

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

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Submitted date: 19/05/2021 • Posted date: 21/05/2021

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Citation information: Terlouw, Tom; Treyer, Karin; bauer, christian; Mazzotti, Marco (2021): Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. ChemRxiv. Preprint. <https://doi.org/10.26434/chemrxiv.14346182.v2>

Prospective energy scenarios usually rely on carbon dioxide removal (CDR) technologies to achieve the climate goals of the Paris Agreement. CDR technologies aim at removing CO₂ from the atmosphere in a permanent way. However, the implementation of CDR technologies typically comes along with unintended environmental side-effects such as land transformation or water consumption. These need to be quantified before large-scale implementation of any CDR option by means of life cycle assessment (LCA). Direct air carbon capture and storage (DACCS) is considered to be among the CDR technologies closest to large-scale implementation, since first pilot and demonstration units have been installed and interactions with the environment are less complex than for biomass related CDR options. However, only very few LCA studies - with limited scope - have been conducted so far to determine the overall life-cycle environmental performance of DACCS. We provide a comprehensive LCA of different low temperature DACCS configurations - pertaining to solid sorbent-based technology - including a global and prospective analysis.

File list (2)

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Life_Cycle_Assessment_of_Direct_Air_Carbon_Capture_... (7.28 MiB)	view on ChemRxiv • download file
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Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources

† Supplementary Information (SI)

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Contents

S1. Verification of information obtained from Climeworks and corresponding contribution analysis (regarding impacts on climate change) of the DAC infrastructure (plant)	2
S2. Selection of locations for DACCS system configurations	7
S3. Overview table of energy system layouts	8
S4. Life cycle inventory: fresnel solar collector	9
S5. LCI – DACCS alternatives and additional information	13
DAC plant	13
Business trips	13
Dismantling	13
Geological storage of CO ₂	13
Sorbent	14
PV electricity	14
S6. LCA results: all environmental impact categories	36
S7. LCA results for land transformation	40
S8. Sensitivity analysis: Reduced electricity consumption for CO ₂ capture	41
S9. Ecoinvent 3.6 datasets used for Figure 3	42
References	43

Our functional unit:

‘Gross removal of 1 ton CO₂ from the atmosphere via the use of a DAC plant combined with geological CO₂ storage’

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 CO₂/year captured), and the other for a near-term future installation (100 kt CO₂/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 CO₂ capture process will stay constant.

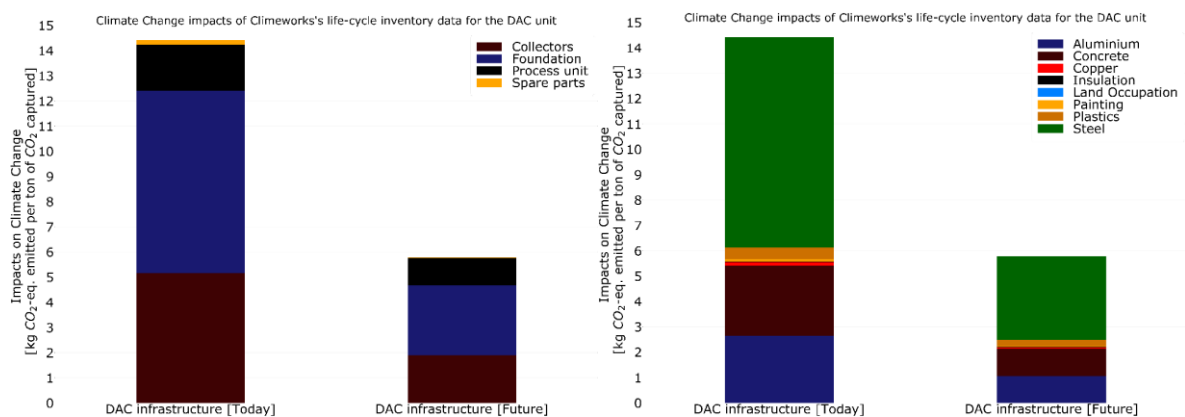


Figure A. Contribution analysis on Climate Change impacts of the main DAC components and materials per ton of CO₂ captured for two scenarios: the current life cycle inventory used in Iceland (4 kt plant) and a future scenario (100 kt plant). Left panel: breakdown per main component; right panel: breakdown 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 CO₂/year and 100 kt CO₂/year capture unit based on the 0.9 kt CO₂/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 CO₂ 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 CO₂/year captured unit) in Hinwil (Switzerland) shows the requirement of 18 collector boxes to capture 0.9 kt CO₂/year^a. Therefore, each collector box captures 50 t CO₂/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 CO₂/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/swisstories/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 m³, with 8 m³ 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/m³) needed for the process unit. Table 1 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 CO₂/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 m³ per process unit. Hence, we linearly scale the amount of process units needed for the 4 kt CO₂/year captured unit, which results in 9 process units with a total volume of 450 m³. 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/m³^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 1. 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 m² for Climeworks' plant in Hinwil. Hence, we apply a linear increase of land use occupation and use 400 m² for the 4 kt CO₂/year capture unit. With a concrete layer of 1 meter, this results in a concrete volume of 400 m³ - with a reinforcement of 120 kg steel/m³ 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 m²), with a lifetime of 50 years. An overview of our self-generated life-cycle inventory for the 4 kt CO₂/year captured unit is presented in Table 2.

For the future DAC unit, we assume that each collector box captures twice as much CO₂ due to an improved capture process. This results in less material consumption, land use as well as a smaller hall/building per unit of CO₂ 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 2.

