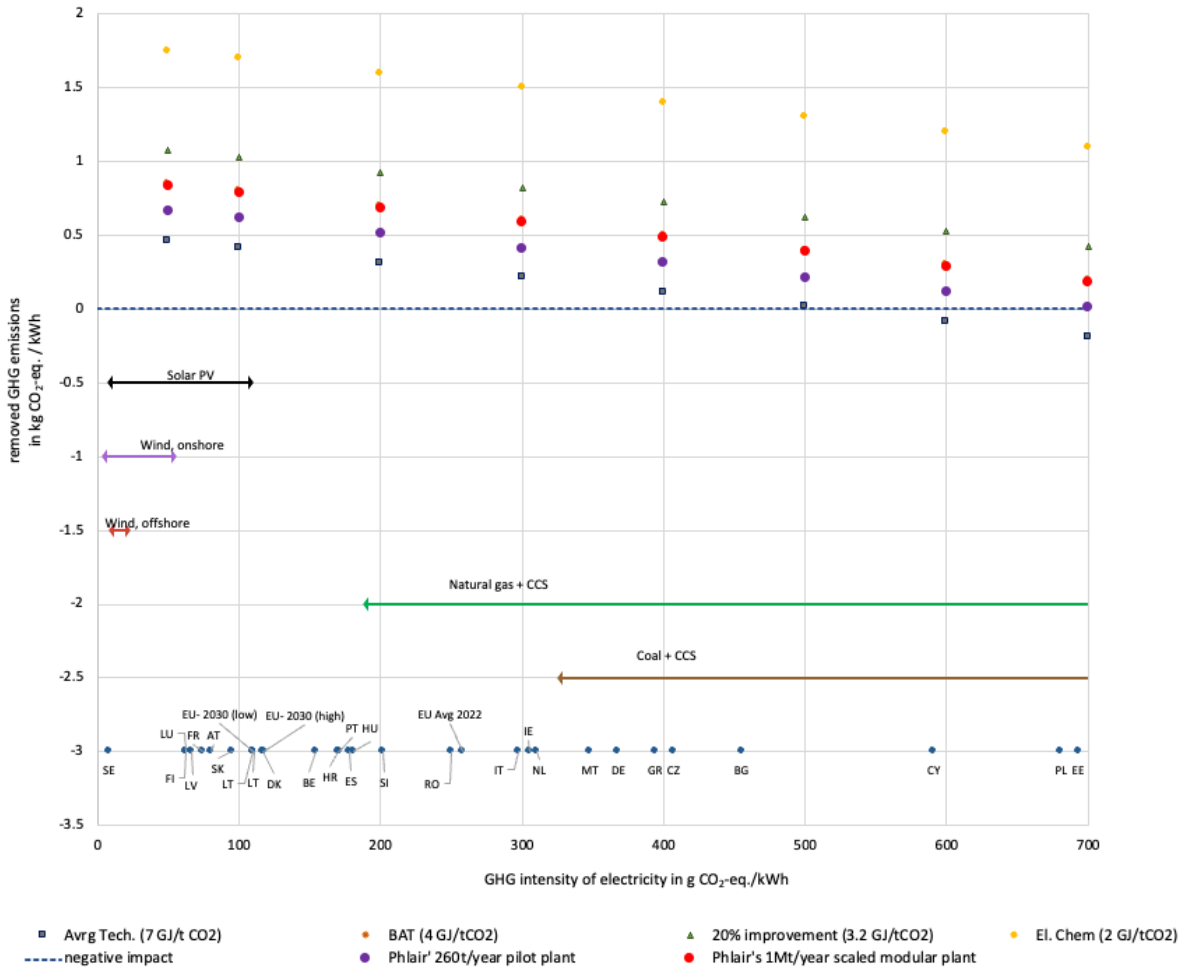

Figure 10: *Carbon footprint of electricity and carbon reduction potential of Phlair's 1Mt/year scaled-modular DAC system.*

3.5. Limitations and uncertainties

The assessment is subject to certain limitations:

- Phlair's DAC technology is still under development and the plants will be set up in the future. To account for uncertainties related to this ex-ante assessment of CO_2 sequestration using Phlair's DAC system, the energy requirements were compared to market averages, scientific literature and values from other published reports. Moreover, we conducted a sensitivity analysis comparing different electricity sources and grid mixes.

- Due to the similarity of the life cycle inventory of the absorber module with a compact passenger vehicle, we modelled it using the relevant passenger car, petrol/ natural gas dataset from ecoinvent 3.10 database - in line with other literature sources (van der Giesen et al. 2017; Terlouw et al. 2021; Casaban et al. 2023).

