Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources

Supplementary Information (SI)

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Contents

Our functional unit:

'Gross removal of 1 ton CO_2 from the atmosphere via the use of a DAC plant combined with geological CO_2 storage'

Life cycle inventories - compatible with Brightway2 - are available in supplementary files **'lci-Fresnel.xlsx'**, **'lci-CS.xlsx'** and **'lci-daccs_activities.xlsx'**.

S1. Verification of information obtained from Climeworks and corresponding contribution analysis (regarding impacts on climate change) of the DAC infrastructure (plant)

1. Contribution analysis of the DAC infrastructure (plant) for today and near-term future obtained from Climeworks regarding life-cycle impacts on climate change

Two direct air capture (DAC) infrastructure specifications were received from Climeworks in terms of material and operational energy inventory: one corresponding to a current unit (4 kt CO_2/year captured), and the other for a near-term future installation (100 kt CO_2/year captured). We present a contribution analysis regarding life-cycle greenhouse gas (GHG) emissions for the DAC infrastructure (*i.e.* the construction of the DAC unit) for both specifications in the following figures. The figures demonstrate that the material intensity is expected to decrease for a near future installation compared to the current plant design, which is due to material savings enabled by technological improvements, while the energy consumption for the CO_2 capture process will stay constant.

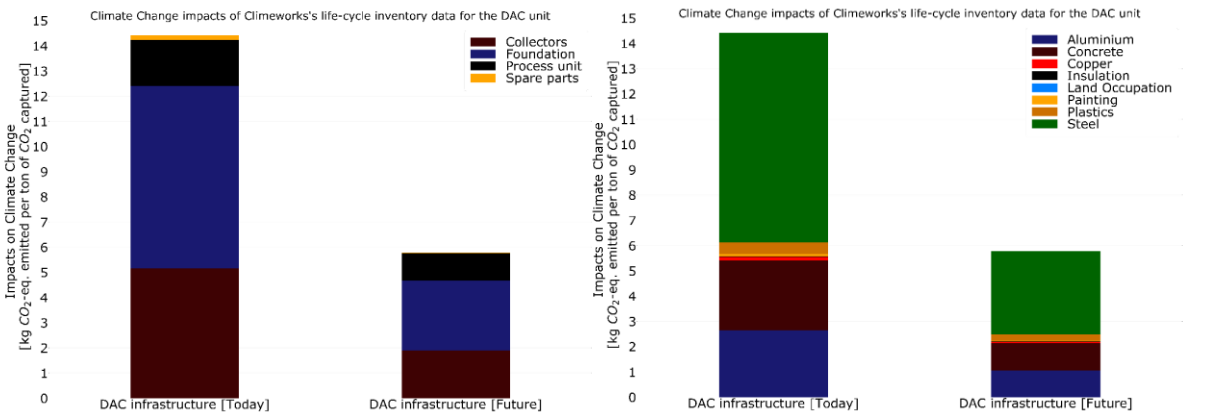


Figure S1. Contribution analysis on Climate Change impacts of the main DAC components and materials per ton of CO_2 captured for two scenarios: the current life cycle inventory used in Iceland (4 kt plant) and a future scenario (100 kt plant). Left panel: breakdown per main component; right panel: breakdown per main material.

2. Verification of information obtained from Climeworks regarding DAC infrastructure material needs and generation of new life-cycle inventory

We are not allowed to publish the complete material inventories of the DAC system we obtained from Climeworks, since Climeworks' DAC infrastructure data is confidential (a proprietary technology). Therefore, we generate a life-cycle inventory (LCI) of the DAC unit based on freely available data on the web in order to verify the LCI of Climeworks. In the following calculations, we check the DAC infrastructure requirements for the 4 kt CO_2/year and 100 kt CO_2/year capture unit based on the 0.9 kt CO_2/year DAC plant in Hinwil (Switzerland), since this plant has already been installed and some data and figures are freely available on the web.

We assume that the DAC system consists of modular collectors for CO_2 capture from air, a process unit (*e.g.* for preparation of sorbent and piping), a steel tank (*i.e.* hot water reservoir) and a hall/building (*e.g.* for control purposes)[a]. First, we estimate that each collector is a box with a width, length and height of 2 meters (based on figures of Climeworks' website and the web[b]). These collector boxes are designed in a modular way, and 6 collectors fit in a 40 foot shipping container (Beuttler, Charles and Wurzbacher, 2019), which corresponds to our estimated sizes of the boxes. Further, the layout of the collector system (0.9 kt CO_2/year captured unit) in Hinwil (Switzerland) shows the requirement of 18 collector boxes to capture 0.9 kt CO_2/year[a]. Therefore, each collector box captures 50 t CO_2/year (Beuttler, Charles and Wurzbacher, 2019), since the collector boxes are designed in a modular way (Beuttler, Charles and Wurzbacher, 2019). Hence, 80 collector boxes are required for a DAC unit capturing 4 kt CO_2/year.

We assume that the life cycle inventory of the collector box (*e.g.* for a fan, steel, insulation, plastics) is – in terms of material composition – similar to the life cycle inventory of a passenger vehicle (e.g. steel, motor, electronics, plastics). Such an assumption has also been made in van der Giesen et al. (van der Giesen *et al.*, 2017). We use a 1200 kg compact size petrol/natural gas car as best available approximation (dataset 'market for passenger car, petrol/natural gas' in ecoinvent 3.6). The dimensions of the car are assumed to be the same as a compact sized car, a Volkswagen Golf, with a width of 1.8

[a] https://houseofswitzerland.org/swissstories/environment/climeworks-technology-reverse-climate-change (08.12.2020).

[b] https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html (07.12.2020).

meter, a length of 4 meter and a height of 1.5 meter (Volkswagen, 2006). Since we calculated the total volume requirement for the collector boxes (640 m^3, with 8 m^3 per collector box), we can calculate the amounts of materials in the life cycle inventory in kg passenger vehicle (with a density of ~110 kg/m^3) needed for the process unit. Table S1 shows the main parameters used for the calculation of our self-generated life cycle inventory.

Based on freely available figures for the DAC unit in Hinwil (0.9 kt CO_2/year captured unit)[a], we obtain that the DAC unit consists of 2 containers (*i.e.* assumed to be the process units, hence, 1 container per 9 collector boxes) with an estimated size of 12 meters length (6 collector boxes), 2 meters width and 2 meters height, *i.e.* a volume of approximately 50 m^3 per process unit. Hence, we linearly scale the amount of process units needed for the 4 kt CO_2/year captured unit, which results in 9 process units with a total volume of 450 m^3. For the sake of simplicity, we use the same approach as with the collector boxes, and assume the life cycle inventory of the process unit to be similar to the one of a passenger vehicle. Furthermore, one steel tank (7850 kg/m^3 [c]) is needed[a] (one steel tank per 18 collector boxes) for storage and is assumed to have a diameter, height and thickness of 2 meters, 6 meters and 0.02 meter, respectively.

Table S1. Main parameters used for our self-generated life cycle inventory.

	Hinwil (Switzerland)	Current technology (4 kt)	Future technology (100 kt)	Unit
Capacity	0.9	4	100	kt CO_2/year
Collector boxes	18	80	1000	-
Specific capacity	50	50	100	CO_2 captured/ collector box/year
Land use occupation	90	400	5000	m^2 land
Hall area	n.a.	300	3750	m^2 building

Further, land preparation required before installation of the DAC unit includes the conversion of grassland to industrial area, and the subsequent coverage of land with concrete (as foundation for the process unit and collectors). Viebahn et al. (Viebahn, Scholz and Zelt, 2019) reported a land occupation for the DAC plant of 90 m^2 for Climeworks' plant in Hinwil. Hence, we apply a linear increase of land use occupation and use 400 m^2 for the 4 kt CO_2/year capture unit. With a concrete layer of 1 meter, this results in a concrete volume of 400 m^3 - with a reinforcement of 120 kg steel/m^3 concrete (Deutz and Bardow, 2021) required.

According to information of Climeworks, a hall/building is installed (*e.g.* for control purposes). However, the dimensions of this hall/building remain unclear, also whether the land occupation of the hall/building is considered in the land occupation presented in Viebahn et al. (Viebahn, Scholz and Zelt, 2019) or not. We estimate that the building/hall occupies 75% of the total surface area (*i.e.* a total surface of 300 m^2), with a lifetime of 50 years. An overview of our self-generated life-cycle inventory for the 4 kt CO_2/year captured unit is presented in Table S2.

For the future DAC unit, we assume that each collector box captures twice as much CO_2 due to an improved capture process. This results in less material consumption, land use as well as a smaller hall/building per unit of CO_2 captured. With this assumption, we are able to generate the life-cycle inventory for the near future DAC plant considering this improved performance. This life-cycle inventory is also presented in Table S2.

[c] https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html (08.12.2020).

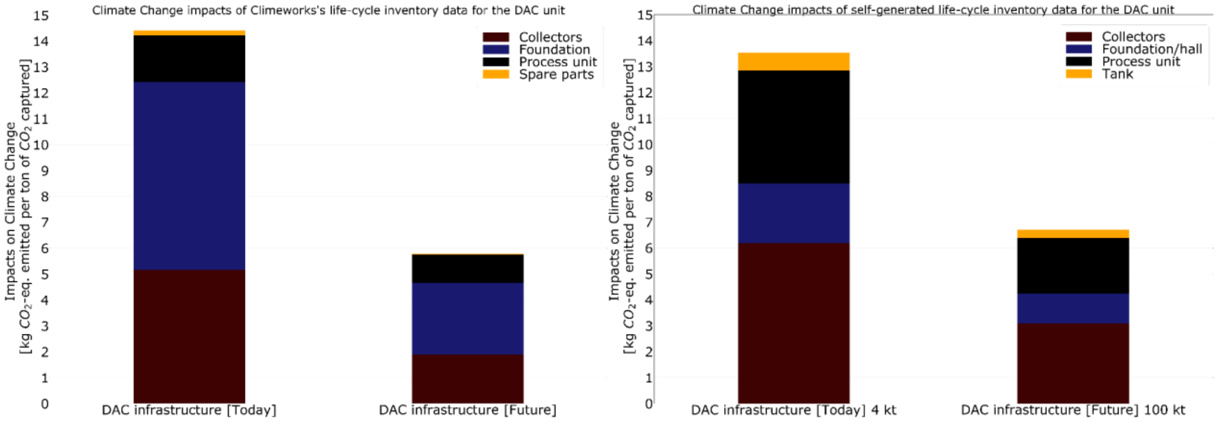


Figure S2. Contribution analysis on Climate Change impacts of the main DAC components (for a DAC plant of 4 kt CO_2 captured/year) per ton of CO_2 captured generated from Climeworks's (figure on the left) inventory and our simplified calculation (figure on the right).

The DAC infrastructures approximated with our simplified calculation exhibits a Climate Change impact for the total DAC infrastructure of 13.5 kg CO_2-eq/t CO_2 captured and 6.7 kg CO_2-eq/t CO_2 captured for the 4 kt CO_2 captured/year and 100 kt CO_2 captured/year DAC units, respectively (see Figure S2). The life cycle inventory for the DAC infrastructure provided by Climeworks' results in 14.4 kg CO_2-eq/t CO_2 captured and 5.8 kg CO_2-eq/t CO_2 captured for the 4 kt CO_2 captured/year and 100 kt CO_2 captured/year DAC units, respectively (see Figure S2). In other words, the difference between both approaches in terms of Climate Change impact is very small: ~1 kg CO_2-eq/t CO_2 captured.

