LIFE CYCLE ASSESSMENT
& SUSTAINABILITY POTENTIAL

Permanent Carbon Sequestration

44.01

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 is published for maximum transparency.

Terminology and abbreviations

CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CHP	Combined heat and power
CED_f	Cumulative fossil energy demand
CO_2-eq.	Carbon dioxide equivalents
COP	Coefficient of performance
CS	Carbon storage
DAC	Direct air capture: a process to extract CO_2 from the atmosphere
Functional unit	Quantified performance of a product system for use as a reference unit
GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory
PV	Photovoltaics
UCO	Used cooking oil
WSI	Water stress index

Summary

The mitigation of climate change requires an urgent reduction in GHG emissions as well as carbon dioxide removal (CDR) from the atmosphere (Haszeldine et al. 2018). **44.01 offers a CDR concept with a permanent CO_2 mineralization in peridotite formations in Oman.** 44.01 intends to use CO_2 obtained from a DAC installation and an industrial point source. The point source is a natural gas power plant in an industrial park. Energy for 44.01's operation is operated with energy supply from renewable sources. 44.01 uses a combination of solar PV and biodiesel to provide continuous energy supply to its facilities. Biodiesel is sourced from a newly developed supply chain using used cooking oil.

This assessment shows that each tonne of sequestered CO_2 results in a net removal of 0.91 t CO_2-eq. from the atmosphere in case of CO_2 supply from DAC or 0.88 t CO_2-eq. in case of CO_2 supply from the industrial point source. In addition to GHG emissions, we also assessed abiotic resource use, fossil energy demand and water demand. **The minimization of transportation distances, the use of energy from fully renewable sources for all energy demand activities as well as the choice of sustainable suppliers (scope 3 emissions) are the biggest leavers to reduce environmental impacts.** In the long-term, upstream industries will become more sustainable reducing the overall impact of 44.01. Overall, the assessment indicates a high carbon removal efficiency and overall low other environmental impacts.

About 44.01

Permanent removal of carbon dioxide (CO_2) will be needed to effectively combat climate change. 44.01 offers permanent removal CO_2 of captured CO_2 from point sources and from direct air capture (DAC) via mineralization in Oman. 44.01 sequesters CO_2 in peridotite formations, offering a permanent CO_2 removal. There are only a few geographies worldwide that have easy access to Peridotite. Oman - and thus the region 44.01 is active in - is one of them. The location offers a high potential for permanently mineralizing large quantities of CO_2 while using energy from renewable sources to operate all processes needed.

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1. About this study

The aim of this report is to provide insights into the potential environmental impacts of 44.01's carbon capture and mineralization in peridotite formations in Oman. The system that is being assessed comprises carbon capture, transportation and mineralization. Taking different means of energy supply into account, the assessment evaluates changes in environmental impacts arising from scaling 44.01. To account for the marginal changes that occur, the life cycle assessment (LCA) follows a consequential LCA approach. Datasets reflecting marginal market changes are used whenever possible. By accounting for these effects, the study provides insights into how environmental impacts might change if CO_2 is captured and permanently stored with the technology of 44.01.

2. System description

The system includes the supply of CO_2 from DAC and industrial point sources. The latter is a natural gas-fired power plant located in an industrial park in proximity to the mineralization site. 44.01 uses renewable energy from local sources to provide process energy to capture CO_2 (in case of DAC) and to mineralise CO_2.

2.1. Functional unit and assessed indicators

The functional unit is **1 kg CO_2 mineralized permanently in peridotite formations in Oman**. 44.01 is not operating at full scale yet. The assessment considers a potential future system as it is planned at present. The system comprises (Figure 1):

- CO_2 supply by DAC and from a point source
- In case of CO_2 supply from the point source: CO_2 transportation, including liquefaction and transportation by truck
- On-site energy supply
- Well construction and closing
- CO_2 sequestration, including conditioning, injection and water recycling
- All background processes and activities needed to operate the aforementioned processes, such as infrastructure, waste treatment, energy supply, transportation, etc. (not depicted in Figure 1).

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).