- While we usually use datasets from ecoinvent's consequential database, we took emission factors (EFs) across all evaluated categories for primary platinum from Buchspies et al. 2017 and secondary platinum from the 2022 report of the International Platinum Group Metals Association e.V. (IPA 2022). This was done to maintain comparability of our results with other scientific literature and industry reports as the EF for Plantinum considered in Ecoinvent 3.10 consequential DB is well above the values published elsewhere.

- The actual quantities of materials used to build the plant are best estimates from the Phlair team. It is highly probable that the actual quantities of materials used in plant construction will differ from the quantities considered in this study.

4. Potential use cases for CO_2 captured with Phlair's systems

The use cases of sequestered CO_2 can be divided into two categories: long-term storage (in rock formations, underground wells etc.) and as a precursor for chemicals (e-fuels, sustainable aviation fuel, green ammonia etc.). In the following section, we provide an overview of possible use cases using Life Cycle Assessments of Planet A's portfolio companies:

4.1. Permanent CO_2 storage - 44.01

44.01 offers permanent removal of captured CO_2 from point sources and direct air capture via mineralization. The company sequesters the CO_2 in peridotite formations.

To permanently store CO_2 captured from Phlair's DAC plants, a few additional steps would need to be taken:

- Transport of CO_2 from the DAC site to the storage location (if the DAC plant is not colocated);
- Well construction, maintenance and closing;
- Carbon dioxide sequestration (injection);
- Energy supply for sequestration site and process.

44.01`s operations result in GHG emissions of 150 kg CO_2-eq. per ton CO_2 permanently mineralized, corresponding to a carbon sequestration efficiency of 85% (only 44.01 operations on-site, including well infrastructure as well as the solar PV and battery system). By far the largest contributor to GHG emissions is water supply, accounting for 91.5% of GHG emissions associated with 44.01's operations (Figure 11). Well infrastructure accounts for 5.5% of GHG emissions. Electricity supply and the battery each account for 1.5% of the GHG emissions emitted by processes operated by 44.01.

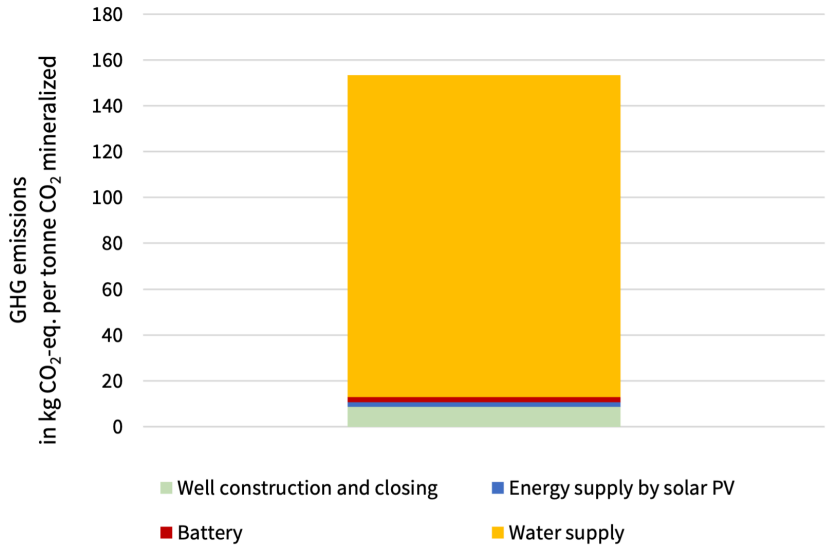

Figure 11: *Breakdown of GHG emissions of carbon mineralization in kg CO_2-eq. per kg CO_2 permanently sequestered in Peridotite formations. CO_2 supply excluded.*

We calculated the net environmental impact of capturing the CO_2 with Phlair's plants and then mineralising CO_2 using 44.01`s technology with the following assumptions:

- Both DAC plants, the 260t/year as well as the 1Mt/year, run on renewable energy;
- The DAC plants are colocated with the storage operations, thus zero CO_2 transport emissions. (Extra transport emissions might be added once the actual location will be known in the future).
- All other parameters are considered as described in our LCA report for 44.01.