Hence, we are able to verify the information from Climeworks and obtain similar results on Climate Change impacts. Further, we confirm that the DAC infrastructure has a small impact on Climate Change per t CO_2 captured (both in absolute and relative terms compared to other DACCS life-cycle contributions). The main difference between the two approaches originates from the foundation and the process unit. We found lower Climate Change impacts for the foundation in our calculation, since our analysis included a general ecoinvent data proxy with a lifetime of 50 years for the 300 m^2 hall, a lifetime which might be optimistic. The contribution of the Process Unit turned out to have a slightly higher Climate Change impact in our analysis, since we estimated the size of the process units based on a figure on the web[a].

This simplified infrastructure analysis does not aim to replace original life cycle inventory from Climeworks, since this back of the envelope calculation applies rough assumptions, which differ from reality. However, performing independent calculations based on public information to verify data from industry - which cannot be disclosed in our article - corresponds to best practice in LCA.

Note, again, that we use the detailed life-cycle inventory of Climeworks in our LCA, and that we do not use the life cycle inventory described in this section. Hence, we recommend not utilizing the life cycle inventory as presented in our simplified calculation.

*Table S2. Life cycle inventory as used in our back of the envelope calculation for a DAC plant of 4 kt CO_2 captured/year and DAC plant of 100 kt CO_2 captured/year. The inventories are being shown such that they can be imported with the Brightway2 software easily. An activity is indicated in **bold** with its corresponding unit and location in column 4 and 6, respectively. Their exchanges can be found under the activity. Activities are separated by a blank row. Please note that the sub-components (collectors, engineering, hall, process unit, tank under 'carbon dioxide capture system_4_kt and 'carbon dioxide capture system_100_kt') are divided by the amount of captured CO_2 during the lifetime (i.e. system lifetime * ton CO_2 captured/year), to obtain the environmental impact per ton of CO_2 captured.*

carbon dioxide capture system_4_kt			per t CO2 captured		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
collectors_4_kt		1.25E-05	unit		RER	technosphere
engineering_4_kt		1.25E-05	unit		RER	technosphere
hall_4_kt		1.25E-05	unit		RER	technosphere
process unit_4_kt		1.25E-05	unit		RER	technosphere
tank_4_kt		1.25E-05	unit		RER	technosphere
collectors_4_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**

market for passenger car, petrol/natural gas	passenger car, petrol/natural gas	7.04E+04	kilogram		GLO	technosphere
engineering_4_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
Occupation, industrial area		8.00E+03	square meter-year	natural resource:land		biosphere
Transformation, from grassland, natural (non-use)		4.00E+02	square meter	natural resource:land		biosphere
Transformation, to industrial area		4.00E+02	square meter	natural resource:land		biosphere
market for concrete, normal	concrete, normal	4.00E+02	cubic meter		CH	technosphere
market for steel, low-alloyed	steel, low-alloyed	4.80E+04	kilogram		GLO	technosphere
hall_4_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for building, hall, steel construction	building, hall, steel construction	1.20E+02	square meter		GLO	technosphere
process unit_4_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for passenger car, petrol/natural gas	passenger car, petrol/natural gas	4.95E+04	kilogram		GLO	technosphere
tank_4_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for steel, low-alloyed	steel, low-alloyed	3.40E+04	kilogram		GLO	technosphere
carbon dioxide capture system_100_kt			per t CO2 captured		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
collectors_100_kt		5.00E-07	unit		RER	technosphere
engineering_100_kt		5.00E-07	unit		RER	technosphere
hall_100_kt		5.00E-07	unit		RER	technosphere
process unit_100_kt		5.00E-07	unit		RER	technosphere
tank_100_kt		5.00E-07	unit		RER	technosphere
collectors_100_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for passenger car, petrol/natural gas	passenger car, petrol/natural gas	8.80E+05	kilogram		GLO	technosphere
engineering_100_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
Occupation, industrial area		1.00E+05	square meter-year	natural resource:land		biosphere
Transformation, from grassland, natural (non-use)		5.00E+03	square meter	natural resource:land		biosphere
Transformation, to industrial area		5.00E+03	square meter	natural resource:land		biosphere

market for concrete, normal	concrete, normal	5.00E+03	cubic meter		CH	technosphere
market for steel, low-alloyed	steel, low-alloyed	6.00E+05	kilogram		GLO	technosphere
hall_100_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for building, hall, steel construction	building, hall, steel construction	1.50E+03	square meter		GLO	technosphere
process unit_100_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for passenger car, petrol/natural gas	passenger car, petrol/natural gas	6.11E+05	kilogram		GLO	technosphere
tank_100_kt			unit		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for steel, low-alloyed	steel, low-alloyed	3.81E+05	kilogram		GLO	technosphere

S2. Selection of locations for DACCS system configurations

We consider DACCS installation in eight different countries with corresponding inventory data in our main analysis (see Figure 2 in the main article). This section explains the selection of these countries. First, Iceland is included since the second DACCS unit (4 kt CO_2 captured/year) of Climeworks will be installed in Hellisheiði (Iceland) in 2021. Second, Norway is included since it presents a nearly optimal situation: Norway has clean grid electricity and has CO_2 storage potentials nearby (Anthonsen *et al.*, 2013). Further, Switzerland is considered as a region with longer transportation distances to CO_2 storage facilities (assumed to be 1500 km), and since a DAC unit of Climeworks is operating in Hinwil (Switzerland) with a relatively clean electricity mix and waste heat.

The autonomous DACCS configurations supplied with solar energy were limited to sites in five countries – Chile (CL), Greece (GR), Jordan (JO), Mexico (MX) and Spain (ES) – due to limited data availability for the Fresnel heat collectors. According to the manufacturer of these heat collectors, the system design and the corresponding inventory data are very specific for each location and should not be used for other locations applying simple scaling factors based on annual solar irradiation. These five countries are also included for the grid-coupled alternatives; hence, we also consider countries with CO_2 intensive grid electricity mixes (e.g. Greece and Mexico). Autonomous energy systems with solar heat and electricity require a high amount of annual solar irradiation for solar energy production, preferably with a direct normal irradiation (DNI) of more than 2000 kWh/m^2 year, especially for the concentrated thermal solar heat collectors (Kurup *et al.*, 2019). Hence, we present a map (see Figure S3) herein to explore other promising locations - with a DNI of more than 2000 kWh/m^2 year - for the installation of the autonomous energy system configurations. Figure S3 reveals that (especially) northern Mexico, south-west USA, middle Chile, northern Africa, south-west Africa, the Middle East and Australia are potentially promising locations for our proposed autonomous DACCS systems in terms of DNI, although a case-specific assessment is needed to determine their overall (environmental) performance.

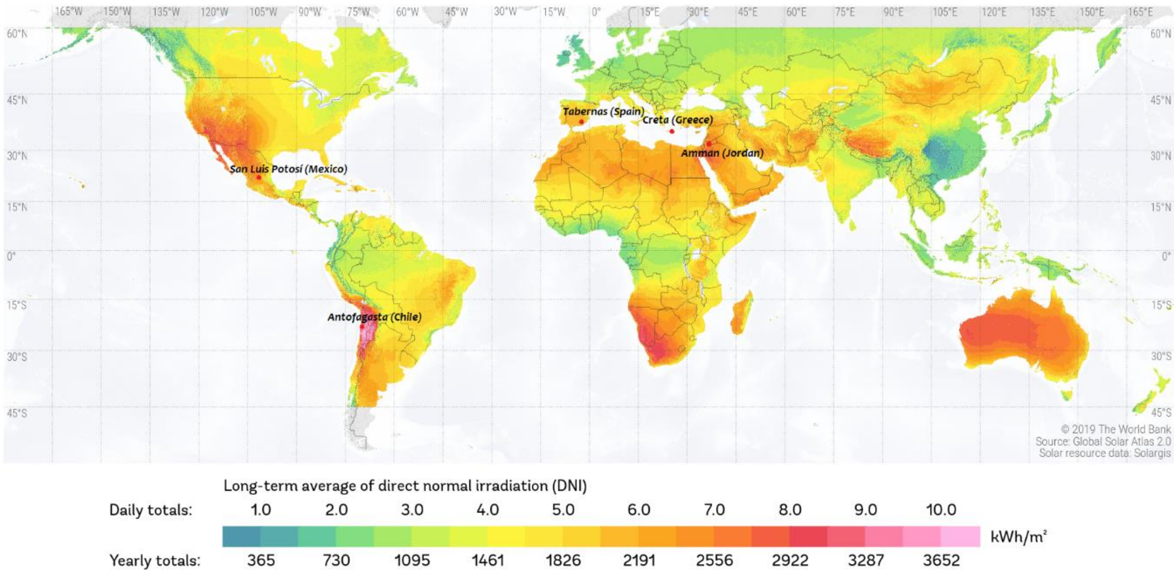


Figure S3. Geographical distribution of average direct normal irradiation (DNI). The map presents promising locations for autonomous DACCS energy systems with solar energy, i.e. with a DNI of more than 2000 kWh/m^2 year. This solar map is obtained from the "Global Solar Atlas 2.0",a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info. Copyright: © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis., under the CC BY 4.0 license (Solargis, 2020). *We added locations to this map as used in our LCA with a red pointer and their name.*

S3. Overview table of energy system layouts

Table S3 presents the sizing of different system layouts. Note that *Autonomous (Fresnel + PV)* has a bigger battery energy storage system and requires more PV electricity generation compared to *Waste heat + PV + Battery*, since the *Autonomous (Fresnel + PV)* layout requires a small additional portion of electricity needed for the system operation of the Fresnel solar collector.

Table S3. Overview of the sizing of system components per alternative.