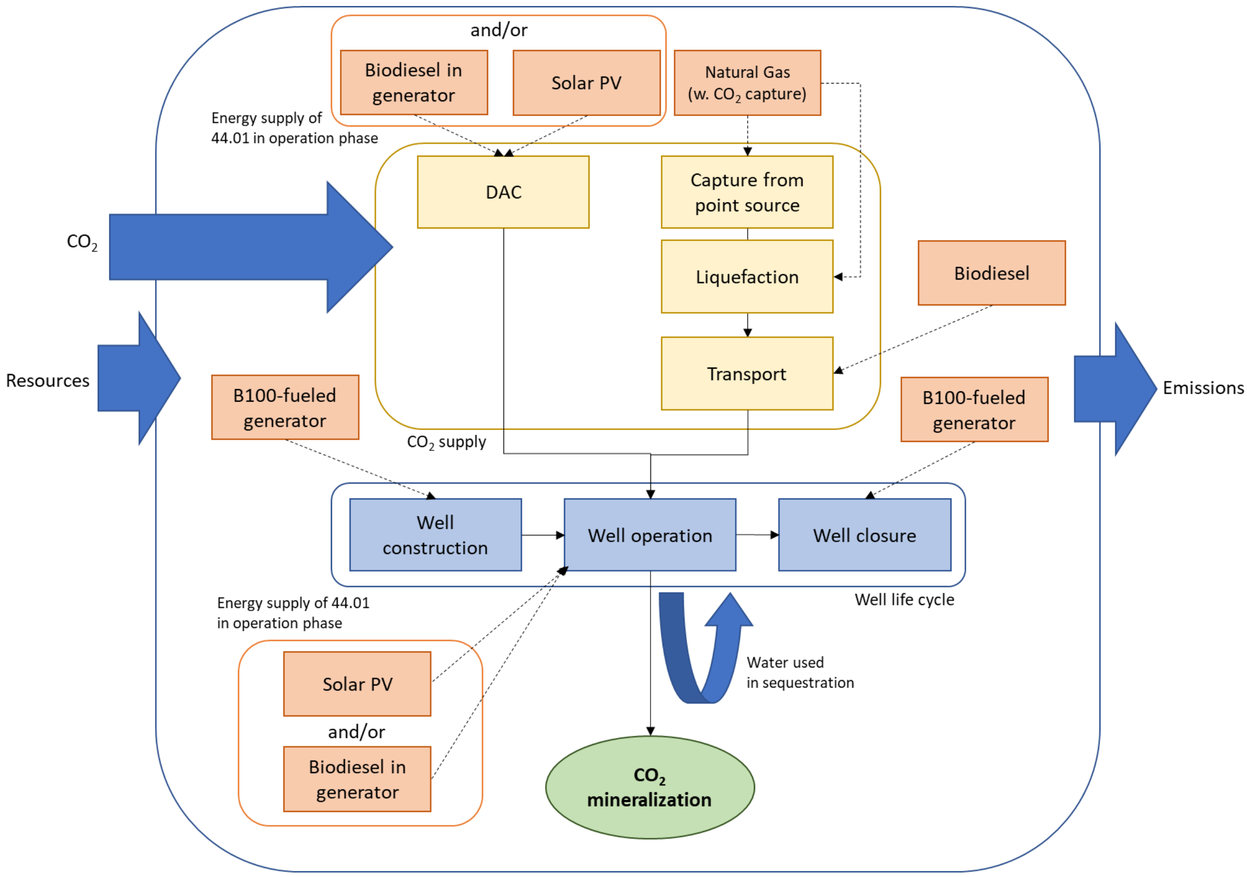

Figure 1 *Depiction of system boundaries. Different supply chains for the provision of carbon dioxide are assessed: DAC and capturing from a point source (a natural gas power plant). Energy supply is depicted by orange boxes. Background processes, e.g. raw material supply, infrastructure, waste treatment, etc. are included in the assessment but not depicted in the figure. Water used in sequestration is fed back into the aquifer from which it was taken. Therefore water does not leave the catchment area. Diesel-fueled machinery operates with biodiesel (B100). Abbr.: DAC - Direct air capture, PV - photovoltaics.*

2.2. Description of the supply chain elements and the life cycle inventory

In the following section, the key elements of the supply chains depicted in Figure 1 will be explained. Most important technical parameters are described. Detailed life cycle inventory tables are provided in the Annex. Background processes are modeled with the ecoinvent 3.8 database (Wernet et al. 2016).

2.2.1. Carbon dioxide capture

CO_2 or CO can be obtained directly from the atmosphere or from industrial point sources (Cuéllar-Franca and Azapagic 2015).

- **Direct air capture:** currently, DAC is the most discussed option to directly obtain CO_2 from the atmosphere. The technologies usually use an absorbent (e.g. amine-based or caustic sorbent) or adsorbent to absorb/adsorb CO_2. In a subsequent step, CO_2 is desorbed and compressed. The data used for the DAC unit stems from Climeworks (Schreiber et al. 2020) and their DAC unit operating in Switzerland (Table A.1 in the Annex). No changes to the inventory and efficiency were assumed in this LCA (the efficiency might differ due to environmental conditions, such as humidity and ambient temperature). The modeled DAC system requires 500 kWh electrical and 1500 kWh thermal energy per t CO_2 captured. The thermal heat at 115°C is provided by a heat pump. It is operated using solar PV. A coefficient of performance (COP) of 2.51 as reported for Climeworks DAC units was used (Deutz and Bardow 2021). The inventory of the Climeworks DAC unit is listed in Table A.1 in the Annex. Additionally, the process requires 3.75 anionic resin per t CO_2 captured. The DAC unit can capture 900 t CO_2 per year over a lifetime of 12 years (Schreiber et al. 2020).