The results of the analysis show that the capturing and the sequestration of CO_2 results in a net change in GHG emissions, of -526 per tonne mineralised in the case of CO_2 supply from the 260t/year pilot and -782 kg CO_2-eq. per tonne mineralized in case of CO_2 supply from the 1Mt/year scaled-modular plant (Figure 12). This corresponds to an overall carbon sequestration efficiency of 53% and 78% respectively. In line with our LCA report for 44.01, the breakdown of emissions reveals that capturing CO_2 is the main driver of total GHG emissions.

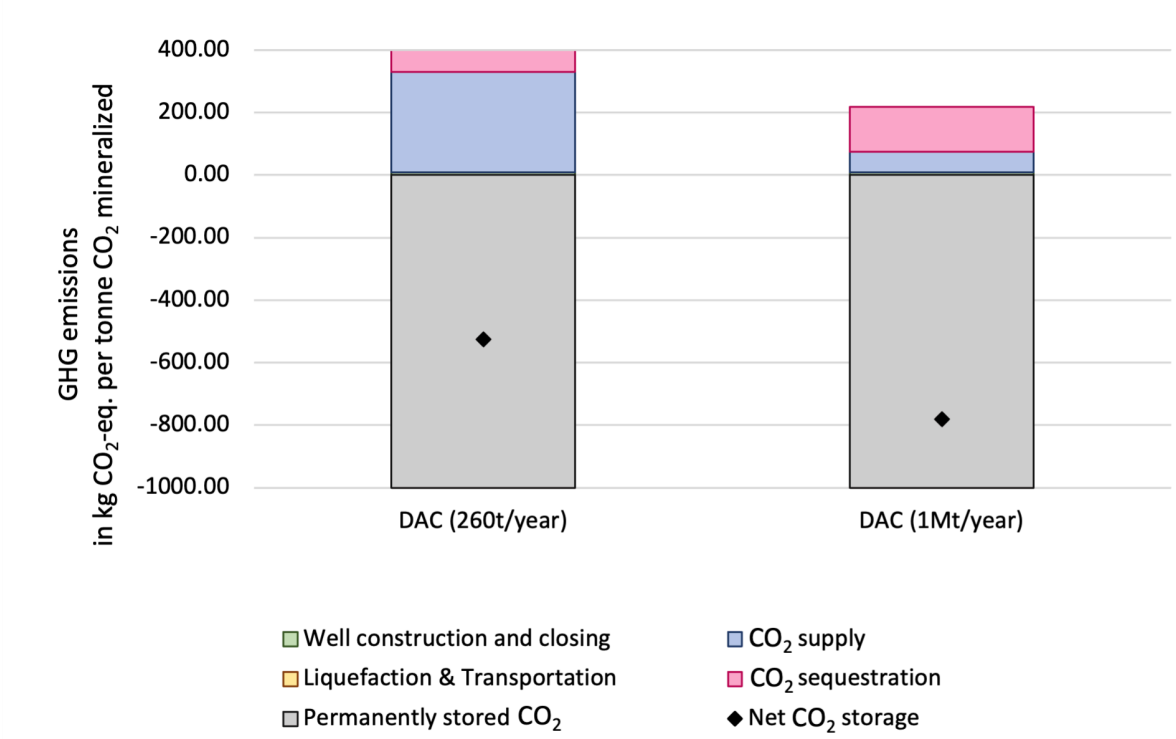

Figure 12 *GHG emissions of carbon capture and mineralization in kg CO_2-eq. per tonne CO_2 permanently sequestered in Peridotite formations (with consideration of the CO_2 mineralization, i.e. -1000 kg CO_2 per tonne CO_2 sequestered).*

For detailed results on various resource demand parameters, please refer to our LCA report for 44.01.

Comparison with other CDR technologies

A recent scientific paper compared the efficiency of different CDR technologies, their permanence and how timely CO_2 removal takes place (Chiquier et al. 2022). The comparison shows that DAC combined with carbon storage operated with low-emission energy is the most efficient CDR technology (Table 1). In addition, permanence and an immediate storage of CO_2 are achieved.