		Autonomous (Fresnel + PV)	**Autonomous (HTHP + PV)**	**HTHP + Grid**	**Waste heat + Grid**	**Waste heat + PV + Battery**	**Unit**	**LCI Ref.**	**Lifetime considered (LT_x = lifetime component)**
Locations	Country	CL, ES, GR, JO, MX	CL, ES, GR, JO, MX	CH, CL, ES, GR, IS, JO, MX, NO	CH, CL, ES, GR, IS, JO, MX, NO	CL, ES, GR, JO, MX	Ecoinvent abb.	(Ecoinvent, 2020)	
Available DAC capacity	Size	100	100	100	100	100	[kt CO_2 captured/year]	Factsheet Climeworks (confidential) and Deutz, Bardow (Deutz and Bardow, 2021)	
	Lifetime	20	20	20	20	20	[years]	Factsheet Climeworks (confidential) and Deutz, Bardow (Deutz and Bardow, 2021)	n.a. (system lifetime)
Battery pack capacity	Size	125	221	0	0	120	[MWh electricity storage]	(Schmidt *et al.*, 2019)	
	Lifetime	12	12	n.a.	n.a.	12	[years]	(Schmidt *et al.*, 2019)	$20/LT_x$
Battery power unit (BoS)	Size	63	110	0	0	60	[MW power capacity]	(Schmidt *et al.*, 2019)	
	Lifetime	20	20	n.a.	n.a.	20	[years]	(Schmidt *et al.*, 2019)	$20/LT_x$
HTHP	Size	0	17	17	0	0	[MW]	Personal communication MAN Energy Solutions, (ecoinvent, 2020)	
	Lifetime	n.a.	20	20	n.a.	n.a.	[years]	(Ecoinvent, 2020)	$20/LT_x$
Heat storage	Size	~210	0	0	0	0	[MWh heat storage]	Personal communication Industrial Solar	
	Lifetime	25	n.a.	n.a.	n.a.	n.a.	[years]	Personal communication Industrial Solar	$20/LT_x$
Fresnel	Size	~77-108	0	0	0	0	[MW_p heat], Under reference conditions	Personal communication Industrial Solar	
	Lifetime	25	n.a.	n.a.	n.a.	n.a.	[years]	Personal communication Industrial Solar	n.a., Already considered in FU
PV system	Size	~37-75	~67-132	0	0	~36-72	[MW_p]	(Ecoinvent, 2020)	
	Lifetime	30	30	n.a.	n.a.	30	[years]	(Ecoinvent, 2020)	n.a., Already considered in FU

S4. Life cycle inventory: additional information Fresnel solar collector

The LCI of the fresnel solar collector is based on personal communication with Industrial Solar (Industrial Solar, 2021). This system is operated in Jordan, while performance data for all other locations are based on calculations provided by Industrial Solar. The Fresnel construction is largely made of low-alloyed steel and (for a smaller part) of stainless steel and aluminium. Industrial Solar offers commercial solar heat systems, such as the Fresnel solar collector LF-11 (Industrial Solar, 2021). Fresnel solar plants use reflective mirrors (made of glass) to concentrate solar irradiation on a solar collector. Water is pumped through the solar collector and is partly evaporated due to the concentration of solar irradiation.

Next, the resulting steam is stored as latent heat in a steam drum reservoir (Industrial Solar, 2021). We scale the heat storage tank, made of low-alloyed steel, to be able to store the amount of steam generated within 12 hours, since the Fresnel plant only produces solar-based heat during the day. The Fresnel plant is produced in Germany by Industrial Solar. Hence, transportation distances to other countries use Freiburg (Germany) as reference point and include freight transportation by lorries and ships. The latter transportation mode is only used when it is more efficient to reach a destination by ship. Further, we include business trips needed for the acquisition, negotiation, installation, trouble shooting and maintenance of the Fresnel plant. Dismantling of the Fresnel plant after the system lifetime is considered, with generic recycling, incineration or disposal activities from the ecoinvent database. A system lifetime of 25 years has been assumed. The efficiency of the Fresnel plant is obtained from modelling work of Industrial Solar. It varies between 40-47%, mainly influenced by - but not linearly linked to - the incoming direct normal irradiance. The functional unit used in the Fresnel LCA is 1 MJ of heat delivered, to be subsequently consumed in the CO_2 capture process of the DAC plant.

The operation of the Fresnel solar collector requires a small amount of electricity. Since Fresnel heat is used in stand-alone systems with a battery, the electricity consumption is compensated with a safety factor (divided by 89%, *i.e.* the roundtrip efficiency of the battery) to include potential electricity losses during a battery cycle (the battery life cycle inventory is attributed to the DACCS configuration). A small amount of electricity is required for the Fresnel heat collector and is assumed to be provided by PV electricity on rooftops representing installation on existing infrastructures, since the electricity requirement is very small. The total business trips are estimated on 51 trips.

The inventories are being shown in supplementary file **'lci-Fresnel.xlsx'**, such that they can be imported with the Brightway2 software easily. An activity is indicated in **bold** with its corresponding unit and location. Their exchanges can be found under the activity. Activities are separated by a blank row.

S5. LCI – DACCS alternatives and additional information

The life cycle inventories of all DACCS alternatives and some additional explanation about the LCI are provided in this section.

DAC plant

The DAC unit as such is the same for all configurations. Specific production and operation data of the DAC plant is based on industrial information provided by Climeworks (Zürich, Switzerland) and cannot be disclosed. However, in order to verify this information, we independently estimate the material requirements for the construction of the DAC unit based on public information. This verification, supplemented by a contribution analysis of life-cycle GHG emissions from the DAC unit construction broken down into contributions by main components is presented in Note S1 within this supplementary information (SI). We demonstrate similar life-cycle GHG emission resulting from our simplified, self-generated life cycle inventory and Climeworks' life cycle inventory. Furthermore, as our LCA results will show, the DAC infrastructure exhibits a small contribution to overall life-cycle GHG emissions and other environmental burdens per ton of gross CO_2 removal, which implies that the DAC infrastructure is less important - in terms of environmental impacts - compared to other processes within our system boundaries. Due to our independent verification and the comparatively low importance regarding LCA results, we consider using the detailed material inventory provided by Climeworks as legitimate, despite the fact that it cannot be disclosed.

We differentiate between two DAC units: a today's state-of-the art unit representing Climeworks' current technology (4 kt CO_2 captured per year), and a future design representing an upscale of their current standard DAC plant to capture 100 kt CO_2 per year. These two units mainly differ in terms of material intensity for construction and adsorbent consumption for CO_2 capture. Energy requirements for CO_2 capture are, however, identical for the two DAC units: 500 kWh per ton CO_2 captured for electricity (without electricity consumption for CO_2 compression) and 1500 kWh per ton CO_2 captured for heat (at around 100°C) (Deutz and Bardow, 2021). For comparison, a recent study of (Hanna *et al.*, 2021) used an energy consumption for DAC of 444 kWh electricity per ton CO_2 captured and 1333 kWh heat per ton CO_2 captured. As previous DACCS studies indicate that the energy consumption has a substantial influence on LCA results (de Jonge *et al.*, 2019; Deutz and Bardow, 2021), we present a detailed analysis of different energy sources used for CO_2 capture, and consider a reduction of electricity consumption to examine the effect on the climate change impacts.

The analysis in the main body of this article represents the upscaled near-future DAC unit, since we expect this upscaling to take place before any large-scale roll-out. To show the consequences of expected technology developments, LCA results for the current DAC unit are shown for comparison in Note S1 of this SI. In our paper, we analyse a DAC plant with an annual gross carbon capture capacity of 100 kt CO_2 and a system lifetime of 20 years (Deutz & Bardow, 2020). Note '*gross*', since GHG emissions from all upstream and downstream activities, generated from the entire DACCS life-cycle, are not included in this figure which inevitably leads to less than 100 kt annual net CO_2 removal from the atmosphere.

The low temperature DAC technology of Climeworks uses a cellulose-based solid sorbent functionalized with amines (Fasihi, Efimova and Breyer, 2019). (Deutz and Bardow, 2021) present an overview and environmental assessment of different sorbents potentially used for the CO_2 capture process of Climeworks. They show small environmental impacts in absolute terms associated with adsorbent consumption. Therefore, we consider a generic proxy for the adsorbent, 'market for chemical, organic'. Further, we assume that the production of DAC components and related engineering work is conducted in Switzerland.

Business trips

We consider environmental impacts of business trips for acquisition, negotiation, installation, trouble shooting and maintenance of the DAC plant by Climeworks engineers. Business flights are estimated based on 100 trips required during the system lifetime of the DAC plant: 40 trips for maintenance, 5 trips for trouble shooting, 45 for installation assistance and 10 trips for acquisition. Further, we assume that the collector, process unit and spare parts are produced in Switzerland and are transported to the DACCS location with freight transport (by ship and lorry).

Dismantling

Dismantling of the DAC plant is included. All main materials for the collector and process unit (*e.g.* steel, plastics, copper and aluminium) are assumed to be treated after the system lifetime of 20 years.

Geological storage of CO_2

After the CO_2 is captured, the CO_2 needs to be compressed from ~1 bar to 110 bar by consuming locally available electricity, which is in our alternatives provided by the electricity grid or PV installations. We assume that CO_2 is transported with pipelines at 110 bar to the injection wells, due to the high capacity needed for large-scale CO_2capture. For simplicity, 80 bar is assumed as pressure at the pipeline end for each configuration (Volkart, Bauer and Boulet, 2013). Additional compression of CO_2 is included when the transportation distance is larger than 200 kilometers to compensate for a pressure drop of CO_2 (Volkart, Bauer and Boulet, 2013). We consider CO_2 leakage from CO_2 transmission pipelines using baseline (*i.e.* Medium) emission factors according to an IPCC report (Holloway *et al.*, 2006), hence we update the LCI of (Volkart, Bauer and Boulet,

2013) accordingly. After that, the CO_2 is injected into wells - using the country-specific electricity mix - to store the CO_2 in suitable geological formations, which is considered to exhibit the highest CO_2 storage potential, hence we focus on these (Volkart, Bauer and Boulet, 2013). We use the LCI from (Volkart, Bauer and Boulet, 2013) for the infrastructure requirements for transportation, (re)compression and drilling of wells. We parameterize this inventory to generate location specific environmental impacts of CO_2 storage, based on the specific transportation distance for CO_2 storage in a country. We assess the feasibility of geological CO_2 storage based on a geological storage map developed by the Global CCS Institute (Global CCS Institute, 2011). Based on this map, we estimate transportation distances to potential CO_2 injection wells in the same or other countries. We categorize our selected countries into short (100 km for Norway, Iceland and Jordan), moderate (500 km for Greece and Spain) and long distances (1500 km for Chile, Mexico and Switzerland) for pipeline transportation of CO_2 to the storage and injection wells. A key advantage of DACCS solutions compared to other CDR options is the location independence of the capture step due to the ubiquitous availability of air as the primary feedstock. Hence, DACCS offers the potential to avoid CO_2 transport by building DAC plants at available storage sites. The proposed transport distances can therefore be seen as maximum reasonable suggestions for the corresponding countries. For simplicity, we assume a generic CO_2 storage depth of 2000 meters for each country, since (Volkart, Bauer and Boulet, 2013) have shown that this depth hardly affects LCA results. CO_2 leakage from injection wells is assumed to be negligible (Alcalde *et al.*, 2018; Kelemen *et al.*, 2019).

The activities 'pipeline, supercritical CO2/km' and 'market for gas turbine, 10MW electrical' (Volkart, Bauer and Boulet, 2013) were initially based on a mass flow quantified by Wildbolz et al.(Wildbolz, 2007) of 250 kg CO_2/s. The same applies for the drilling of boreholes 'drilling, deep borehole/m' (injection rate of 125 kg/s (Wildbolz, 2007)). For simplicity, we linearly scale these life cycle inventories down to represent our mass flow, by multiplying it with a mass flow ratio (Volkart, Bauer and Boulet, 2013). The latter life cycle inventory is presented in supplementary file '**lci-CS.xlsx**'.