- **Point-sources providing CO_2:** Certain industrial processes produce large amounts of CO_2 due to the combustion processes or as a result of other chemical reactions. The main source of anthropogenic CO_2 is fuel combustion (e.g. power plants, refineries, kilns etc.). In addition, other processes emit process-based CO_2. For example, clinker production emits large amounts of CO_2 in the process of calcination (converting calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and CO_2). Additionally, there are many biogenic processes used in industrial applications using biogenic feedstock to produce food, feed, chemicals, energy or fuels producing CO_2 as a metabolic or process-related side-product, e.g. ethanol production and anaerobic digestion. In addition, the combustion of carbonaceous biofuels emits CO_2 that can be captured and utilized. For instance, solid biomass or biomethane can be combusted in power plants to supply process energy or base-load energy supply. There are numerous technologies to obtain CO_2 from any point source mentioned, such as absorption by chemical solvents, adsorption by solid sorbents (e.g. zeolites), membrane separation, pressure/vacuum swing adsorption.

  We assess a CO_2 capture based on monoethanolamine (MEA) absorption in this study (Table A.2 in the Annex). The CO_2 point source modeled is a natural gas power plant. The heat to regenerate the MEA was assumed to be taken from the power plant (no additional emissions considered). The additional electricity demand is supplied by the power plant. The model uses data of a conventional natural gas power plant from the ecoinvent 3.8 database.

2.2.2. Carbon dioxide transportation

Depending on the source, two different means of CO_2 transportation are considered:

- Point source: The point source is located 200 km from the injection site. We thus consider a round-trip of 400 km covered with trucks. 44.01 cooperates with WAKUD, a newly founded company that produces biodiesel from used vegetable oils (UCO). A supply agreement ensures that the trucks can operate using biodiesel (UCO methyl ester). The UCO methyl ester production and truck operation was modeled with the corresponding processes of the Ecoinvent 3.8 database. CO_2 is liquefied for transportation. This process consumes 250 kWh/t CO_2. Electricity is supplied from the point source (with carbon capture installed).
- DAC: If CO_2 is supplied by DAC, no transportation is assumed because the DAC facility is located at the injection site.

2.2.3. Well construction, maintenance and closing

Wells are needed to inject CO_2 into the subsurface and to monitor CO_2 mineralization. Overall, one observation well is needed per two injection wells. 44.01 targets a well depth of 1000m. Assuming an average depth of 1000 m and the given ratio of wells, this yields a total depth of 1500 m (1.5*1000m). Since there is a degree of uncertainty related to the well depth, a range of well depths of 600 to 2000 m was assessed in the sensitivity analysis (Figure 2).

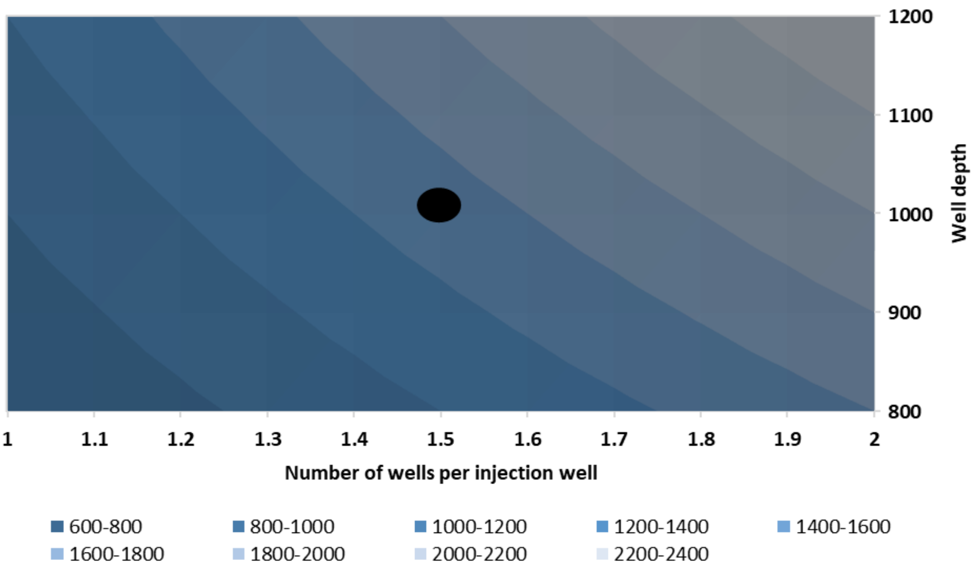

Figure 2 *Total well depth as a function of well depth and number of wells required per injection well. The black circle marks the targeted depth and number of observation wells per injection well needed.*

Data for well construction and closure was taken from geothermal wells and enriched with data from 44.01. (Table A.3 and A.4 in the Annex). The LCI includes efforts to drill wells (diesel powered machinery, fueled by biodiesel) as well as materials and activities to establish wells. Data was taken from geothermal wells (Blanc et al. 2020; Lacirignola et al. 2014; Menberg et al. 2016) and combined with first-hand data from 44.01.