Table 1 *Comparison of different CDR technologies (Chiquier et al. 2022). The content is provided by Chiquier et al. (2022) under a CC BY 3.0 licence. The formatting was changed and the results from the present assessment were added. No additional changes were made. Abbr. CCS - Carbon capture and storage, CDR - CO_2 removal, CS - Carbon storage, DAC - Direct air capture, yr - years.*

CDR Technology	**CDR efficiency**		**Effectiveness**	**Timing**	**Permanence**
	100 yrs	1000 yrs	Is CDR effective? Why?	Is CDR immediate? Why?	Is CDR permanent? If not, why?
Afforestation/ Reforestation	63 - 99%	31 - 95%	Very high, Forest establishment & management has a negligible impact on CDR efficiency	Decades, Forest growth takes time	Very low, Owing to the risk of natural disturbances, such as wildfires or weather events
Bioenergy and CCS	52 - 87%	78 - 87%	Moderate to high, Biomass supply chain emissions	Immediate to decades, (i) LUC change effects	High/very high, Permanent CO_2 storage in geological reservoirs
Biochar	20 - 39%	-3 - 5%	Low, Pyrolysis (conditions with low biochar yield), biomass supply chain emissions	Immediate, the carbon of biochar is relatively stable and sequestered in soil	Low/very low, Decay rate of biochar reduces stored carbon over time
DAC + CS current energy system	-5 - 90%	-5 - 90%	Moderate to high, CO_2 intensity of the energy consumed	Immediate, CO_2 capture from the air/ocean	Very high, Permanent CO_2 storage in geological reservoirs
DAC + CS low emission energy	92 - 100%[a]	92 - 100%[a]	High	Immediate, CO_2 capture from the air/ocean	Very high, Permanent CO_2 storage in geological reservoirs
Enhanced weathering	17 - 92%	51 - 92%	Moderate to high, Rock supply chain emissions	Immediate to decades, Carbonation rate (residence time)	High/very high, Chemical reactions permanently store carbon in rock minerals
This study (Capture + permanent CS)	*53-79%[a]*	*53-79%[a]*	*High*	*Immediate, CO_2 capture from the air/point source*	*Very high, Permanent CO_2 mineralisation[b]*
Our LCA for 44.01 (permanent CS only)	*85%*	*85%*	*High*	*Immediate, without CO_2 capture*	*Very high, Permanent CO_2 mineralisation[b]*

[a] *Chiquier et al. assume a GHG intensity of 0 g CO_2-eq. of electricity from renewable sources. In the present study an emission factor of 50 g CO_2-eq. per kWh is used for renewable energy. Using this emission factor, CO_2 supply by DAC emits 81-258 g CO_2-eq. per kg CO_2 captured (see Figure 8). Adding these emissions to values provided by Chiquier et al. reduces the stated efficiencies. Likewise, DAC requires massive infrastructure deployments resulting in GHG emissions.*

[b] *The CO_2 is removed permanently by mineralization (i.e. millions of years).*

Note 1: Chiquier et al. provide carbon removal efficiencies over a 100 year and a 1000 year period. Removing CO_2 from the atmosphere for a certain period of time shifts the negative consequences to the future without eliminating the negative consequences of today's actions. Additionally, Chiquier et al. do not specify what type of carbon storage is used in the CCS and CS cases (bioenergy + CCS and DAC + CS). Storage could imply the injection of CO_2 in depleted oil and gas reservoirs where CO_2 is supposed to be locked up for a certain period of time. Still, CO_2 remains in the form of CO_2 and could potentially be released in future. Thus, storing CO_2 in the form of CO_2 is likely an *impermanent storage* for a (long) period of time. In contrast, the mineralization of CO_2 in rock formations is a *permanent elimination* of the CO_2 molecule preventing a future release *permanently*.

Note 2: The authors report very high savings (up to 100%). Such high values are very unlikely considering the massive infrastructure deployment needed for some of the listed solutions, e.g. deployment of energy supply from renewable sources and carbon capture infrastructure. Adding the GHG intensity of renewable electricity used in this study to the values of Chiquier et al., the CDR efficiency is reduced by 8%-pt.

4.2. Captured CO_2 as a precursor for chemicals

CO_2 from DAC can be used to manufacture different chemicals. Below we present two examples:

i) Power to X- INERATEC

INERATEC offers modular synthesis units that allow the production of hydrocarbons that can directly replace conventional fossil-based, gaseous or liquid fuels, chemicals or waxes. The synthesis units **convert CO_2** (**from various sources, including DAC e.g. CO_2 from Phlair's DAC plants**) and hydrogen to synthetic natural gas (SNG), liquid fuels (naphtha, diesel, gasoline and kerosene), methanol and waxes. These products can readily replace fossil-derived fuels and chemicals using today's infrastructure. In the future, these synthesis units will likely use hydrogen produced by electrolysis. Therefore, these processes are often labelled power-to-X (PtX) processes.