Further, we calculate the electricity requirement for injection (for a storage depth of 2000 meter: 24 kWh/t CO_2 captured) and compression (114 kWh/t CO_2 captured, with compression units with a lifetime of 10 years) using an equation presented in (Hendriks, Chris; Wina, Graus; and Bergen V., 2004). Note that a compensation factor for CO_2 compression electricity at the DAC unit - division by 89%, *i.e.* the roundtrip efficiency of the battery - is applied for electricity requirements in DACCS configurations with battery deployment, to compensate for losses during battery cycles. Full life cycle inventory per system layout is provided in supplementary file '**lci-daccs_activities.xlsx**'. The exchange 'Carbon dioxide, fossil' refers to losses of CO_2 during transportation in pipelines. Further, detailed LCI of the 'carbon dioxide capture system' and 'end of life, carbon dioxide capture system' activities cannot be provided due to confidential LCI information of Climeworks, although Climeworks expects to publish their LCI in the near future (a simplified calculation to verify the Climeworks inventory has been provided in Note S1 of this SI).

Sorbent

Adsorbent consumption is expected to decrease from 7.5 to 3.0 kg adsorbent per ton CO_2 captured, based on Climework's analysis and future targets for sorbent consumption (Deutz and Bardow, 2021). The data proxy 'sorbent, generic' refers to the following dataset:

*Table S4. Life cycle inventory of sorbent. The inventories are being shown such that they can be imported with the Brightway2 software easily. An activity is indicated in **bold** with its corresponding unit and location in column 4 and 6, respectively.*

sorbent, generic			kilogram		RER	
Name	**Reference Product**	**Amount**	**Unit**	**Categories**	**Location**	**Type**
market for chemical, organic	chemical, organic	1.00E+00	kilogram		GLO	technosphere
treatment of spent anion exchange resin from potable water production, municipal incineration	spent anion exchange resin from potable water production	-1.00E+00	kilogram		RoW	technosphere

PV electricity

For PV-coupled system layouts, we assume that PV electricity is produced with large ground mounted PV installations: 'electricity production, photovoltaic, 570kWp open ground installation, multi-Si'. For Chile, Greece and Jordan there is no such country-specific PV electricity data available in the ecoinvent 3.6 database. Hence, we create new activities based on the annual kWh yield per kWp panel installed, which are assumed to be 1906 kWh/kWp, 1617 kWh/kWp and 1884 kWh/kWp for Chile (Antofagasto), Greece (Creta) and Jordan (Amman), respectively (ESMAP *et al.*, 2020).

Multiple exchanges of 'market for electricity, low voltage' can occur for DACCS configurations, such identical exchanges are required for capture (electricity and heat pump), compression as well as the injection of CO_2. Land use for the injection wells is not considered, since it is assumed that their corresponding land use is minor as well as they could be situated in marine areas.

Life cycle inventory for the production of pipelines, drilling of boreholes and the transportation of CO_2, are provided in supplementary file '**lci-CS.xlsx**'. CO_2 losses during transportation with pipelines are considered separately, as described in this Note S5 of the SI. The inventories are being shown such that they can be imported with the Brightway2 software easily. An activity is indicated in **bold** with its corresponding unit and location. Their exchanges can be found under the activity. Activities are separated by a blank row.

Life cycle inventory of all configurations is provided in supplementary file '**lci-daccs_activities.xlsx**'. Again, the inventories are being shown such that they can be imported with the Brightway2 software easily. An activity is indicated in **bold** with its corresponding unit and location. Their exchanges can be found under the activity. Activities are separated by a blank row.

S6. LCA results: all environmental impact categories

Table S5 presents the full results for all system layouts on all environmental impact categories. **Red** shaded cells represent a high environmental impact for the specific environmental impact category compared to other system layouts, **light blue** means an average environmental impact for the specific environmental impact category compared to other system layouts, while **dark blue** means a low environmental impact for the specific environmental impact category compared to other system layouts.

Table S5. LCA results for all environmental impact categories for all DACCS alternatives per functional unit: "Gross removal of 1 ton CO_2 from the atmosphere".

	Land transformation	carcinogenic effects	climate change total	fossils	freshwater and terrestrial acidification	freshwater ecotoxicity	freshwater eutrophication	ionising radiation	land use	marine eutrophication	minerals and metals	non-carcinogenic effects	ozone layer depletion	photochemical ozone creation	respiratory effects, inorganics	terrestrial eutrophication	water consumption
Unit	m^2	CTUh	kg CO_2-Eq.	megajoule	mol H+-Eq.	CTU	kg P-Eq.	kg U235-Eq.	points	kg N-Eq.	kg Sb-Eq.	CTUh	kg CFC-11.	kg NMVOC-.	disease i.	mol N-Eq.	m^3-eq.
Autonomous Fresnel + PV, CL	7.16E-01	6.03E-06	1.25E+02	1.69E+03	9.29E-01	1.57E+02	7.40E-02	1.75E+01	4.24E+03	1.30E-01	1.09E-02	3.72E-05	9.61E-06	4.24E-01	6.38E-06	1.36E+00	2.30E+00
Autonomous Fresnel + PV, ES	9.66E-01	6.34E-06	1.09E+02	1.64E+03	9.46E-01	1.72E+02	6.94E-02	1.49E+01	6.23E+03	1.24E-01	1.38E-02	4.05E-05	9.36E-06	4.25E-01	6.50E-06	1.30E+00	2.06E+00
Autonomous Fresnel + PV, GR	7.51E-01	5.99E-06	1.08E+02	1.56E+03	9.21E-01	1.61E+02	9.99E-02	8.84E+00	4.71E+03	1.18E-01	1.19E-02	3.77E-05	8.91E-06	3.84E-01	5.81E-06	1.17E+00	1.72E+00
Autonomous Fresnel + PV, JO	6.43E-01	5.03E-06	8.71E+01	1.30E+03	7.68E-01	1.39E+02	5.05E-02	5.21E+00	4.04E+03	9.50E-02	1.08E-02	3.24E-05	7.50E-06	3.35E-01	4.96E-06	1.02E+00	1.36E+00
Autonomous Fresnel + PV, MX	1.19E+00	7.73E-06	1.62E+02	2.30E+03	1.13E+00	2.02E+02	1.02E-01	2.39E+01	7.67E+03	1.68E-01	1.56E-02	4.73E-05	1.29E-05	5.47E-01	8.09E-06	1.72E+00	2.72E+00
Autonomous HTHP + PV, CL	1.03E+00	6.01E-06	1.48E+02	2.05E+03	1.29E+00	2.03E+02	1.01E-01	1.99E+01	6.79E+03	1.54E-01	1.75E-02	5.21E-05	1.15E-05	5.15E-01	7.86E-06	1.60E+00	3.04E+00
Autonomous HTHP + PV, ES	1.50E+00	6.46E-06	1.47E+02	2.20E+03	1.42E+00	2.31E+02	1.04E-01	1.85E+01	1.04E+04	1.72E-01	2.24E-02	5.90E-05	1.30E-05	5.88E-01	8.71E-06	1.78E+00	3.22E+00
Autonomous HTHP + PV, GR	1.11E+00	5.73E-06	1.36E+02	1.99E+03	1.32E+00	2.08E+02	1.29E-01	1.16E+01	7.67E+03	1.52E-01	1.88E-02	5.31E-05	1.16E-05	5.03E-01	7.42E-06	1.50E+00	2.57E+00
Autonomous HTHP + PV, JO	9.51E-01	4.79E-06	1.11E+02	1.67E+03	1.14E+00	1.84E+02	7.78E-02	7.67E+00	6.57E+03	1.23E-01	1.74E-02	4.71E-05	9.72E-06	4.37E-01	6.41E-06	1.30E+00	2.11E+00
Autonomous HTHP + PV, MX	1.87E+00	8.17E-06	2.06E+02	2.95E+03	1.63E+00	2.73E+02	1.42E-01	2.81E+01	1.29E+04	2.17E-01	2.56E-02	6.85E-05	1.68E-05	7.19E-01	1.09E-05	2.20E+00	4.16E+00
HTHP + Grid, CH	5.64E-01	7.21E-06	1.86E+02	6.55E+03	1.02E+00	1.58E+02	1.54E-01	2.81E+02	3.69E+03	1.83E-01	3.01E-03	4.25E-05	2.70E-05	4.72E-01	5.89E-06	1.89E+00	1.28E+01
HTHP + Grid, CL	3.77E-01	1.00E-05	7.43E+02	1.11E+04	6.02E+00	3.00E+02	5.30E-01	1.79E+01	1.87E+03	1.36E+00	3.50E-03	7.41E-05	2.60E-05	3.59E+00	3.67E-05	1.41E+01	2.48E+00
HTHP + Grid, ES	6.17E-01	8.07E-06	4.20E+02	1.04E+04	3.59E+00	2.17E+02	1.74E-01	2.77E+02	3.70E+03	5.63E-01	3.52E-03	6.42E-05	4.39E-05	1.58E+00	1.00E-05	5.84E+00	4.25E+00
HTHP + Grid, GR	2.45E-01	1.76E-05	9.14E+02	1.51E+04	5.79E+00	5.73E+02	1.96E+00	3.55E+01	9.62E+02	8.51E-01	4.21E-03	1.24E-04	8.08E-05	1.63E+00	1.77E-05	5.05E+00	5.60E+00