2.2.4. Carbon dioxide injection

Captured carbon dioxide is mixed with water and pumped into the wells (data of the operation was supplied by 44.01). The total electricity demand is 225 kWh per t CO_2 stored: injection, recycling and condition require 75, 50 and 100 kWh per CO_2 sequestered (at 1000 meters below ground level). The energy is supplied by a combination of solar PV and locally sourced biodiesel to operate the facility during night times (see section “Energy supply” below). No infrastructure requirements are considered for the above-ground facilities. CO_2 injected to the well is trapped and finally mineralized, allowing a permanent removal of CO_2. 44.01’s core process, the CO_2 mineralization, uses a combination of solar PV and biodiesel burned in a generator to provide electricity (25/75 split). In the results section a 100% energy supply by either technology is also assessed. The energy supply was modeled with data from the ecoinvent database and a comprehensive review of LCAs of renewable energy technologies (United Nations 2021; Wernet et al. 2016). The water demand of CO_2 sequestration is a function of depth and depends on CO_2 solubility (solubility model provided by 44.01). A water recycling of 45% is considered.

3. Environmental impact of permanent CO_2 removal

3.1. GHG emissions

The capturing and the sequestration of CO_2 results in a net change in GHG emissions of -0.91 kg CO_2-eq. per kg mineralized in case of CO_2 supply from DAC and -0.88 kg CO_2-eq. per kg mineralized from the industrial point source if energy is supplied by biodiesel and solar PV (75/25 split). The emissions of all activities and processes required to supply and mineralize CO_2 amount to 0.08 and 0.12 kg CO_2-eq. per kg mineralized CO_2 in case of CO_2 supply from DAC and a point source, respectively (Figure 3). The main reason for the better performance of the DAC system is the lack of transportation requirements. The transport and liquefaction emit 0.07 kg CO_2-eq. per kg of CO_2 mineralized. In this scenario, it is assumed that all electric energy required for all activities and processes that happen at the point source, i.e. CO_2 capturing and liquefaction, are supplied by electric energy from the natural gas power plant (90% CO_2 capture). If the liquefaction is operated with electricity from solar PV, the overall emissions are reduced by 0.05 kg CO_2-eq per kg CO_2 mineralized.