Here are the results for GHG emissions by producing e-fuels using captured CO_2 (see our LCA report on INERATEC):

Almost all PtX supply chains result in a net decrease in GHG emissions if fossil counterparts are displaced (Table 2, Figure 13). The average net reduction in GHG emissions in 2030 is -57 g CO_2-eq per MJ PtL fuel (gasoline, diesel and kerosene), -66 g CO_2-eq. for methanol and -40 g CO_2-eq. for synthetic natural gas. In all synthesis pathways electricity production plays the most important role in terms of GHG emissions, except for the synthesis pathway using oxy-fuel. Only in those scenarios in which grid electricity is used in 2030 (still comprising a certain share of non-renewable electricity), no net decrease in GHG emissions is achieved. The results also show that the availability of renewable energy plays an important role: PtX production in locations with high annual full load hours results in much lower GHG emissions than those at locations with a lower amount of full load hours. For instance, PtX production using offshore wind power in Germany or solar power in the MENA region exhibits significantly lower emissions than the use of solar PV in Germany. The comparison of the two operating modes (maximising full load hours of the synthesis unit or operation of the synthesis-only unit when renewable electricity is available) shows that the former operating mode results in lower GHG emissions. On average (among all synthesis pathways), an operation that maximises the full load hours of the synthesis unit results in 17% less GHG emissions. Such an operation mode increases the need for renewable electricity. It also increases the product quantity produced (and hence the displacement of fossil fuels).

The results show that the synthesis units only have a minor influence on overall results. Due to the high importance of electricity production, minor differences between the modelling data and real-world data of renewable electricity production will result in much higher deviations of modelling results from real-world emissions and impacts.

Table 2 *GHG emissions of PtX provision. Upper part: only PtX supply chain. Lower part: Net change in GHG emissions if fossil counterparts are displaced. All values in g CO_2-eq. per MJ.*

		PtL			MeOH			PtG		
		2015	2030	2050	2015	2030	2050	2015	2030	2050
Only PtX	Average	57.32	33.45	18.93	64.38	28.59	21.74	43.52	22.99	11.12
	Median	25.65	21.53	13.13	35.63	20.06	17.37	21.43	14.98	10.73
	Minimum	14.69	12.91	8.29	17.90	9.90	8.66	6.87	6.59	4.42
	Maximum	374.35	132.85	85.02	346.43	124.38	124.37	301.97	106.34	32.27
	5% Percentile	15.48	13.14	8.51	18.48	9.98	8.80	7.11	6.68	4.50
	95% Percentile	374.35	132.84	84.44	346.42	105.94	77.90	301.97	106.34	25.19

		PtL			MeOH			PtG	
	2015	2030	2050	2015	2030	2050	2015	2030	2050
Delta	Average	-32.68	-56.55	-71.07	-30.62	-66.41	-73.26	-19.48	-40.01	-51.88
	Median	-64.35	-68.47	-76.87	-59.37	-74.94	-77.63	-41.57	-48.02	-52.27
	Minimum	-75.31	-77.09	-81.71	-77.10	-85.10	-86.34	-56.13	-56.41	-58.58
	Maximum	284.35	42.85	-4.98	251.43	29.38	29.37	238.97	43.34	-30.73
	5% Percentile	-74.52	-76.86	-81.49	-76.52	-85.02	-86.20	-55.89	-56.32	-58.50
	95% Percentile	284.35	42.84	-5.56	251.42	10.94	-17.10	238.97	43.34	-37.81