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

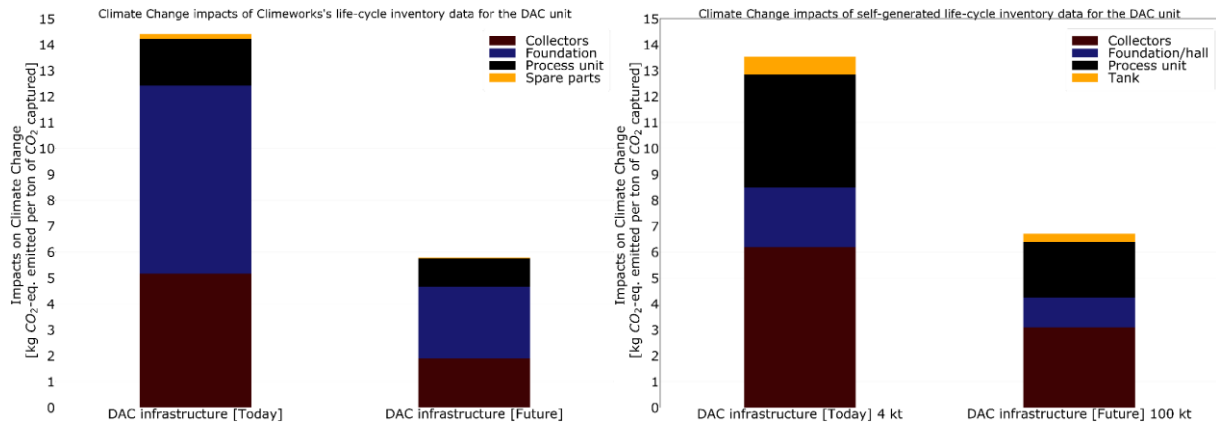


Figure B. Contribution analysis on Climate Change impacts of the main DAC components (for a DAC plant of 4 kt CO₂ captured/year) per ton of CO₂ captured generated from Climeworks's (figure on the left) inventory and our simplified calculation (figure on the right).

The DAC infrastructures approximated with our simplified calculation exhibits a Climate Change impact for the total DAC infrastructure of 13.5 kg CO₂-eq/t CO₂ captured and 6.7 kg CO₂-eq/t CO₂ captured for the 4 kt CO₂ captured/year and 100 kt CO₂ captured/year DAC units, respectively (see Figure B). The life cycle inventory for the DAC infrastructure provided by Climeworks' results in 14.4 kg CO₂-eq/t CO₂ captured and 5.8 kg CO₂-eq/t CO₂ captured for the 4 kt CO₂ captured/year and 100 kt CO₂ captured/year DAC units, respectively (see Figure A). In other words, the difference between both approaches in terms of Climate Change impact is very small: ~1 kg CO₂-eq/t CO₂ 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 CO₂ 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 m² 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 2. Life cycle inventory as used in our back of the envelope calculation for a DAC plant of 4 kt CO₂ captured/year and DAC plant of 100 kt CO₂ 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.

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	technosphe re
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	technosphe re
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	technosphe re
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	technosphe re

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 CO₂ captured/year) of Climeworks will be installed in Helliheiði (Iceland) in 2021. Second, Norway is included since it presents a nearly optimal situation: Norway has clean grid electricity and has CO₂ storage potentials nearby (Anthonson *et al.*, 2013). Further, Switzerland is considered as a region with longer transportation distances to CO₂ 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 CO₂ 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/m² year, especially for the concentrated thermal solar heat collectors (Kurup *et al.*, 2019). Hence, we present a map (see Figure C) herein to explore other promising locations - with a DNI of more than 2000 kWh/m² year - for the installation of the autonomous energy system configurations. Figure C 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.

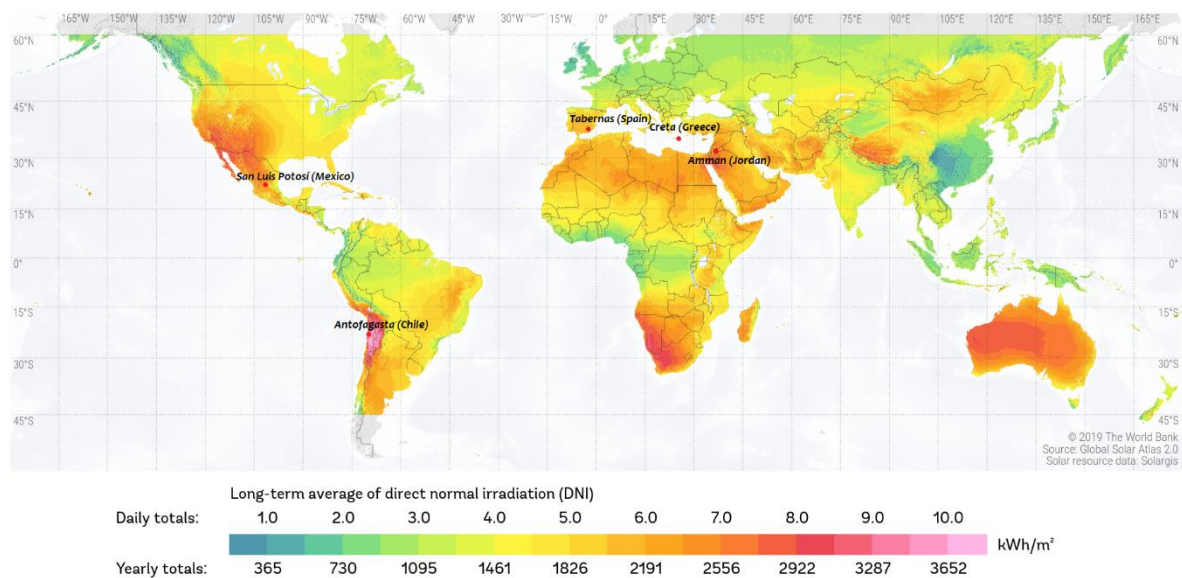


Figure C. Geographical distribution of average direct normal irradiation (DNI). The map presents promising locations for autonomous DACCS energy systems with solar energy, i.e. with a DNI of more than 2000 kWh/m² year. This solar map is obtained from the "Global Solar Atlas 2.0", a free, web-based application 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 3 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 3. 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 <i>et al.</i> , 2019)	
	Lifetime	12	12	n.a.	n.a.	12	[years]	(Schmidt <i>et al.</i> , 2019)	20/LT _x
Battery power unit (BoS)	Size	63	110	0	0	60	[MW power capacity]	(Schmidt <i>et al.</i> , 2019)	
	Lifetime	20	20	n.a.	n.a.	20	[years]	(Schmidt <i>et al.</i> , 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 ₀ 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 ₀]	(Ecoinvent, 2020)	
	Lifetime	30	30	n.a.	n.a.	30	[years]	(Ecoinvent, 2020)	n.a., Already considered in FU

S4. Life cycle inventory: 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 CO₂ 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.