	Land transformation	carcinogenic effects	climate change total	fossils	freshwater and terrestrial acidification	freshwater ecotoxicity	freshwater eutrophication	ionising radiation	land use	marine eutrophication	minerals and metals	non-carcinogenic effects	ozone layer depletion	photochemical ozone creation	respiratory effects, inorganics	terrestrial eutrophication	water consumption
Unit	m^2	CTUh	kg CO_2-Eq.	megajoule	mol H+-Eq.	CTU	kg P-Eq.	kg U235-Eq.	points	kg N-Eq.	kg Sb-Eq.	CTUh	kg CFC-11.	kg NMVOC-.	disease i.	mol N-Eq.	m^3-eq.
HTHP + Grid, IS	2.60E-01	5.91E-06	8.26E+01	4.52E+02	2.84E-01	1.19E+02	2.65E-02	1.67E+00	2.48E+02	3.84E-02	2.36E-03	1.95E-05	2.22E-06	1.48E-01	2.52E-06	4.32E-01	2.68E+01
HTHP + Grid, JO	2.17E-01	5.95E-06	7.22E+02	1.20E+04	1.77E+00	2.03E+02	3.38E-02	8.76E+00	6.04E+02	3.59E-01	3.14E-03	2.57E-05	5.65E-05	1.13E+00	1.12E-05	3.81E+00	1.66E+00
HTHP + Grid, MX	2.51E-01	9.34E-06	8.31E+02	1.23E+04	3.96E+00	4.20E+02	3.93E-01	8.93E+01	8.77E+02	6.34E-01	3.29E-03	5.33E-05	6.97E-05	1.82E+00	1.89E-05	6.05E+00	2.20E+00
HTHP + Grid, NO	1.50E-01	5.33E-06	4.66E+01	6.87E+02	2.99E-01	1.03E+02	2.98E-02	1.47E+01	7.04E+02	4.21E-02	2.35E-03	1.93E-05	2.99E-06	1.46E-01	2.48E-06	4.77E-01	3.62E+01
Waste heat + Grid, CH	3.44E-01	5.21E-06	1.32E+02	3.94E+03	6.62E-01	1.07E+02	9.94E-02	1.58E+02	2.17E+03	1.27E-01	1.83E-03	2.70E-05	1.64E-05	3.35E-01	4.21E-06	1.29E+00	7.63E+00
Waste heat + Grid, CL	2.59E-01	6.91E-06	4.37E+02	6.45E+03	3.40E+00	1.89E+02	3.06E-01	1.57E+01	1.20E+03	7.69E-01	2.13E-03	4.53E-05	1.62E-05	2.04E+00	2.12E-05	7.98E+00	1.88E+00
Waste heat + Grid, ES	3.55E-01	5.15E-06	2.45E+02	5.90E+03	2.03E+00	1.30E+02	1.00E-01	1.55E+02	2.10E+03	3.21E-01	2.04E-03	3.68E-05	2.50E-05	9.10E-01	6.05E-06	3.33E+00	2.48E+00
Waste heat + Grid, GR	1.51E-01	1.07E-05	5.20E+02	8.56E+03	3.26E+00	3.34E+02	1.09E+00	2.11E+01	6.07E+02	4.88E-01	2.46E-03	7.13E-05	4.56E-05	9.53E-01	1.04E-05	2.96E+00	3.23E+00
Waste heat + Grid, IS	1.53E-01	4.09E-06	5.56E+01	3.83E+02	2.00E-01	8.04E+01	2.19E-02	1.23E+00	1.85E+02	3.61E-02	1.41E-03	1.32E-05	1.90E-06	1.25E-01	1.90E-06	3.75E-01	1.49E+01
Waste heat + Grid, JO	1.29E-01	4.11E-06	4.09E+02	6.79E+03	1.02E+00	1.27E+02	2.59E-02	5.14E+00	3.82E+02	2.13E-01	1.84E-03	1.67E-05	3.19E-05	6.68E-01	6.70E-06	2.24E+00	1.00E+00
Waste heat + Grid, MX	1.79E-01	6.55E-06	4.89E+02	7.17E+03	2.28E+00	2.55E+02	2.37E-01	5.63E+01	6.75E+02	3.78E-01	2.02E-03	3.40E-05	4.01E-05	1.08E+00	1.14E-05	3.60E+00	1.53E+00
Waste heat + Grid, NO	8.97E-02	3.48E-06	3.37E+01	4.96E+02	1.92E-01	6.45E+01	1.78E-02	8.38E+00	4.23E+02	2.99E-02	1.37E-03	1.15E-05	2.13E-06	1.07E-01	1.73E-06	3.31E-01	2.01E+01
Waste heat + PV + Battery, CL	6.16E-01	4.72E-06	1.14E+02	1.53E+03	8.32E-01	1.36E+02	7.35E-02	1.68E+01	3.88E+03	1.16E-01	9.72E-03	3.33E-05	8.30E-06	3.70E-01	5.56E-06	1.18E+00	2.18E+00
Waste heat + PV + Battery, ES	8.33E-01	4.27E-06	9.71E+01	1.47E+03	8.47E-01	1.38E+02	6.18E-02	1.42E+01	5.73E+03	1.09E-01	1.23E-02	3.40E-05	8.22E-06	3.70E-01	5.33E-06	1.12E+00	1.92E+00
Waste heat + PV + Battery, GR	6.23E-01	4.26E-06	9.77E+01	1.42E+03	8.31E-01	1.36E+02	9.82E-02	8.17E+00	4.25E+03	1.09E-01	1.04E-02	3.30E-05	8.04E-06	3.41E-01	4.84E-06	1.04E+00	1.59E+00
Waste heat + PV + Battery, JO	5.28E-01	3.49E-06	7.74E+01	1.16E+03	6.81E-01	1.16E+02	4.97E-02	4.55E+00	3.62E+03	8.52E-02	9.57E-03	2.83E-05	6.49E-06	2.91E-01	4.10E-06	8.77E-01	1.25E+00
Waste heat + PV + Battery, MX	1.06E+00	5.92E-06	1.50E+02	2.11E+03	1.02E+00	1.75E+02	1.01E-01	2.30E+01	7.18E+03	1.51E-01	1.41E-02	4.23E-05	1.14E-05	4.83E-01	7.06E-06	1.51E+00	2.60E+00

Visualization in spider graphs

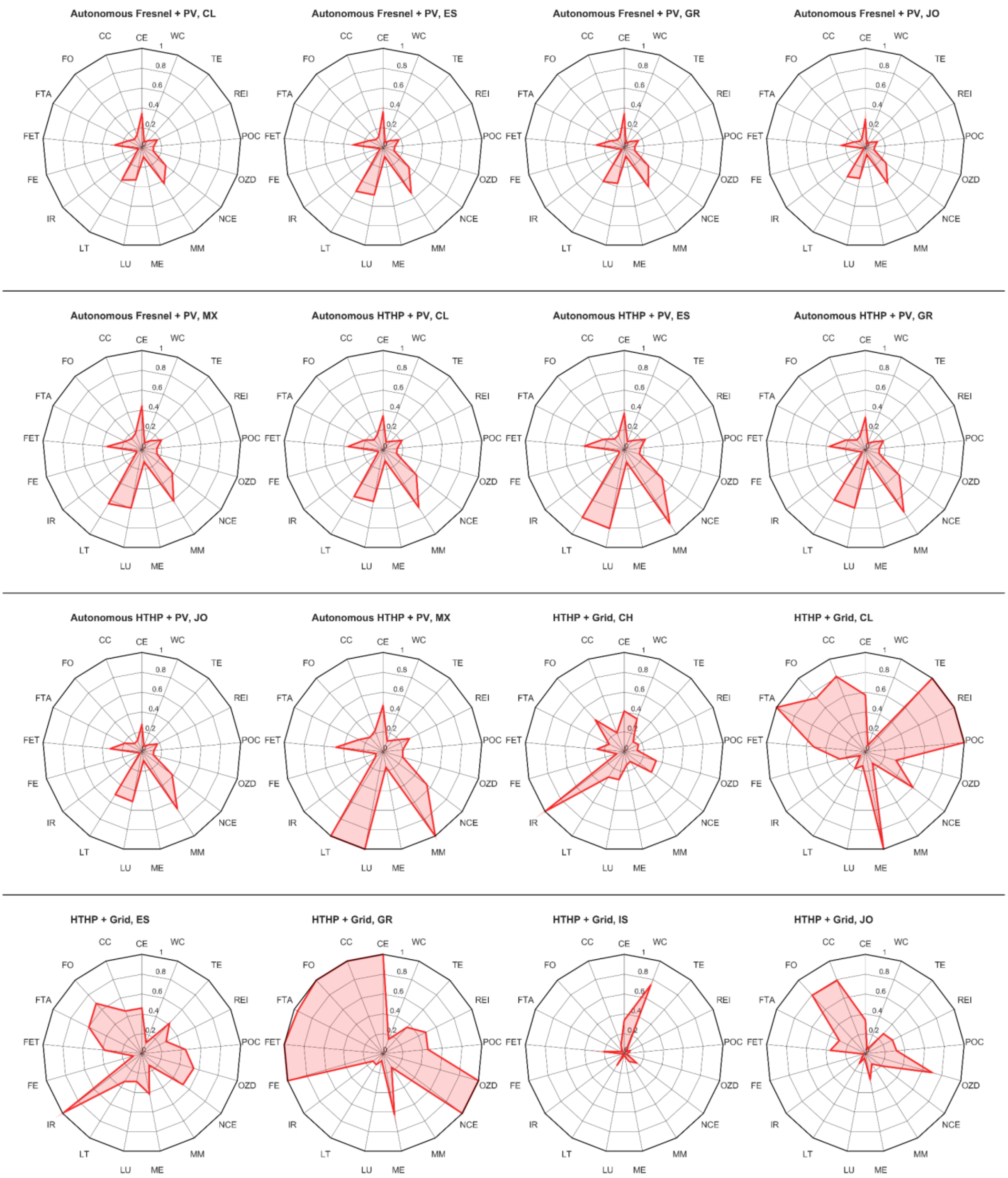
Spider graphs for all DACCS system configurations on all environmental impact categories are presented in Figure S4. The environmental impacts per category are normalized to the maximum score – on an environmental impact category - of the considered DACCS configurations. The maximum scores of environmental impact categories can be found in Table S6 as well as in Table S5 with the **red** values.

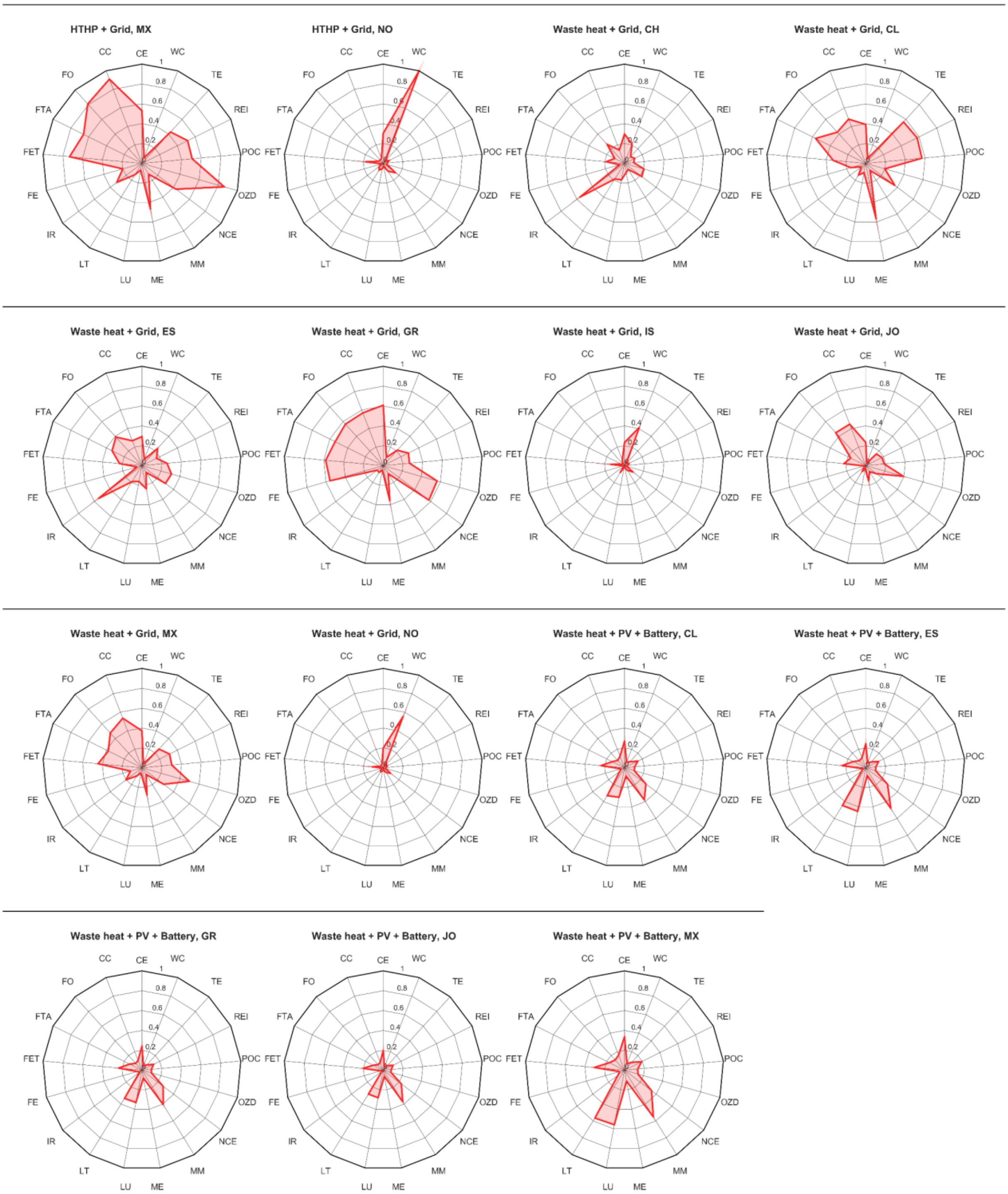
Table S6. Maximum environmental impacts - per ton of gross CO_2 removal with the DAC plant - used in Figure 4 in the main body of the text and Figure S4 in this SI, i.e. representing a normalized impact of '1'.