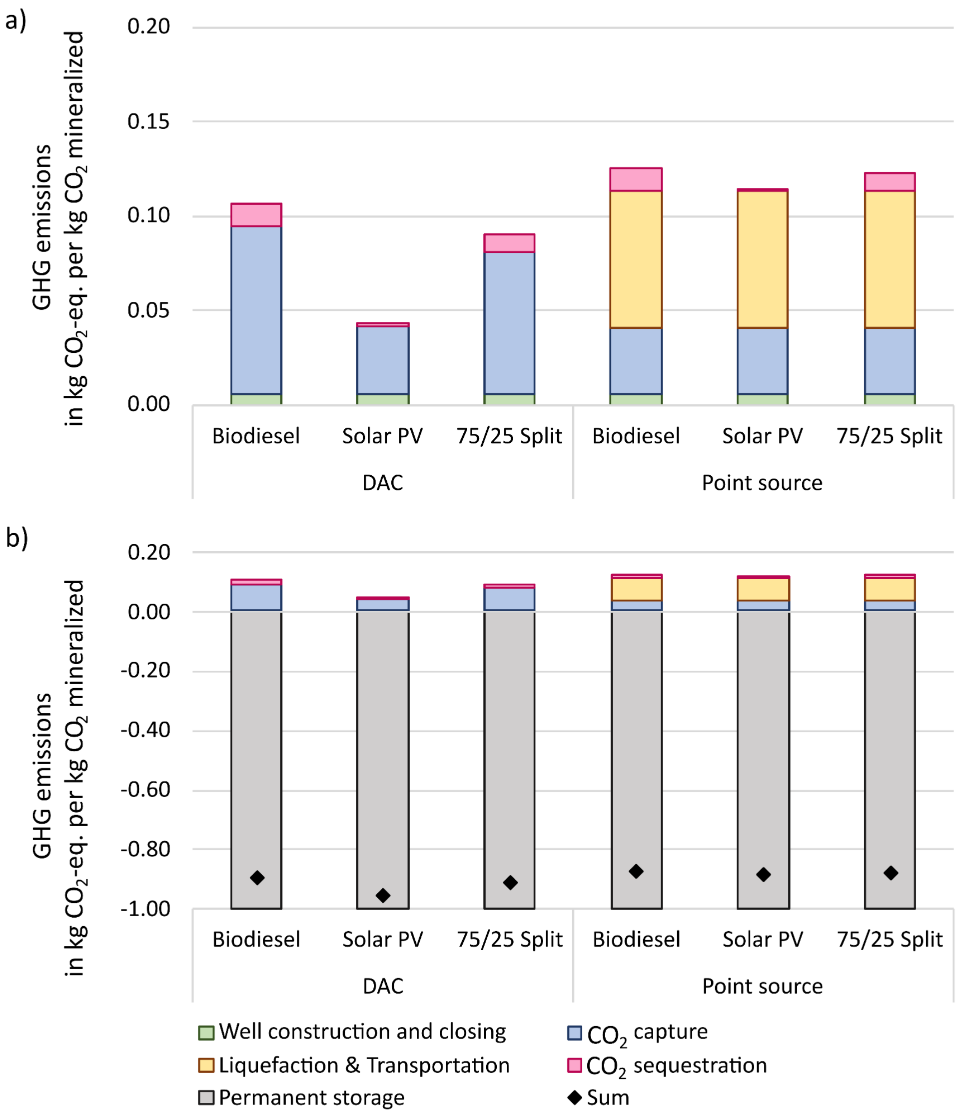

Figure 3 *GHG emissions of carbon capture and mineralization in kg CO_2-eq. per kg CO_2 permanently sequestered in Peridotite formations without (a) and with (b) the consideration of the CO_2 mineralization, i.e. -1 kg CO_2 per kg CO_2 sequestered. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, PV - photovoltaics.*

The breakdown of emissions shows that the main drivers of total GHG is CO_2 capturing. Overall, both systems perform quite similarly, even though point source capture has a lower energy demand due to the higher CO_2 concentration in the flue gas compared to DAC. However, the use of electricity supplied by the natural gas power plant (including CO_2 capture) evens out the lower energy demand.

A detailed analysis of carbon capture and storage by Deutz and Bardow using DAC reports capture efficiencies of 85.4 to 93.1% (Deutz and Bardow 2021). The authors assumed storage in depleted oil and gas reservoirs and did not include well infrastructure in their assessment assuming the re-use of existing well infrastructure. If well infrastructure is excluded in the present assessment, comparable CO_2 removal efficiencies of 88.3 to 91.5% are achieved (75/25 split).

Figure 4 shows the results from a sensitivity analysis assessing the dependence of results on key parameters.

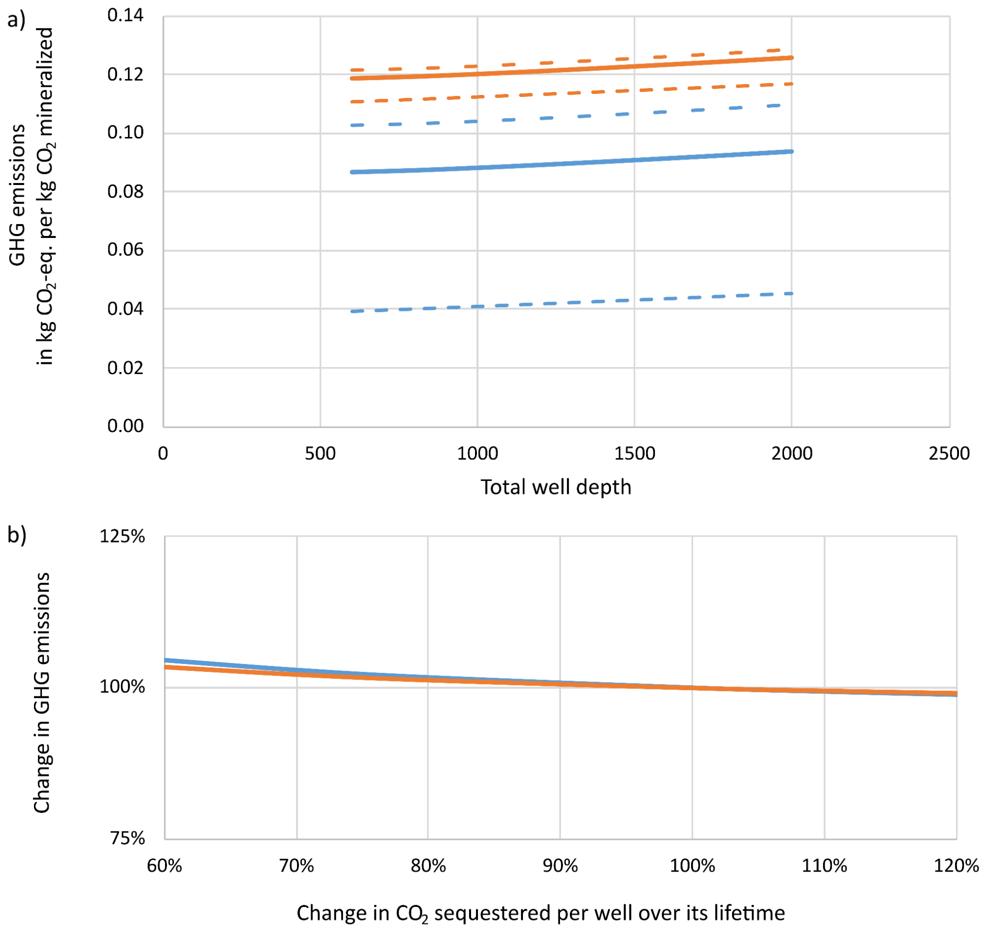

Figure 4 *Sensitivity analyses: dependence of results on the total well depth (a), and the total quantity of CO_2 that can be mineralized with a single well over its lifetime (b). Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, PV - photovoltaics.*