Table 4. Life cycle inventory of the fresnel solar collector. 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.

collector construction, Fresnel plant, Jordan			unit		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Occupation, arable land, unspecified use		3.00E+04	square meter-year	natural resource:land		biosphere
Occupation, urban, green area		1.75E+04	square meter-year	natural resource:land		biosphere
Occupation, urban/industrial fallow (non-use)		2.50E+03	square meter-year	natural resource:land		biosphere
Transformation, from grassland, natural (non-use)		2.00E+03	square meter	natural resource:land		biosphere
Transformation, to arable land, unspecified use		1.20E+03	square meter	natural resource:land		biosphere
Transformation, to urban, green area		7.00E+02	square meter	natural resource:land		biosphere
Transformation, to urban/industrial fallow (non-use)		1.00E+02	square meter	natural resource:land		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	1.00E+00	unit		JO	production
market for aluminium, wrought alloy	aluminium, wrought alloy	2.28E+03	kilogram		GLO	technosphere
market for copper	copper	2.77E+02	kilogram		GLO	technosphere
market for polyethylene, high density, granulate	polyethylene, high density, granulate	6.98E+01	kilogram		GLO	technosphere
market for silver	silver	1.77E+00	kilogram		GLO	technosphere
market for solar glass, low-iron	solar glass, low-iron	1.33E+04	kilogram		GLO	technosphere
market for steel, chromium steel 18/8, hot rolled	steel, chromium steel 18/8, hot rolled	2.72E+03	kilogram		GLO	technosphere
market for steel, low-alloyed, hot rolled	steel, low-alloyed, hot rolled	2.84E+04	kilogram		GLO	technosphere
market for tempering, flat glass	tempering, flat glass	1.33E+04	kilogram		GLO	technosphere
zinc coating, coils	zinc coat, coils	1.99E+02	square meter		RoW	technosphere

storage unit production, Fresnel plant, Jordan, 12h storage			unit		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Occupation, industrial area		2.50E+04	square meter-year	natural resource:land		biosphere
Transformation, from grassland, natural (non-use)		1.00E+03	square meter	natural resource:land		biosphere
Transformation, to industrial area		1.00E+03	square meter	natural resource:land		biosphere
		-				
market for scrap steel	scrap steel	5.22E+05	kilogram		RoW	technosphere
market for steel, low-alloyed, hot rolled	steel, low-alloyed, hot rolled	8.03E+05	kilogram		GLO	technosphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	1.00E+00	unit		JO	production
		-				
treatment of waste reinforcement steel, recycling	waste reinforcement steel	2.81E+05	kilogram		RoW	technosphere
transport pipes installation, Fresnel plant, Jordan			unit		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
market for drawing of pipe, steel	drawing of pipe, steel	4.44E+03	kilogram		GLO	technosphere
market for steel, low-alloyed, hot rolled	steel, low-alloyed, hot rolled	4.44E+03	kilogram		GLO	technosphere
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	1.00E+00	unit		JO	production
end of life, Fresnel solar collector plant, Jordan			unit		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	1.00E+00	unit		JO	production
		-				
market for scrap copper	scrap copper	2.77E+02	kilogram		RoW	technosphere
		-				
market for scrap steel	scrap steel	2.31E+04	kilogram		RoW	technosphere
		-				
market for waste glass	waste glass	1.33E+04	kilogram		RoW	technosphere
		-				
market for waste polyethylene	waste polyethylene	6.98E+01	kilogram		RoW	technosphere
		-				
treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter	aluminium, wrought alloy	2.28E+03	kilogram		RoW	technosphere
		-				
treatment of waste reinforcement steel, recycling	waste reinforcement steel	1.25E+04	kilogram		RoW	technosphere
heat production, Fresnel solar collector plant, Amman, Jordan			megajoule		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Water, unspecified natural origin		4.82E-07	cubic meter	natural resource:in water		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	9.69E-09	unit		JO	technosphere
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	electricity, low voltage	4.76E-03	kilowatt hour		SA	technosphere
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	9.69E-09	unit		JO	technosphere
heat production, Fresnel solar collector plant, Amman, Jordan	heat, central or small-scale, Fresnel plant	1.00E+00	megajoule		JO	production
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	9.69E-09	unit		JO	technosphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	3.20E-04	ton kilometer		RoW	technosphere

transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	9.16E-04	ton kilometer		RER	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.89E-03	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.01E-03	person kilometer		GLO	technosphere
heat production, Fresnel solar collector plant, Antofagasto, Chile			megajoule		CL	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Water, unspecified natural origin		4.05E-07	cubic meter	natural resource:in water		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	8.14E-09	unit		JO	technosphere
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	electricity, low voltage	4.00E-03	kilowatt hour		CL	technosphere
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	8.14E-09	unit		JO	technosphere
heat production, Fresnel solar collector plant, Antofagasto, Chile	heat, central or small-scale, Fresnel plant	1.00E+00	megajoule		CL	production
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	8.14E-09	unit		JO	technosphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	1.10E-03	ton kilometer		RoW	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	8.34E-04	ton kilometer		RoW	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.13E-02	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, long haul	transport, passengers, aircraft, long haul	4.75E-03	person kilometer		GLO	technosphere
heat production, Fresnel solar collector plant, San Luis Potosi, Mexico			megajoule		MX	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Water, unspecified natural origin		5.63E-07	cubic meter	natural resource:in water		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	1.13E-08	unit		JO	technosphere
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	electricity, low voltage	5.56E-03	kilowatt hour		MX	technosphere
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	1.13E-08	unit		JO	technosphere
heat production, Fresnel solar collector plant, San Luis Potosi, Mexico	heat, central or small-scale, Fresnel plant	1.00E+00	megajoule		MX	production
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	1.13E-08	unit		JO	technosphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	5.32E-04	ton kilometer		RoW	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	1.16E-03	ton kilometer		RoW	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.07E-02	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, long haul	transport, passengers, aircraft, long haul	5.55E-03	person kilometer		GLO	technosphere
heat production, Fresnel solar collector plant, Tabernas, Spain			megajoule		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Water, unspecified natural origin		5.48E-07	cubic meter	natural resource:in water		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	1.10E-08	unit		JO	technosphere
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	electricity, low voltage	5.41E-03	kilowatt hour		ES	technosphere
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	1.10E-08	unit		JO	technosphere
heat production, Fresnel solar collector plant, Tabernas, Spain	heat, central or small-scale, Fresnel plant	1.00E+00	megajoule		ES	production
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	1.10E-08	unit		JO	technosphere

transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	0.00E+00	ton kilometer		RoW	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.38E-03	ton kilometer		RER	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	0.00E+00	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.77E-04	person kilometer		GLO	technosphere
heat production, Fresnel solar collector plant, Creta, Greece			megajoule		GR	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Water, unspecified natural origin		5.34E-07	cubic meter	natural resource:in water		biosphere
collector construction, Fresnel plant, Jordan	collector, Fresnel plant, Jordan	1.07E-08	unit		JO	technosphere
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	electricity, low voltage	5.27E-03	kilowatt hour		GR	technosphere
end of life, Fresnel solar collector plant, Jordan	end of life, Fresnel solar collector plant, Jordan	1.07E-08	unit		JO	technosphere
heat production, Fresnel solar collector plant, Creta, Greece	heat, central or small-scale, Fresnel plant	1.00E+00	megajoule		GR	production
transport pipes installation, Fresnel plant, Jordan	transport pipes, Fresnel plant, Jordan	1.07E-08	unit		JO	technosphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	0.00E+00	ton kilometer		RoW	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	1.10E-03	ton kilometer		RER	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	5.72E-03	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.18E-03	person kilometer		GLO	technosphere

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 of this SI 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 CO₂ 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 CO₂ captured per year), and a future design representing an upscale of their current standard DAC plant to capture 100 kt CO₂ per year. These two units mainly differ in terms of material intensity for construction and adsorbent consumption for CO₂ capture. Energy requirements for CO₂ capture are, however, identical for the two DAC units: 500 kWh per ton CO₂ captured for electricity (without electricity consumption for CO₂ compression) and 1500 kWh per ton CO₂ 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 CO₂ captured and 1333 kWh heat per ton CO₂ 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 CO₂ 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 CO₂ 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 CO₂ removal from the atmosphere.

The LT 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 CO₂ 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 CO₂

After the CO₂ is captured, the CO₂ 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 CO₂ is transported with pipelines at 110 bar to the injection wells, due to the high capacity needed for large-scale CO₂ capture. For simplicity, 80 bar is assumed as pressure at the pipeline end for each configuration (Volkart, Bauer and Boulet, 2013). Additional compression of CO₂ is included when the transportation distance is larger than 200 kilometers to compensate for a pressure drop of CO₂ (Volkart, Bauer and Boulet, 2013). We consider CO₂ leakage from CO₂ 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 CO₂ is injected into wells - using the country-specific electricity mix - to store the CO₂ in suitable geological formations, which is considered to exhibit the highest CO₂ 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 CO₂ storage, based on the specific transportation distance for CO₂ storage in a country. We assess the feasibility of geological CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ storage depth of 2000 meters for each country, since (Volkart, Bauer and Boulet, 2013) have shown that this depth hardly affects LCA results. CO₂ 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 CO₂/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 Table 6.

Further, we calculate the electricity requirement for injection (for a storage depth of 2000 meter: 24 kWh/t CO₂ captured) and compression (114 kWh/t CO₂ captured, with compression units with a lifetime of 10 years) using an equation presented in Hendriks *et al.* (Hendriks, Chris; Wina, Graus; and Bergen V., 2004). Note that a compensation factor for CO₂ 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 Table 7. The exchange 'Carbon dioxide, fossil' refers to losses of CO₂ 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 CO₂ 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 5. 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 (Crete) 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 CO₂. 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.

Table 6. Life cycle inventory for the production of pipelines, drilling of boreholes and the transportation of CO₂. CO₂ losses during CO₂ with pipelines transportation are considered separately, as described in this Note S5 of the SI. Note that ‘pipeline, supercritical CO₂/km’, ‘market for gas turbine, 10MW electrical’ and ‘drilling, deep borehole/m’ are initially based on bigger mass flow ratio, hence these are scaled down by making use of a mass flow ratio. 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.

pipeline, supercritical CO₂/km			kilometer		RER	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Occupation, construction site		3.33E+03	square meter-year	natural resource:land		biosphere
Transformation, from forest, unspecified		2.00E+03	square meter	natural resource:land		biosphere
Transformation, to heterogeneous, agricultural		2.00E+03	square meter	natural resource:land		biosphere
Water, unspecified natural origin		1.87E+02	cubic meter	natural resource:in water		biosphere
drawing of pipe, steel	drawing of pipe, steel	2.70E+05	kilogram	Materials/fuels	RER	technosphere
gravel and sand quarry operation	sand	4.40E+06	kilogram	Materials/fuels	CH	technosphere
market for diesel, burned in building machine		3.31E+06	megajoule	Materials/fuels	GLO	technosphere
market for steel, low-alloyed		2.70E+05	kilogram	Materials/fuels	GLO	technosphere
market for stone wool, packed	stone wool, packed	5.12E+03	kilogram	Materials/fuels	GLO	technosphere
market for transport, freight train		5.51E+04	ton kilometer	Materials/fuels	Europe without Switzerland	technosphere
market for transport, freight, lorry, unspecified		3.15E+05	ton kilometer	Materials/fuels	RER	technosphere
pipeline, supercritical CO₂/km		1.00E+00	kilometer	NEEDS_2000:CCS	RER	production
transport, helicopter		2.60E+01	hour	Materials/fuels	GLO	technosphere
transport, helicopter, LTO cycle		1.04E+01	unit	Materials/fuels	GLO	technosphere
treatment of inert waste, inert material landfill		4.40E+06	kilogram	Waste to treatment	CH	technosphere
treatment of scrap steel, inert material landfill	scrap steel	1.35E+05	kilogram	Waste to treatment	CH	technosphere
treatment of waste mineral wool, inert material landfill	waste mineral wool, for final disposal	5.12E+03	kilogram	Waste to treatment	CH	technosphere
transport, pipeline, supercritical CO₂, 200km w recompression			ton kilometer		RER	
Name	Reference Product	Amount	Unit	Categories	Location	Type
market for gas turbine, 10MW electrical		8.04E-11	unit	Materials/fuels	GLO	technosphere
market group for electricity, medium voltage		3.89E-02	kilowatt hour	Materials/fuels	ENTSO-E	technosphere
pipeline, supercritical CO₂/km		4.23E-09	kilometer	Materials/fuels	RER	technosphere
transport, pipeline, supercritical CO ₂ , 200km w recompression		1.00E+00	ton kilometer	NEEDS_2000:CCS	RER	production
transport, pipeline, supercritical CO₂, 200km w/o recompression			ton kilometer		RER	
Name	Reference Product	Amount	Unit	Categories	Location	Type
pipeline, supercritical CO₂/km		4.23E-09	kilometer	Materials/fuels	RER	technosphere
transport, pipeline, supercritical CO ₂ , 200km w/o recompression		1.00E+00	ton kilometer	NEEDS_2000:CCS	RER	production
drilling, deep borehole/m			meter		RER	
Name	Reference Product	Amount	Unit	Categories	Location	Type
AOX, Adsorbable Organic Halogen as Cl		4.78E-07	kilogram	water:surface water		biosphere