Category	**Maximum environmental impact value**	**Unit**
Land transformation	1.87E+00	m^2
carcinogenic effects	1.76E-05	CTUh
climate change total	9.14E+02	kg CO_2-Eq.
fossils	1.51E+04	megajoule
freshwater and terrestrial acidification	6.02E+00	mol H+-Eq.
freshwater ecotoxicity	5.73E+02	CTU
freshwater eutrophication	1.96E+00	kg P-Eq.
ionising radiation	2.81E+02	kg U235-Eq.
land use	1.29E+04	points
marine eutrophication	1.36E+00	kg N-Eq.
minerals and metals	2.56E-02	kg Sb-Eq.
non-carcinogenic effects	1.24E-04	CTUh
ozone layer depletion	8.08E-05	kg CFC-11.
photochemical ozone creation	3.59E+00	kg NMVOC-.
respiratory effects, inorganics	3.67E-05	disease i.
terrestrial eutrophication	1.41E+01	mol N-Eq.
water consumption	3.62E+01	m^3-eq.

Figure S4. Spider graphs illustrating environmental trade-offs of DACCS systems configurations on all environmental impact categories. CE = Carcinogenic Effects, CC = Climate Change Total, FO = Fossils, FTA = Freshwater And Terrestrial Acidification, FET = Freshwater Ecotoxicity, FE = Freshwater Eutrophication, IR = Ionising Radiation, LT = Land Transformation, LU = Land Use, ME = Marine Eutrophication, MM = Minerals

And Metals, NCE = Non-Carcinogenic Effects, OZD = Ozone Layer Depletion, POC = Photochemical Ozone Creation, REI = Respiratory Effects; Inorganics, TE = Terrestrial Eutrophication, WC = Water Consumption.




HTHP + Grid, MX
HTHP + Grid, NO
Waste heat + Grid, CH
Waste heat + Grid, CL
Waste heat + Grid, ES
Waste heat + Grid, GR
Waste heat + Grid, IS
Waste heat + Grid, JO
Waste heat + Grid, MX
Waste heat + Grid, NO
Waste heat + PV + Battery, CL
Waste heat + PV + Battery, ES
Waste heat + PV + Battery, GR
Waste heat + PV + Battery, JO
Waste heat + PV + Battery, MX
CC
CE
WC
TE
REI
POC
OZD
NCE
MM
ME
LU
LT
IR
FE
FET
FTA
FO
1
0.8
0.6
0.4
0.2

S7. LCA results for land transformation

Figure S5 shows the results on land transformation for each DACCS configuration considered in the main analysis. We aggregate all life cycle inventory flows containing "*Transformation, from..*" within this analysis in order to represent land use. The stacked bars labeled with "direct" represent direct land use at the DAC site: area occupied by the DAC unit itself, by solar PV and solar heat installations, and by energy storage units, while the stacked bars labeled with "life-cycle" represent overall land use including indirect contributions.

Autonomous energy systems exhibit large land transformation, mainly due to the installation of PV panels (on the ground) and the Fresnel heat collector with large surface area requirements, while the DAC unit as separate system has very low land transformation impacts. In reality, direct land transformation is also generated from the installation of pipelines, but are excluded in the direct land transformation impacts of Figure S5, since land is not directly transformed at the DAC location. Therefore, the main indirect contribution originates from land use of pipelines, and scales with CO_2 transportation distance.

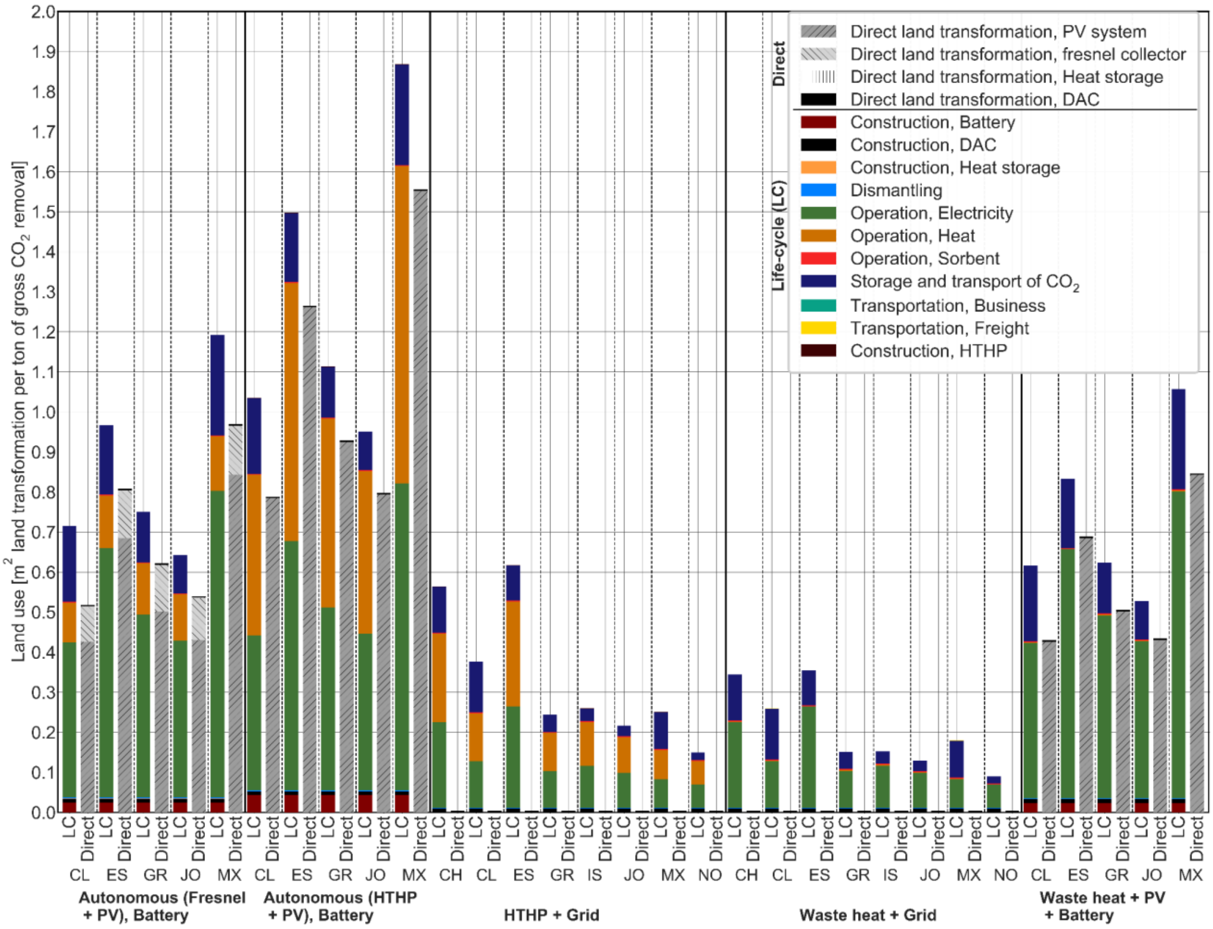


Figure S5. Land transformation results for all considered DACCS configurations and countries of our main analysis. For each country, the total life-cycle land transformation (including indirect land transformation) is represented by the colored stacked bars. The direct land use transformation at the DAC site for the main system components is represented by the black-grey-white colored bars: PV system, fresnel collector, heat storage and the DAC unit. LC = Life-Cycle, CL = Chile, ES = Spain, GR = Greece, JO = Jordan, MX = Mexico, CH = Switzerland, IS = Iceland and NO = Norway.

S8. Sensitivity analysis: Reduced electricity consumption for CO_2 capture

Figure S6 shows the sensitivity analysis regarding electricity consumption of the DAC unit and the effects on life-cycle GHG emissions per ton of CO_2 captured.

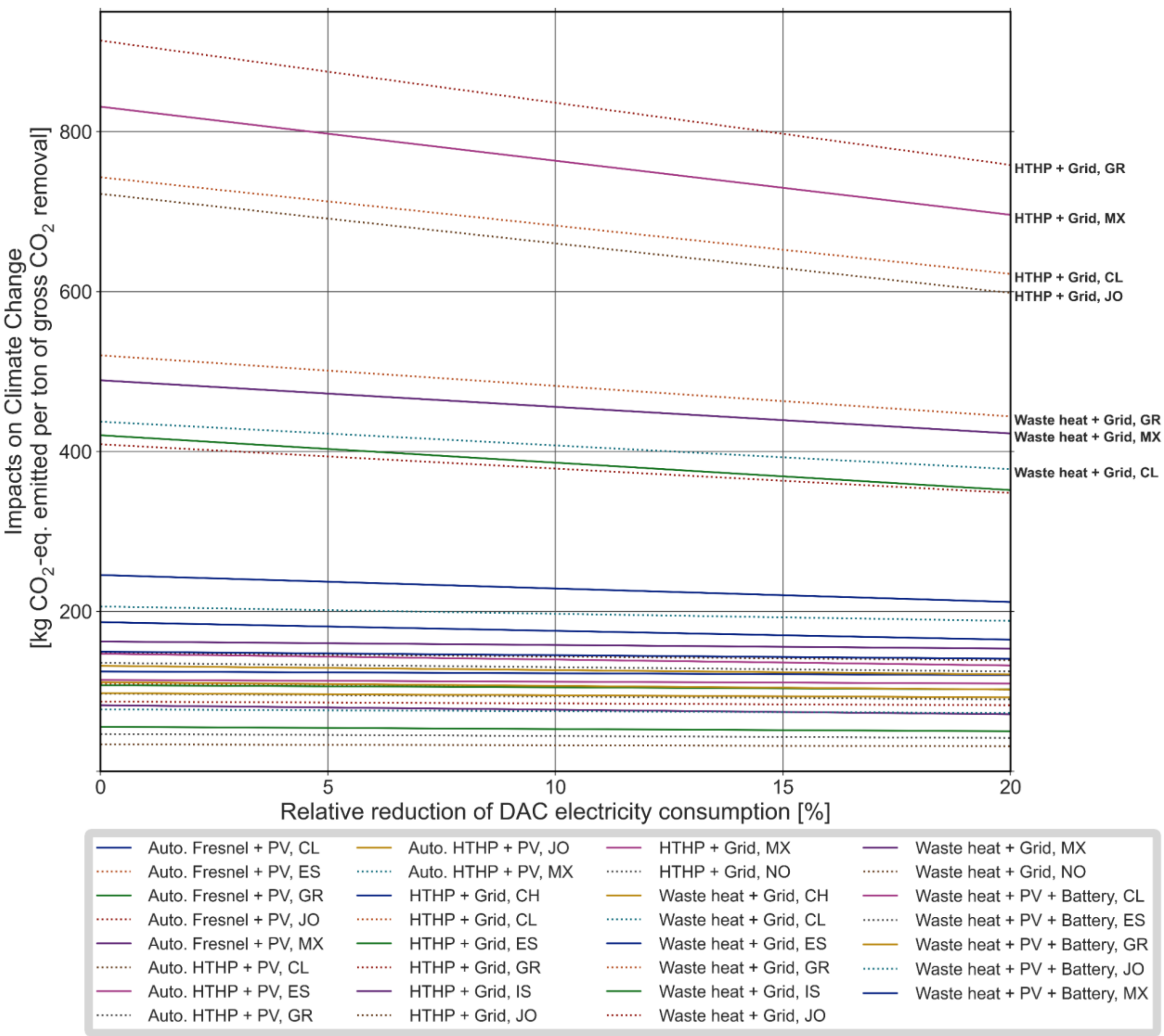


Figure S6. Sensitivity analysis on the Climate Change impact category with a reduction of electricity consumption for CO_2 capture.