3.2. Resource demand

3.2.1. Abiotic resource demand

The capturing and sequestration of CO_2 results in net change in abiotic resource demand of 10.7 $\cdot$ 10^{-6} and 1.0 $\cdot$ 10^{-6} kg Sb-eq. per kg mineralized if energy is supplied by biodiesel and solar PV (75/25 split) in case of CO_2 supply from DAC and from the industrial point source, respectively (Figure 5). The resource demand is dominated by materials used in the DAC facility. It should be noted that the results are highly dependent on the materials used and the completeness of the inventory data. In this study, the DAC unit and the CO_2 capturing unit from point sources were taken from literature, both reflecting industrial units from different suppliers. The key contribution to abiotic resource demand is copper used in the DAC facility. Copper has the highest characterization factor (signifying the highest importance regarding abiotic resource use[1]). The small negative values for biodiesel originate from catalysts used for methanol production (Wernet et al. 2016; Althaus et al. 2007). Metal mining and subsequent processing often produces a number of (companion) metals. If certain companion metals are co-mined or produced, this potentially results in a decreased abiotic resource depletion potential. Thus, an increase in methanol production to produce biodiesel requires more catalysts, resulting in the manufacture of these catalysts entailing co-production of other metals.

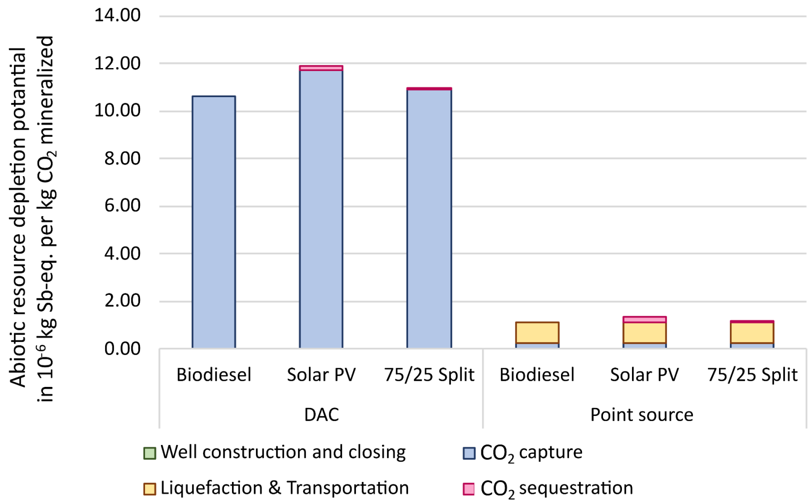

Figure 5 *Abiotic resource demand (abiotic resource depletion) of carbon capture and mineralization in 10^{-6} kg Sb-eq. per kg CO_2 permanently sequestered in Peridotite formations. Abbr.: DAC - Direct air capture, PV - photovoltaics.*

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[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]() and [here]().

3.2.2. Fossil energy demand

The sequestration of carbon dioxide and its supply result in an overall demand for fossil energy resources of 2.18 and 2.33 MJ per kg CO_2 sequestered in case of CO_2 supply from DAC and from the point source, respectively (75/25 split operation, Figure 6). Methanol use in biodiesel production is the key driver of the CO_2 sequestration process running on biodiesel. The fossil resource demand of CO_2 supply by DAC originates from adsorbent production and building materials. These results show that the overall system is likely to improve significantly, if the supply chain becomes more sustainable, i.e. methanol, adsorbents and building materials are produced in a more sustainable way. Again, both systems would perform almost the same, if there was no transportation needed.