Aluminium		6.00E-02	kilogram	water:surface water		biosphere
Arsenic, ion		4.20E-04	kilogram	water:surface water		biosphere
BOD5, Biological Oxygen Demand		3.00E-01	kilogram	water:surface water		biosphere
Barium		6.00E-03	kilogram	water:surface water		biosphere
Boron		9.00E-03	kilogram	water:surface water		biosphere
COD, Chemical Oxygen Demand		3.00E+00	kilogram	water:surface water		biosphere
Calcium, ion		6.00E-01	kilogram	water:surface water		biosphere
Chloride		6.00E+00	kilogram	water:surface water		biosphere
Chromium, ion		6.00E-04	kilogram	water:surface water		biosphere
DOC, Dissolved Organic Carbon		3.00E-01	kilogram	water:surface water		biosphere
Fluoride		3.00E-03	kilogram	water:surface water		biosphere
Hydrocarbons, aromatic		3.00E-03	kilogram	water:surface water		biosphere
Iron, ion		1.80E-01	kilogram	water:surface water		biosphere
Magnesium		1.20E-01	kilogram	water:surface water		biosphere
Manganese		3.00E-03	kilogram	water:surface water		biosphere
Methane, dichloro-, HCC-30		6.00E-02	kilogram	water:surface water		biosphere
Particulates, > 10 um		1.48E-02	kilogram	air:non-urban air or from high stacks		biosphere
Phosphorus		1.20E-03	kilogram	water:surface water		biosphere
Potassium, ion		9.00E-01	kilogram	water:surface water		biosphere
Silicon		3.00E-02	kilogram	water:surface water		biosphere
Sodium, ion		6.00E+00	kilogram	water:surface water		biosphere
Strontium		1.80E-02	kilogram	water:surface water		biosphere
Sulfur		1.20E-01	kilogram	water:surface water		biosphere
TOC, Total Organic Carbon		3.00E-01	kilogram	water:surface water		biosphere
Water, well, in ground		3.34E+00	cubic meter	natural resource:in water		biosphere
Zinc, ion		1.20E-03	kilogram	water:surface water		biosphere
activated bentonite production	activated bentonite	2.00E+01	kilogram	Materials/fuels	DE	technosphere
barite production	barite	2.70E+02	kilogram	Materials/fuels	RER	technosphere
cement production, Portland	cement, Portland	2.00E+02	kilogram	Materials/fuels	CH	technosphere
diesel, burned in diesel-electric generating set, 18.5kW		6.30E+03	megajoule	Materials/fuels	GLO	technosphere
drilling, deep borehole/m		1.00E+00	meter	NEEDS_2000:CCS	RER	production
lignite mine operation	lignite	2.00E-01	kilogram	Materials/fuels	RER	technosphere
market for chemical, organic		9.05E+00	kilogram	Materials/fuels	GLO	technosphere
market for chemicals, inorganic		4.22E+01	kilogram	Materials/fuels	GLO	technosphere
market for lubricating oil		6.00E+01	kilogram	Materials/fuels	RER	technosphere
market for steel, low-alloyed		2.10E+02	kilogram	Materials/fuels	GLO	technosphere
market for transport, freight train		4.87E+02	ton kilometer	Materials/fuels	Europe without Switzerland	technosphere
market for transport, freight, lorry, unspecified		8.11E+01	ton kilometer	Materials/fuels	RER	technosphere
treatment of drilling waste, landfarming	drilling waste	2.37E+02	kilogram	Waste to treatment	CH	technosphere

treatment of drilling waste, residual material landfill	drilling waste	1.58E+02	kilogram	Waste to treatment	CH	technosphere
treatment of hazardous waste, hazardous waste incineration		5.00E+00	kilogram	Waste to treatment	CH	technosphere

Table 7. Life cycle inventory of all configurations. 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.

carbon dioxide, captured from atmosphere, Waste heat + Grid, ES			ton		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		7.00E+00	kilogram	air:urban air close to ground		biosphere
carbon dioxide capture system		5.00E-07	unit		RER	technosphere
drilling, deep borehole/m		3.38E-05	meter		RER	technosphere
end of life, carbon dioxide capture system		5.00E-07	unit		RoW	technosphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40E+03	megajoule		ES	technosphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35E-06	unit		GLO	technosphere
market for electricity, low voltage	electricity, low voltage	5.00E+02	kilowatt hour		ES	technosphere
market for electricity, low voltage	electricity, low voltage	1.14E+02	kilowatt hour		ES	technosphere
market for electricity, low voltage	electricity, low voltage	2.42E+01	kilowatt hour		ES	technosphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54E-08	unit		GLO	technosphere
sorbent, generic		3.00E+00	kilogram		RER	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	3.55E-01	ton kilometer		RoW	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	7.04E-01	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.58E-01	person kilometer		GLO	technosphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00E+02	ton kilometer		RER	technosphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00E+02	ton kilometer		RER	technosphere
carbon dioxide, captured from atmosphere, Waste heat + PV + Battery, ES			ton		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		9.99E-02	kilowatt hour		GLO	technosphere
Carbon dioxide, fossil		7.00E+00	kilogram	air:urban air close to ground		biosphere
Energy management system, kWh		9.99E-02	kilowatt hour		GLO	technosphere
Li-ion (NMC)		9.99E-02	kilowatt hour		GLO	technosphere
Power conditioning system, container system		3.00E-02	kW		GLO	technosphere
carbon dioxide capture system		5.00E-07	unit		RER	technosphere
drilling, deep borehole/m		3.38E-05	meter		RER	technosphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62E+02	kilowatt hour		ES	technosphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29E+02	kilowatt hour		ES	technosphere
end of life, carbon dioxide capture system		5.00E-07	unit		RoW	technosphere

heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoule		ES	technosphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	technosphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		ES	technosphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	technosphere
sorbent, generic		3.00 E+00	kilogram		RER	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	3.55 E-01	ton kilometer		RoW	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	7.04 E-01	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.58 E-01	person kilometer		GLO	technosphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilometer		RER	technosphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilometer		RER	technosphere
carbon dioxide, captured from atmosphere, HTHP + Grid, ES			ton		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosphere
carbon dioxide capture system		5.00 E-07	unit		RER	technosphere
drilling, deep borehole/m		3.38 E-05	meter		RER	technosphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	technosphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	technosphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	technosphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		ES	technosphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		ES	technosphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		ES	technosphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		ES	technosphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	technosphere
sorbent, generic		3.00 E+00	kilogram		RER	technosphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	3.55 E-01	ton kilometer		RoW	technosphere
transport, freight, sea, container ship	transport, freight, sea, container ship	7.04 E-01	ton kilometer		GLO	technosphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.58 E-01	person kilometer		GLO	technosphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilometer		RER	technosphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilometer		RER	technosphere
carbon dioxide, captured from atmosphere, Autonomous Fresnel + PV, ES			ton		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.04 E-01	kilowatt hour		GLO	technosphere
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosphere

Energy management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.04 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.13 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		ES	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		ES	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat production, Fresnel solar collector plant, Tabernas, Spain	heat, central or small-scale, Fresnel plant	5.40 E+03	megajoule		ES	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		ES	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	4.00 E-07	unit		JO	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	3.55 E-01	ton kilometre		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	7.04 E-01	ton kilometre		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.58 E-01	person kilometre		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilometre		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilometre		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous HTHP + PV, ES			ton		ES	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosphere
Energy management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.84 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		5.52 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		ES	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		ES	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.81 E+02	kilowatt hour		ES	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		ES	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere

sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	3.55 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	7.04 E-01	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.58 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, CH			ton		CH	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		CH	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		CH	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		NO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	7.44 E-02	ton kilomete r		RoW	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, CH			ton		CH	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		CH	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		CH	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		CH	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		NO	techno sphere

market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	7.44 E-02	ton kilomete r		RoW	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, CL			ton		CL	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		CL	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		CL	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		BR	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	8.21 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.02 E+00	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + PV + Battery, CL			ton		CL	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		9.99 E-02	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.00 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		CL	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		CL	techno sphere

end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoule		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		BR	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilometer		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	8.21 E+00	ton kilometer		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.02 E+00	person kilometer		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilometer		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilometer		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, CL			ton		CL	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		CL	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		CL	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		CL	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		BR	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilometer		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	8.21 E+00	ton kilometer		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.02 E+00	person kilometer		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilometer		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilometer		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous Fresnel + PV, CL			ton		CL	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere

Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.04 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.13 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		CL	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		CL	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat production, Fresnel solar collector plant, Antofagasto, Chile	heat, central or small- scale, Fresnel plant	5.40 E+03	megajoul e		CL	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		BR	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	4.00 E-07	unit		JO	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	8.21 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.02 E+00	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous HTHP + PV, CL			ton		CL	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.84 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		5.52 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		CL	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		CL	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.81 E+02	kilowatt hour		CL	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere

market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		BR	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	8.21 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.02 E+00	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, NO			ton		NO	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		NO	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		NO	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		NO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		NO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	3.04 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.48 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, NO			ton		NO	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		NO	techno sphere

market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		NO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		NO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		NO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	3.04 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	1.48 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, GR			ton		GR	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		GR	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		GR	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		GR	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.16 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.02 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + PV + Battery, GR			ton		GR	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		9.99 E-02	kilowatt hour		GLO	techno sphere

Power conditioning system, container system		3.00 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		GR	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		GR	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		GR	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.16 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.02 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, GR			ton		GR	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		GR	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		GR	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		GR	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		GR	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.16 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.02 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere

transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous Fresnel + PV, GR			ton		GR	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.04 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.13 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		GR	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		GR	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat production, Fresnel solar collector plant, Creta, Greece	heat, central or small-scale, Fresnel plant	5.40 E+03	megajoul e		GR	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		GR	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	4.00 E-07	unit		JO	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.16 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.02 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous HTHP + PV, GR			ton		GR	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		7.00 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.84 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		5.52 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		GR	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		GR	techno sphere

electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.81 E+02	kilowatt hour		GR	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		GR	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.16 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.02 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		3.00 E+02	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, JO			ton		JO	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		JO	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		JO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		JO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	9.44 E-02	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.71 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.00 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + PV + Battery, JO			ton		JO	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere

Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		9.99 E-02	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.00 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		JO	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		JO	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		JO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	9.44 E-02	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.71 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.00 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, JO			ton		JO	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		JO	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		JO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E-02	kilowatt hour		JO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		JO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	9.44 E-02	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere

transport, freight, sea, container ship	transport, freight, sea, container ship	1.71 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.00 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO ₂ , 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous Fresnel + PV, JO			ton		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.04 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.13 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		JO	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		JO	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat production, Fresnel solar collector plant, Amman, Jordan	heat, central or small-scale, Fresnel plant	5.40 E+03	megajoul e		JO	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		JO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	4.00 E-07	unit		JO	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	9.44 E-02	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.71 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.00 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO ₂ , 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous HTHP + PV, JO			ton		JO	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.84 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		5.52 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere

drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		JO	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		JO	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.81 E+02	kilowatt hour		JO	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		JO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	9.44 E-02	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	1.71 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	3.00 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, MX			ton		MX	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		MX	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		MX	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		US	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	2.37 E-01	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.42 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.96 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere

transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + PV + Battery, MX			ton		MX	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		9.99 E-02	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		9.99 E-02	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.00 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		MX	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		MX	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		US	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	2.37 E-01	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.42 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.96 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, MX			ton		MX	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		MX	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		MX	techno sphere