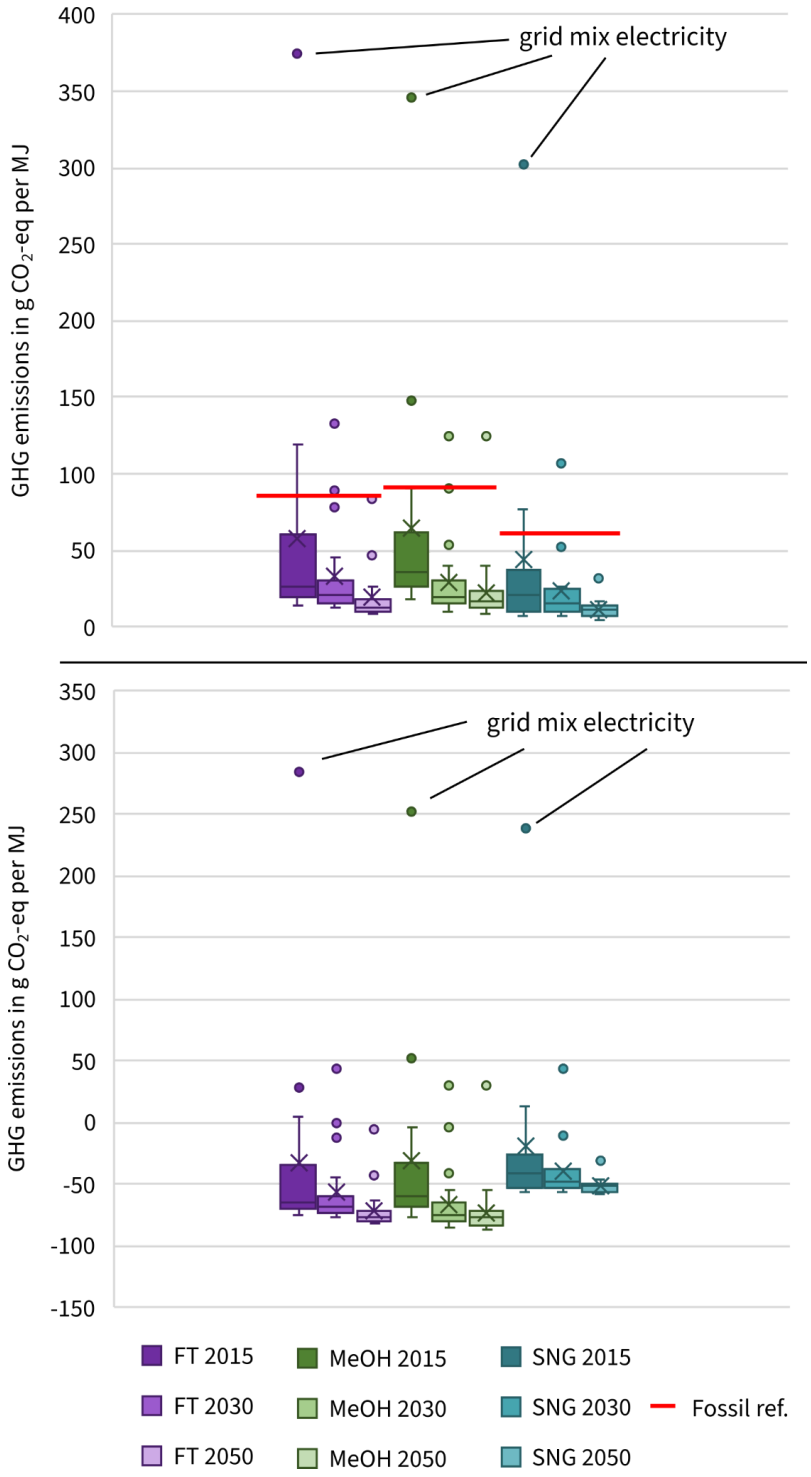

Figure 13: *Top: net change in GHG emissions due to the production and use of PtX products substituting fossil reference products (data obtained from {Liebich 2020 #1496}). PtL comprises liquid fuels commonly used in the transportation sector (gasoline, diesel and kerosene). Bottom: GHG emissions of PtX production and its fossil counterparts (Fossil. ref.). Please note: CO_2 emitted by the use of these products is not included in the graph. Please see text for further information on the attribution of CO_2 emissions of PtX product use. Abbr.: FT - Fischer-Tropsch (gasoline, diesel & kerosene), GHG - greenhouse gas, MeOH - methanol, SNG - synthetic natural gas.*

For detailed results on various resource demand parameters and a discussion of other alternatives to fossil fuels, please refer to our LCA report on INERATEC.

ii) Green Methanol - C1

Methanol is a widely discussed alternative to conventional fuels. For instance, shipping companies currently setup methanol strategies to ramp up the use of sustainably produced methanol. Aside from the shipping industries, methanol or fuels produced from it can be used as additives in liquid fuels in the road transportation sector. Aside from its use in the transportation sector, methanol is an important bulk chemical used to synthesise a wide range of products from plastics to solvents. At present, almost all methanol is produced from fossil resources, such as natural gas and coal, accounting for 65 and 35% of the methanol production, respectively. Due to its suitability to be used in the maritime sector and other transportation sectors, as well as due to its importance in the chemical industry, sustainable means of producing methanol will play a key role in the decarbonization of the economy. C1 developed a homogeneous catalyst that allows a highly efficient synthesis of methanol. Combined with a renewable energy supply and a carbon source, such as biomass or **captured CO_2 (e.g. CO_2 from Phlair's DAC plants)**, methanol can be produced without using fossil energy resources.