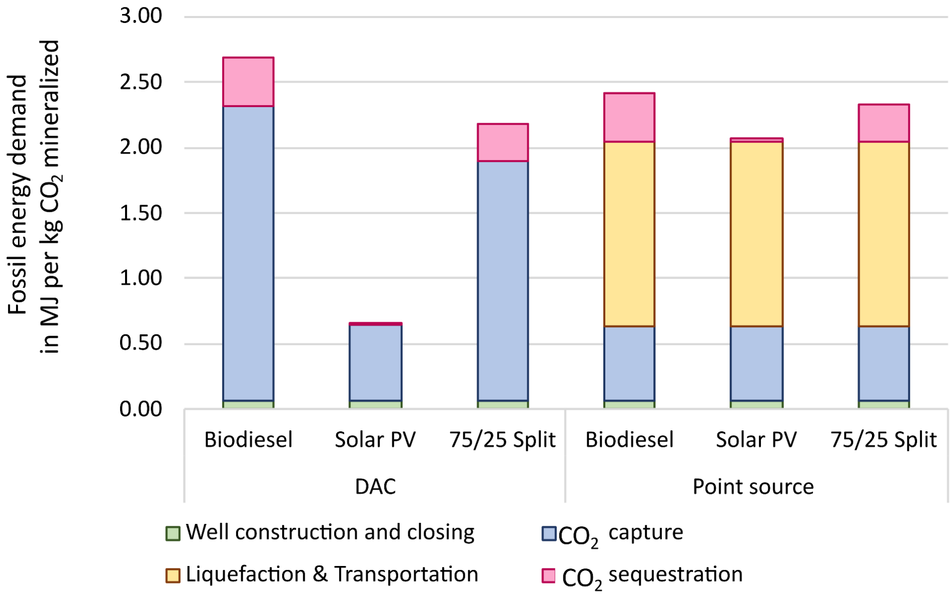

Figure 6 *Fossil energy demand of carbon capture and mineralization in MJ per kg CO_2 permanently sequestered in Peridotite formations. Abbr.: DAC - Direct air capture, PV - photovoltaics.*

3.2.3. Water demand

The water demand is 8.4 and 6.0 L per kg CO_2 sequestered in case of CO_2 supply from DAC and from the point source, respectively (75/25 split operation, Figure 7). The water demand for sequestration arises from energy supply. 44.01 is still optimizing the process and also considers using seawater and brine for the overall process. Since water is taken and re-injected at the same site, no water is removed from the catchment area. The main other processes that require water is liquefaction (energy supply) and the DAC unit (process materials). Some of the water enriched with CO_2 is consumed in the carbonation reactions of serpentinite and olivine. The quantity of water consumed for hydration reactions (serpentinization) of ultramafic rocks depends on how pre-hydrated the rock is. At present the water consumed in this reaction is not considered in the assessment.

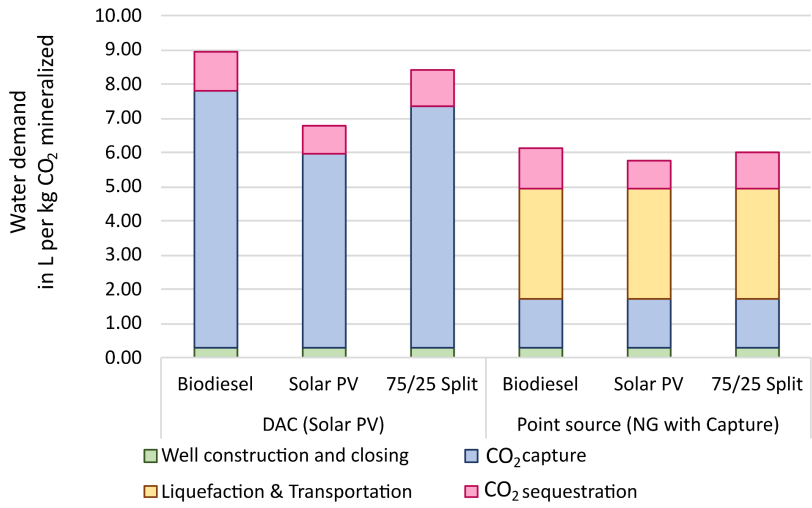

Figure 7 *Water use of carbon capture and mineralization in L per kg CO_2 permanently sequestered in Peridotite formations. Abbr.: DAC - Direct air capture, PV - photovoltaics.*

3.3. Comparison with other CDR technologies

A recent scientific paper of Chiquier et al. 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, a high permanence and an immediate storage of CO_2 are achieved. **Note:** 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, mineralization of CO_2 in rock formations is a *permanent elimination* of the CO_2 molecule preventing a future release *permanently*.

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 license. The formatting was changed and the results from the present assessment 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 removal 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 CO2 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%	92 - 100%	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	*87-96%*[a]	*87-96%*[a]	*High*	*Immediate, CO_2 capture from the air/point source*	*Very high, Permanent CO_2 mineralization*

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

4. Limitations

There a several limitations that should be considered when interpreting the presented results:

- 44.01 does not operate at full scale yet. Therefore, certain data points are based on modeling results, field trials and scientific literature.
- The used background data (e.g. all material supplies) are modeled with currently available LCA databases and studies. However, in the next decades, the overall economy is likely to transform towards less fossil-based and towards more sustainable activities. Thus, the overall impact of materials used in the supply chain is likely to decrease in time. Such effects would further decrease the impact of 44.01.
- In this study, well design is based on geothermal and first-hand data on cement requirements. Drilling energy requirements, tubing and additives might differ from the geothermal well.
- The biodiesel sourced by 44.01 is made from UCO. Before the partnership with WAKUD, the UCO was treated as waste. Since all carbon in UCO is of biogenic origin, CO_2 emissions of the avoided decomposition at the disposal site were considered equal to those CO_2 emissions emitted when the biofuel is combusted. Potential methane emissions occurring in landfills were neglected. This is a conservative estimate, because 44.01./WAKUD's newly established biodiesel supply reduces the quantity of UCO disposed of and thereby also might reduce landfill emissions, including methane.
- In the supply chain, certain displacement effects might occur. For instance, biodiesel production also produces glycerin. So far, potential benefits of producing glycerin (e.g. displacing other products on the market) have been neglected. If glycerin substitutes other products, additional reductions in GHG emissions and other positive impacts can be expected.
- This assessment assesses how impacts change if 44.01 scales the sequestration of CO_2. Thus, changes in environmental impacts are assessed and a consequential LCA approach is applied. For certification purposes, e.g. CDR (carbon dioxide removal) certificates, datasets reflecting an attributional perspective should be used. More information on these two approaches can be found here.