market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		MX	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		US	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	2.37 E-01	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.42 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.96 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous Fresnel + PV, MX			ton		MX	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Battery management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.04 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.04 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		3.13 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		MX	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		MX	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat production, Fresnel solar collector plant, San Luis Potosi, Mexico	heat, central or small- scale, Fresnel plant	5.40 E+03	megajoul e		MX	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		US	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
storage unit production, Fresnel plant, Jordan, 12h storage	storage unit, Fresnel plant, Jordan, 12h storage	4.00 E-07	unit		JO	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	2.37 E-01	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.42 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.96 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere

transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Autonomous HTHP + PV, MX			ton		MX	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Battery management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Carbon dioxide, fossil		2.10 E+01	kilogram	air:urban air close to ground		biosph ere
Energy management system, kWh		1.84 E-01	kilowatt hour		GLO	techno sphere
Li-ion (NMC)		1.84 E-01	kilowatt hour		GLO	techno sphere
Power conditioning system, container system		5.52 E-02	kW		GLO	techno sphere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.62 E+02	kilowatt hour		MX	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	1.29 E+02	kilowatt hour		MX	techno sphere
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	5.81 E+02	kilowatt hour		MX	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
market group for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		US	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO4	transport, freight, lorry >32 metric ton, EURO4	2.37 E-01	ton kilomete r		RoW	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	6.42 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	9.96 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w recompression		1.30 E+03	ton kilomete r		RER	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		2.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, Waste heat + Grid, IS			ton		IS	
Name	Reference Product	Amount	Unit	Categories	Location	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	heat, district or industrial, other than natural gas	5.40 E+03	megajoul e		RoW	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		IS	techno sphere

market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		IS	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		IS	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	3.12 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.73 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere
carbon dioxide, captured from atmosphere, HTHP + Grid, IS			ton		IS	
Name	Reference Product	Amo unt	Unit	Categories	Loca tion	Type
Carbon dioxide, fossil		1.40 E+00	kilogram	air:urban air close to ground		biosph ere
carbon dioxide capture system		5.00 E-07	unit		RER	techno sphere
drilling, deep borehole/m		3.38 E-05	meter		RER	techno sphere
end of life, carbon dioxide capture system		5.00 E-07	unit		RoW	techno sphere
heat pump production, brine-water, CO2 refrigerant, 10kW		8.56 E-04	unit		CH	techno sphere
market for air compressor, screw-type compressor, 300kW	air compressor, screw-type compressor, 300kW	4.35 E-06	unit		GLO	techno sphere
market for electricity, low voltage	electricity, low voltage	5.00 E+02	kilowatt hour		IS	techno sphere
market for electricity, low voltage	electricity, low voltage	1.14 E+02	kilowatt hour		IS	techno sphere
market for electricity, low voltage	electricity, low voltage	5.17 E+02	kilowatt hour		IS	techno sphere
market for electricity, low voltage	electricity, low voltage	2.42 E+01	kilowatt hour		IS	techno sphere
market for gas turbine, 10MW electrical	gas turbine, 10MW electrical	2.54 E-08	unit		GLO	techno sphere
sorbent, generic		3.00 E+00	kilogram		RER	techno sphere
transport, freight, lorry >32 metric ton, EURO6	transport, freight, lorry >32 metric ton, EURO6	2.53 E-01	ton kilomete r		RoW	techno sphere
transport, freight, sea, container ship	transport, freight, sea, container ship	3.12 E+00	ton kilomete r		GLO	techno sphere
transport, passengers, passenger aircraft, medium haul	transport, passengers, aircraft, medium haul	2.73 E-01	person kilomete r		GLO	techno sphere
transport, pipeline, supercritical CO2, 200km w/o recompression		1.00 E+02	ton kilomete r		RER	techno sphere

S6. LCA results: all environmental impact categories

Table 8 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 8. LCA results for all environmental impact categories for all DACCS alternatives per FU "Gross removal of 1 ton CO₂ from the atmosphere".

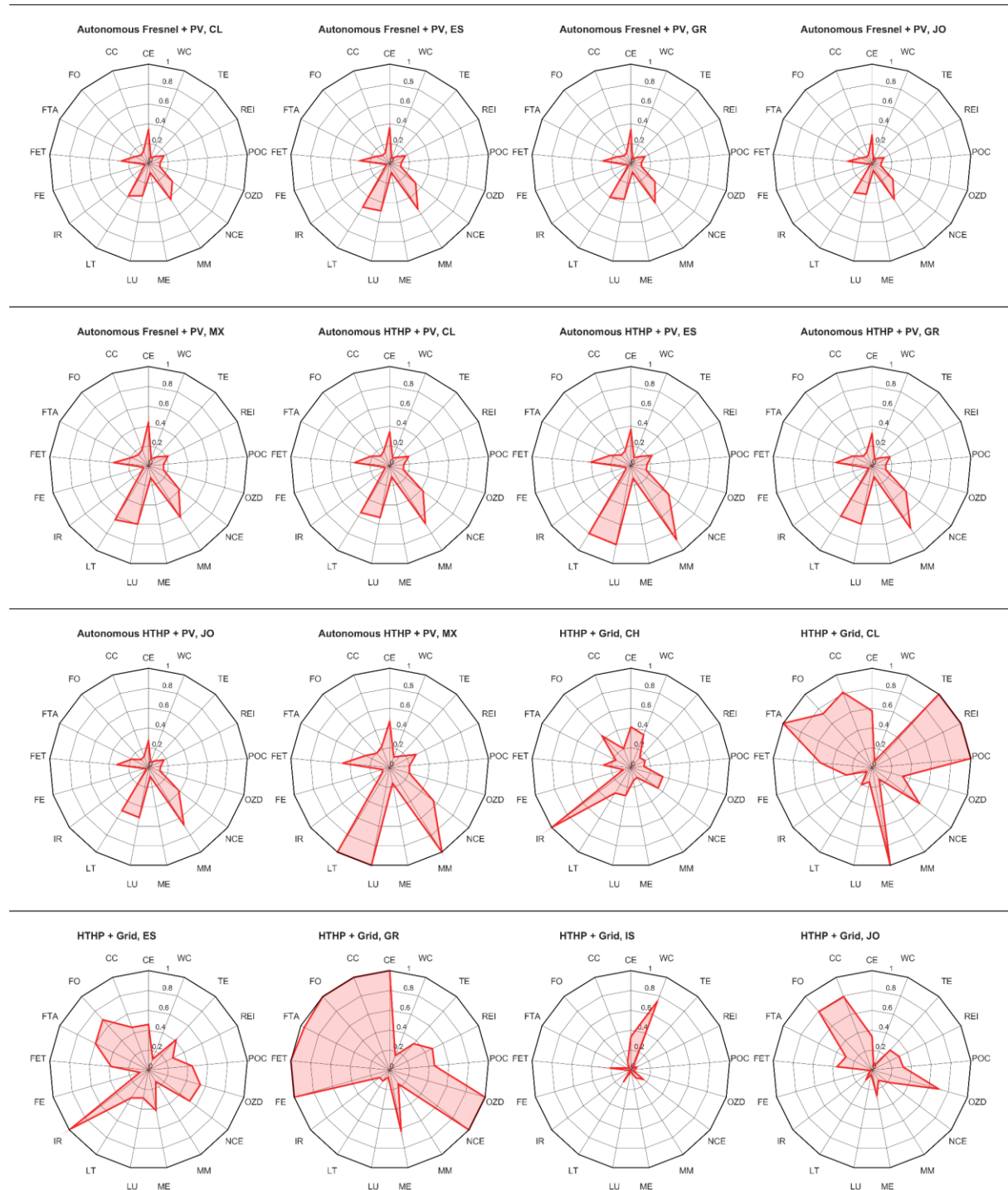
	Land transformation	carcinogenic effects	climate change total	fossils	freshwater and terrestrial acidification	freshwater ecotoxicity	freshwater eutrophication	ionising radiation	land use	marine eutrophication	minerals and metals	non-carcinogenic effects	ozone layer depletion	photochemical ozone creation	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