S9. Ecoinvent 3.6 datasets used for Figure 3.

Table S7 shows ecoinvent datasets used – represented on the x-axis – in Figure 3 of the main article.

Table S7. Ecoinvent 3.6 datasets used on the x-axis - representing the Climate Change impacts of electricity datasets - in Figure 3 of the main article.

Electricity dataset in Figure 3	**ecoinvent reference product | name | location | unit |database**
Wind	electricity, high voltage | electricity production, wind, >3MW turbine, onshore | RoW | kilowatt hour | cutoff 36 **[50%]** electricity, high voltage | electricity production, wind, 1-3MW turbine, offshore | RoW | kilowatt hour | cutoff 36 **[50%]**
Iceland	electricity, low voltage | market for electricity, low voltage | IS | kilowatt hour | cutoff 36
Photovoltaics	electricity, low voltage | electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | ES | kilowatt hour | cutoff 36
Switzerland	electricity, low voltage | market for electricity, low voltage | CH | kilowatt hour | cutoff 36
Denmark	electricity, low voltage | market for electricity, low voltage | DK | kilowatt hour | cutoff 36
United Kingdom	electricity, low voltage | market for electricity, low voltage | GB | kilowatt hour | cutoff 36
Europe [ENTSO-E]	electricity, low voltage | market group for electricity, low voltage | ENTSO-E | kilowatt hour | cutoff 36
Natural gas	electricity, high voltage | electricity production, natural gas, combined cycle power plant | RoW | kilowatt hour | cutoff 36
Germany	electricity, low voltage | market for electricity, low voltage | DE | kilowatt hour | cutoff 36
World	electricity, low voltage | market group for electricity, low voltage | GLO | kilowatt hour | cutoff 36
Oil	electricity, high voltage | electricity production, oil | RoW | kilowatt hour | cutoff 36

S10. Contribution analysis: other environmental impact categories

Additional figures are presented in this SI Note - Figure S7-S10 - to show the contribution analysis of environmental impact categories besides climate change and land transformation. These contribution analyses demonstrate that green (electricity) and orange (heat) colors drive the results for all environmental impact categories, and therefore renewable electricity and an improved design of heat consumption as well as heat and electricity storage mediums are highly recommended.

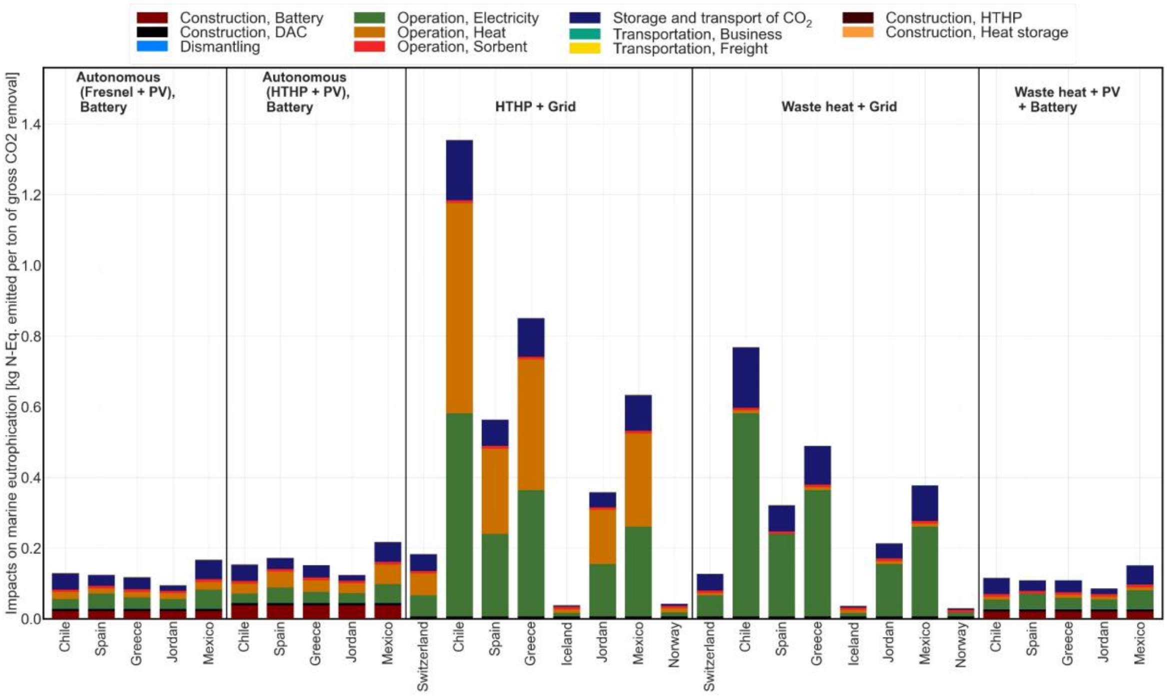


Figure S7. Contribution analysis of Marine Eutrophication.

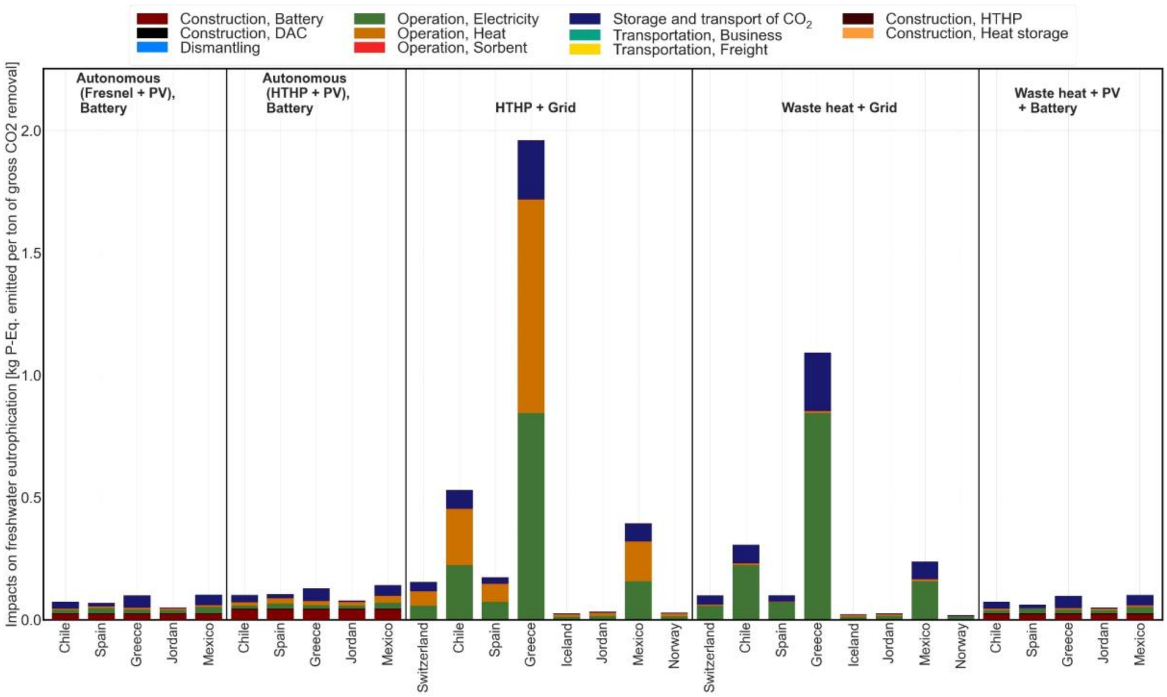


Figure S8. Contribution analysis of Freshwater Eutrophication.

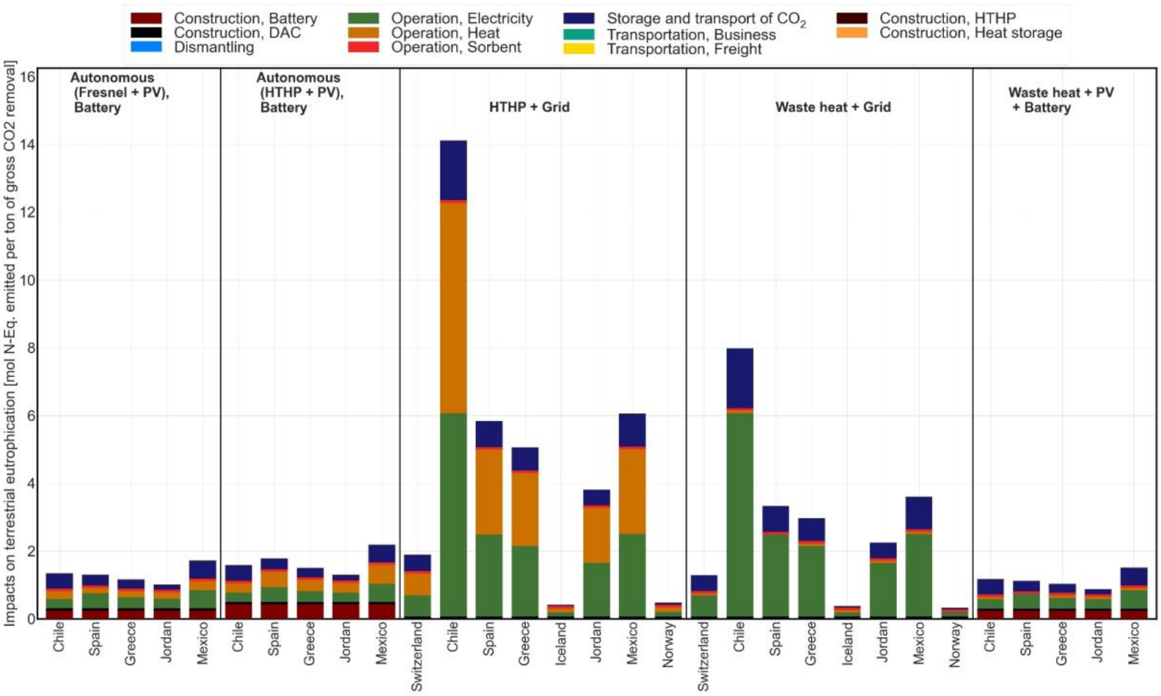


Figure S9. Contribution analysis of Terrestrial Eutrophication.