5. Conclusion

CDR offers a way to permanently remove CO_2 from the atmosphere. CDR technologies will be needed as part of the portfolio of technologies that need to be scaled to mitigate climate change (Haszeldine et al. 2018). **44.01 offers a permanent carbon mineralisation using CO_2 captured from a DAC installation and an industrial point source**. The assessment shows that the sequestration of CO_2 results in a net reduction of GHG emissions and in an increase in resource demand (abiotic resources, fossil energy demand and water). Several of the assessed impacts originate from activities and processes in the supply chain, i.g. materials production and energy supply in the chemical industry. **44.01's overall environmental impact is in several of the assessed impact categories largely determined by energy supply**. **44.01 already considered sustainability aspects when designing their system**. For instance, a biodiesel supply chain was developed just for the purpose of providing locally sourced, non-fossil based fuels to operate building machinery for well construction and closure, to run facilities at night and to fuel transportation trucks. The use of energy from sustainable sources in all cases, e.g. pure biodiesel or or energy supply at the point source using electricity provided by solar PV, presents the biggest lever to reduce GHG emissions and other impacts. The choice of suppliers with lowest impacts present the most immediate way to further decrease environmental impacts related to building materials and consumables.

The overall process exhibits a high overall CO_2 removal efficiency of 87 to 96%. The mineralization in peridotite formations is a permanent and safe CO_2 storage without any leakage risk once the CO_2 is mineralized. In comparison with other CDR technologies, the system of 44.01 exhibits a high CO_2 removal efficiency and a higher permanence of CO_2 storage than other CDR technologies.

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A. Annex

A.1. Additional Life Cycle Inventory

Table A.1 *LCI of a Climeworks DAC unit (Schreiber et al. 2020).*

Material	Unit	Value	Comment
Aluminum, primary, ingot	t	2.096	
Concrete, normal	m^3	1	
Copper, anode	t	1.7	
Ethylene glycol	t	15	
Gravel, crushed	t	93.1	
Sand	t	89.6	
Silicone product	t	1.1	
Steel, chromium steel 18/8, hot rolled	t	3.63	
Steel, low-alloyed	t	3.03	
Stone wool	t	8.7	
Wire drawing, copper	t	1.7	

Table A.2 *LCI of a CO_2 capturing from flue gas (Giordano, Roizard, and Favre 2018).*

	Material	Unit	Value
In	Activated carbon, granular	kg	$7.00\ 10^{-2}$
	Electricity	kWh	98.3
	Heat	GJ	3.2
	Monoethanolamine	kg	1.44
	Sodium hydroxide, without water, in 50% solution state	kg	0.12
	Tap water	kg	18.1
Out	Acetaldehyde	kg	$1.50\ 10^{-4}$
	Ammonia	kg	0.03
	Argon-40	kg	54.8
	Carbon dioxide (captured)	kg	1000
	Formaldehyde	kg	$2.40\ 10^{-4}$
	hazardous waste, for incineration	kg	2.9
	Monoethanolamine	kg	$6.00\ 10^{-4}$
	Nitrogen	kg	3202.2
	Spent activated carbon, granular, treated in sanitary landfill	kg	0.07
	Water	m^3	$8.75\ 10^{-2}$

Table A.3 *LCI of well drilling. Data sources (Lacirignola et al. 2014; Menberg et al. 2016) and 44.01.*

		Unit	Value
Inputs	Decarbonized water	kg	1110
	Salt	kg	50.5
	Reinforcing steel	kg	111.3
	Cement	kg	73.3
	Blast furnace slag cement	kg	4.9
	Chemicals inorganic	kg	2.81
	Bentonite	kg	8.78
	Silica sand	kg	1.52
	Sodium hydroxide, 50% in water	kg	2.8
	Soda powder	kg	0.6
	Steel, metal working	kg	111.3
	Electricity	MJ	400
Output	Geothermal well	m	1
	disposal, drilling waste, 71.5% water, to residual material landfill	kg	290
	Wastes	Equivalent quantities of material inputs	

Table A.4 *LCI of well closing (Blanc et al. 2020).*

		Unit	Mean	Max
Inputs	B100	MJ	1,075,000.00	1,290,000.00
	Concrete	m^3	10.42	13.02
	Filler	kg	5000.00	6250.00

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