Here we present the results for GHG emissions from our LCA report on C1:

The supply of green methanol using captured CO_2 results in GHG emissions ranging from 0.12 to 1.18 kg CO_2-eq. kg methanol (see Figure 14). The range is caused by the GHG intensity of different energy supply variants: energy supply is by far the most important contributor to GHG emissions accounting for more than 74% of the GHG emissions in all assessed variants of the variants using electrolysis (water electrolysis and co-electrolysis). Using natural gas for heat supply more than doubles the GHG emissions in most cases: all variants in which heat is supplied by using waste heat or biomass emit less than 0.5 kg CO_2 per kg methanol, whereas those variants in which heat is supplied using natural gas result in GHG emissions above 0.59 kg CO_2-eq. The setup using biomass gasification emits considerably lower GHG emissions (0.1 kg CO_2-eq per kg methanol). Biomass supply accounts for 35% of these emissions. The remainder comes from consumables used in the gasification step. The catalyst used by C1 and the infrastructure only has a minor influence on results.

These results show that the most determining factor of C1 production will be energy supply if a setup is chosen that relies on captured CO_2 and (co-)electrolysis. Therefore, these types of technical setups should rely on energy supply with low associated GHG emissions. In contrast, biomass gasification results in much lower GHG emissions and is clearly the most favourable variant in terms of GHG emissions.

For detailed results on various resource demand parameters and discussion on other alternatives to fossil heavy fuel oils, please refer to our LCA report on C1.