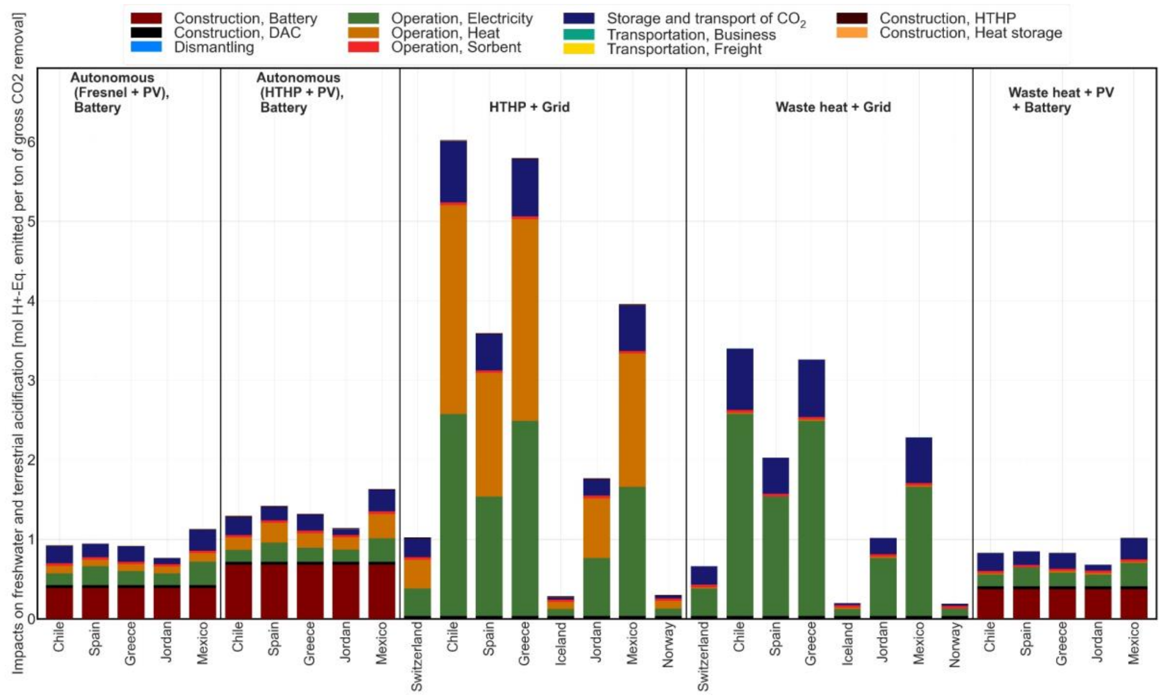


Figure S10. Contribution analysis of Freshwater and Terrestrial Acidification.

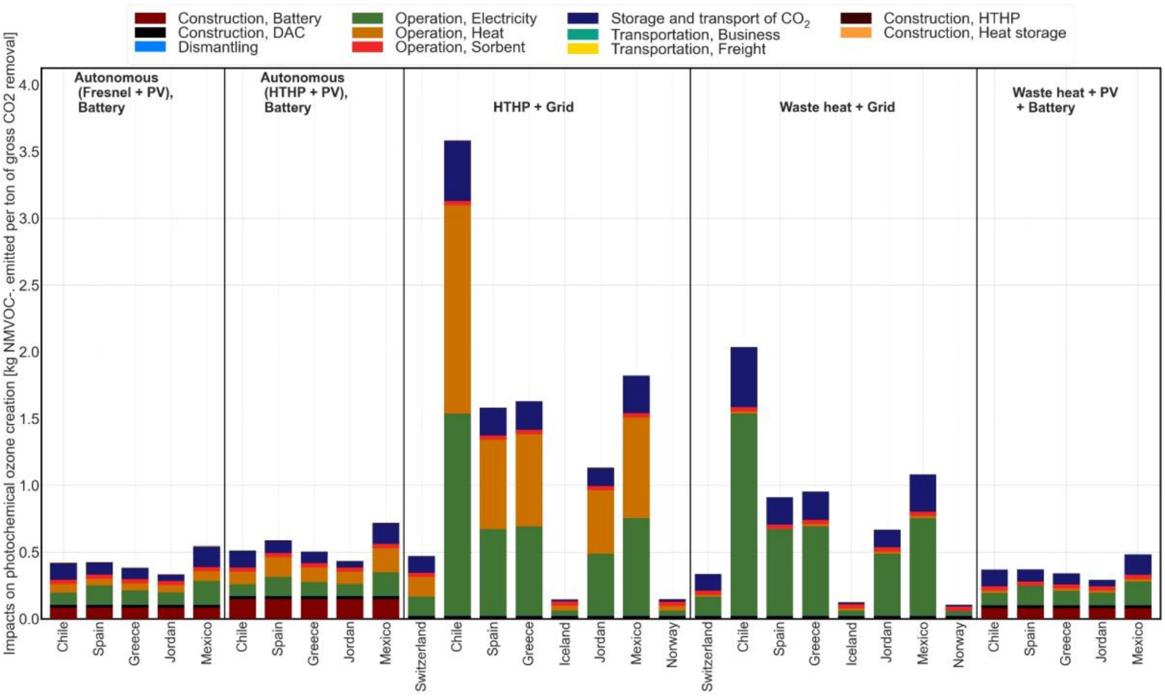


Figure S11. Contribution analysis of Photochemical Ozone Creation.

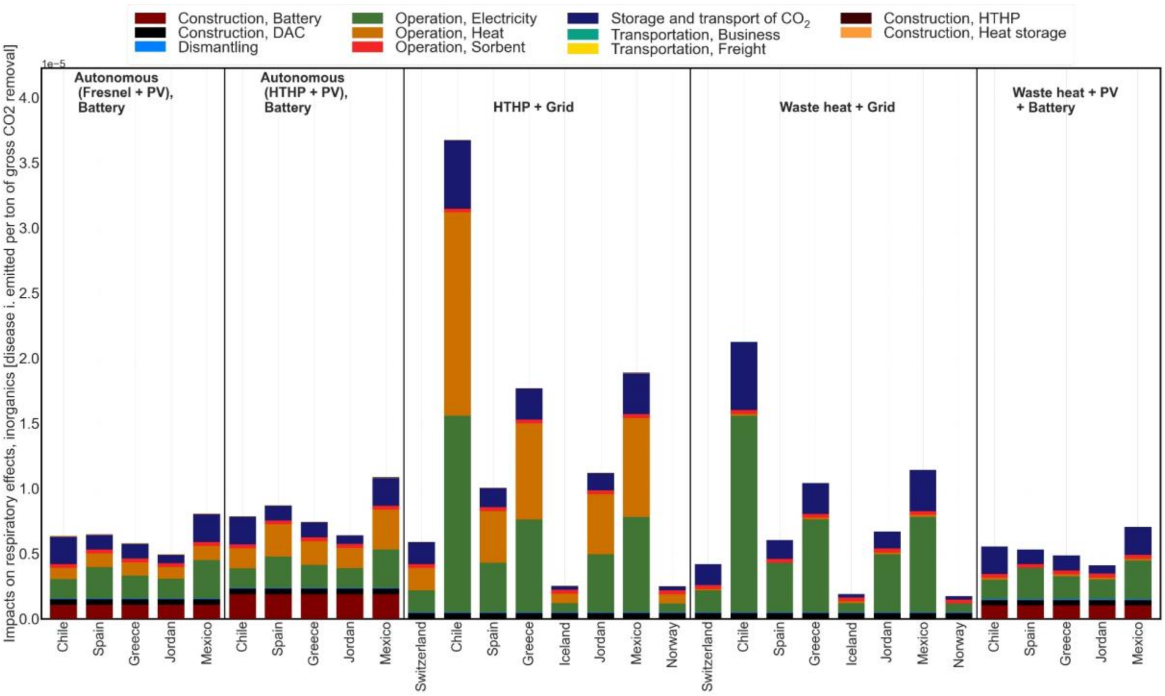


Figure S12. Contribution analysis of Respiratory Effects, Inorganics.

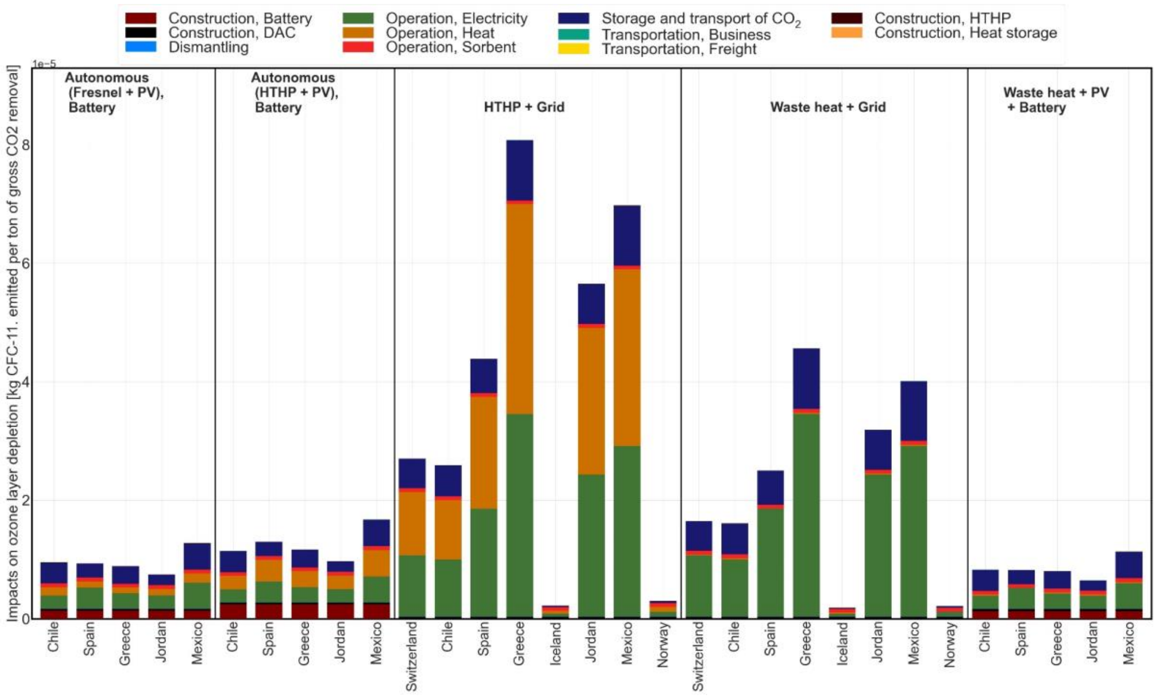


Figure S13. Contribution analysis of Ozone Layer Depletion.

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