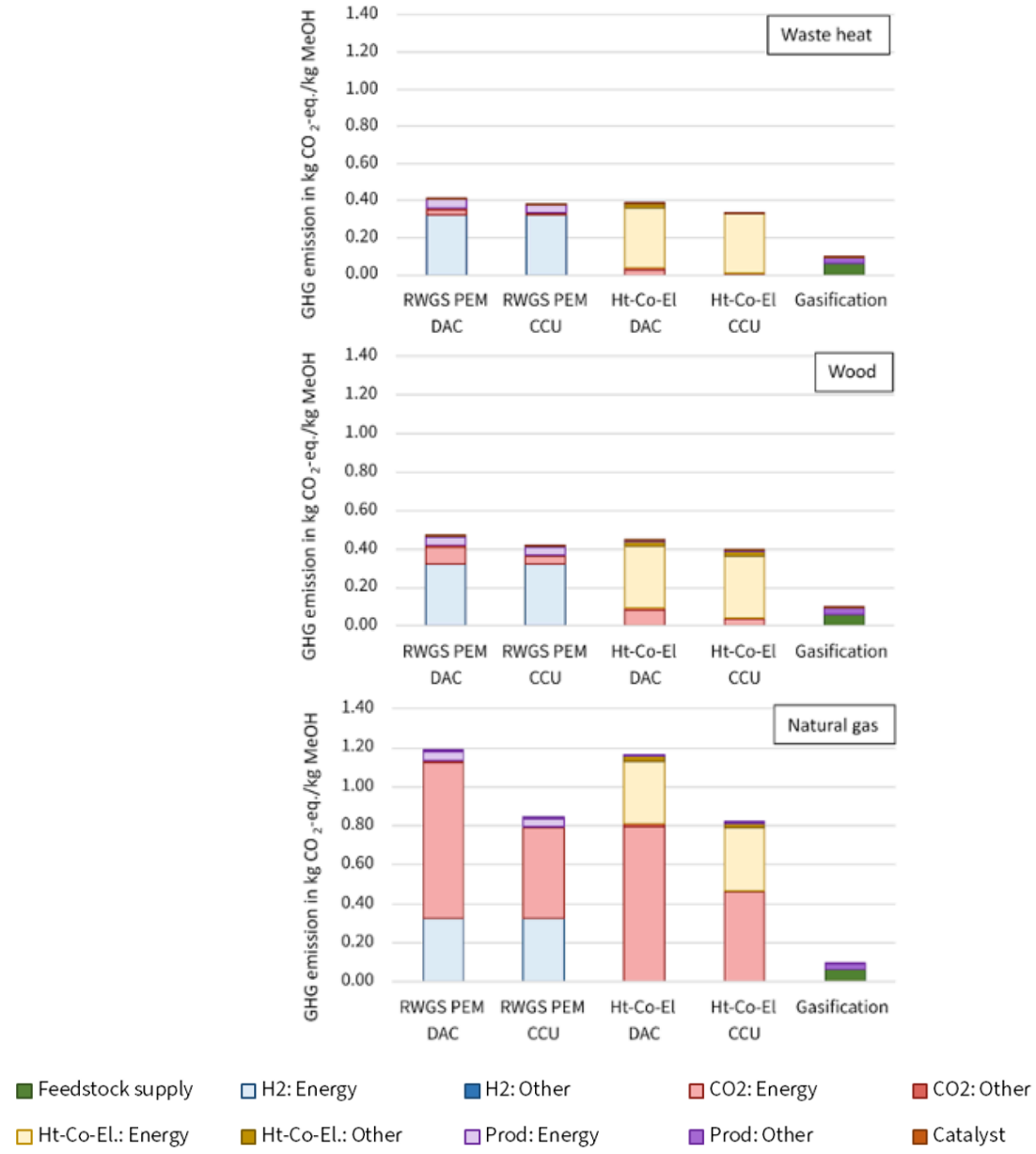

Figure 14: *CHC emissions of green methanol production. The diagrams show 5 different technical setups (rWCS with hydrogen from PEM electrolysis combined with CO_2 supply from DAC or flue gas stripping, high-temperature co-electrolysis with CO_2 supply from DAC or flue gas stripping and biomass gasification) with three heat supply variants (excess waste heat (top), wood chips (middle) and natural gas (bottom)). In all cases, electricity is supplied by a supply mix compatible with a 95% CHC emissions reduction in the energy sector. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, NC - Natural gas, PEM - Proton exchange membrane.*

4.3. Enhanced oil recovery

CCS combined with enhanced oil recovery (EOR) has gained attention as a method to both mitigate climate change and increase oil production. This technique has been commercially used to extract extra oil from mature fields while storing significant amounts of CO_2 in geological formations (Al-Shargabi et al. 2022). The process involves capturing CO_2 from industrial sources or air and injecting it into oil reservoirs to improve oil recovery by up to 20% (Yasemi et al. 2023). This can potentially reduce greenhouse gas emissions from oil by up to 33% (Farajzadeh et al. 2020).

However, CO_2-EOR carries environmental risks, including the potential for CO_2 leakage from storage sites, which could undermine its environmental benefits. The long-term stability of CO_2 storage and the impact of EOR on soil, water, and air quality remain concerns. A significant downside of EOR is its role in delaying the transition to a green economy by perpetuating reliance on fossil fuels, contributing to greenhouse gas emissions when the oil is burned.

Moreover, using captured CO_2 for EOR diverts resources from developing renewable energy technologies, creating a "carbon lock-in" effect that hinders the shift to sustainable energy systems (Araújo et al. 2021). Economic incentives for CO_2-EOR, such as tax credits, further support the fossil fuel industry, undermining long-term climate goals. Consequently, while EOR might offer short-term benefits, it ultimately hinders the transition to a low-carbon economy. Therefore, Planet A does not support using carbon capture for EOR, advocating for the responsible use of technologies like DAC to combat climate change without undermining efforts to reduce emissions.

5. Conclusion

This LCA provides insight into the potential environmental benefits of CO_2 sequestration from Phlair's technology. The analysis of the energy consumption shows that the 260t/year pilot plant is better than the average technology deployed today and the 1Mt/year scaled-modular plant is at par with the best available technology, with significant potential for energy efficiency improvement. **The captured CO_2 leads to a net reduction in GHG emissions of 679 kg CO_2 per tonne of CO_2 sequestered from the air for the 260t/year pilot plant leading to a 68% net carbon removal efficiency. Deploying the 1Mt/year scaled-modular DAC plant leads to a net reduction in GHG emissions of 934 kg CO_2 per tonne of CO_2 sequestered from the air, i.e. a 93% net carbon removal efficiency.** Energy supply (and its associated emissions) and the recycling of metals including copper used in the plant cables and precious metals like platinum and titanium used in Phalir's electrolysers are important factors in determining the net carbon removal efficiency.

CO_2 captured using Phlair's DAC plants can either be permanently stored underground (as described using example of 44.01) or can be used to produce various chemicals, hydrocarbons and synthetic fuels (as described using the examples of Ineratec and C1). In all cases, using renewable energy instead of fossils is the most important factor to increase the net reductions in GHG emissions in the whole value chain of the CO2 sequestration, starting with CO_2 capture to use or storage.

While efforts to reduce GHG emissions should always take priority, meeting climate goals will also require carbon dioxide removal at the billion-tonne scale by mid-century. Carbon removal is needed not only to balance out residual emissions that cannot be or are not eliminated by 2050, but also to reduce the high concentration of carbon dioxide in the air which is triggering increasingly devastating effects. Phlair`s innovation has the potential to achieve large-scale carbon removal, making it an important technological solution to mitigate climate change.

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