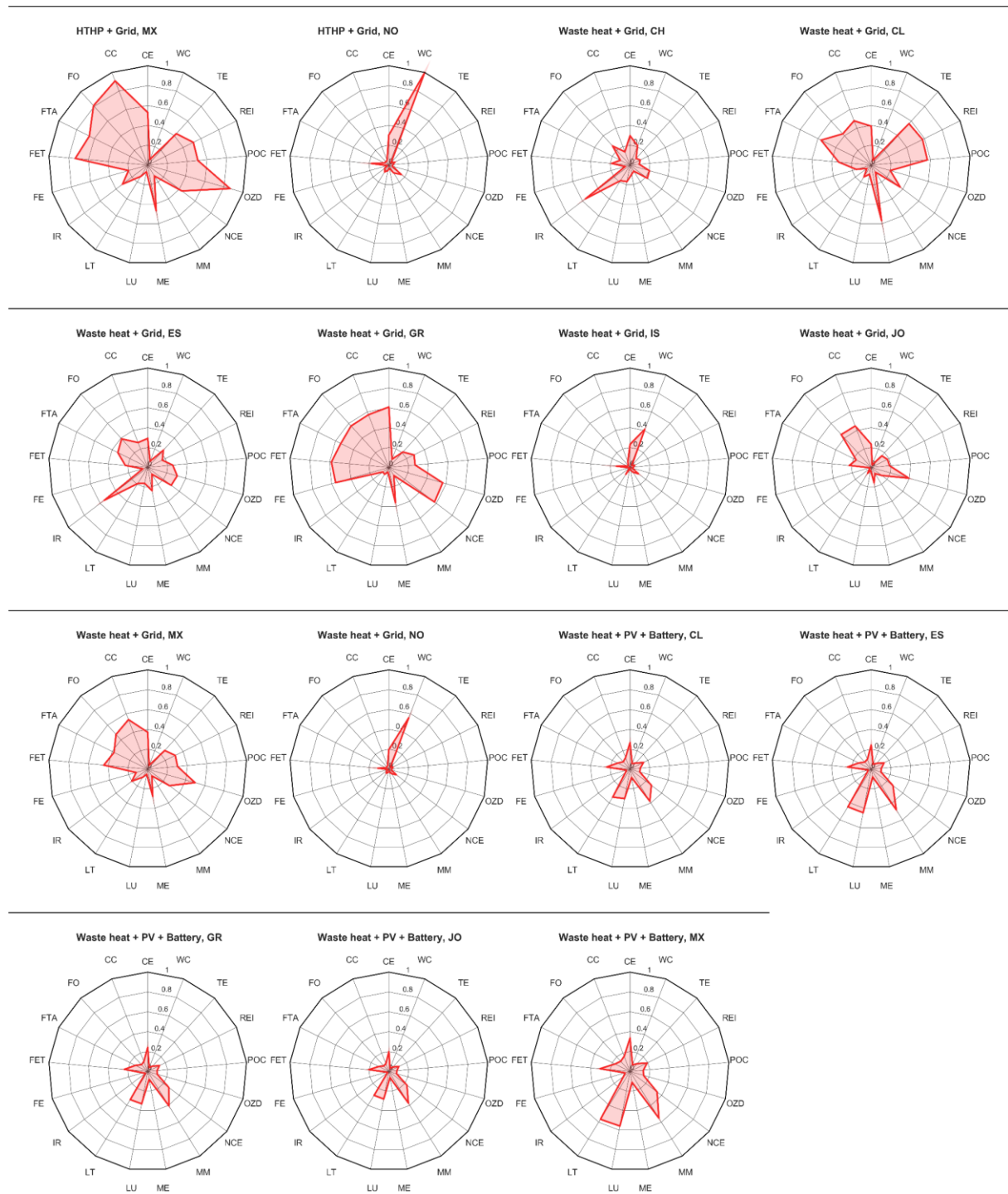
	Land transformation	carcinogenic effects	climate change total	fossils	freshwater and terrestrial acidification	freshwater ecotoxicity	freshwater eutrophication	ionising radiation	land use	marine eutrophication	minerals and metals	non-carcinogenic effects	ozone layer depletion	photochemical ozone creation	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 D. 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 **Red** in Table 8.

Figure D. 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.





S7. LCA results for land transformation

Figure E 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. In reality, direct land transformation is also generated from the installation of pipelines, but are excluded in the direct land transformation impacts of Figure E, since land is not directly transformed at the DAC location. Therefore, the main indirect contribution originates from land use of pipelines, and scales with CO₂ transportation distance.

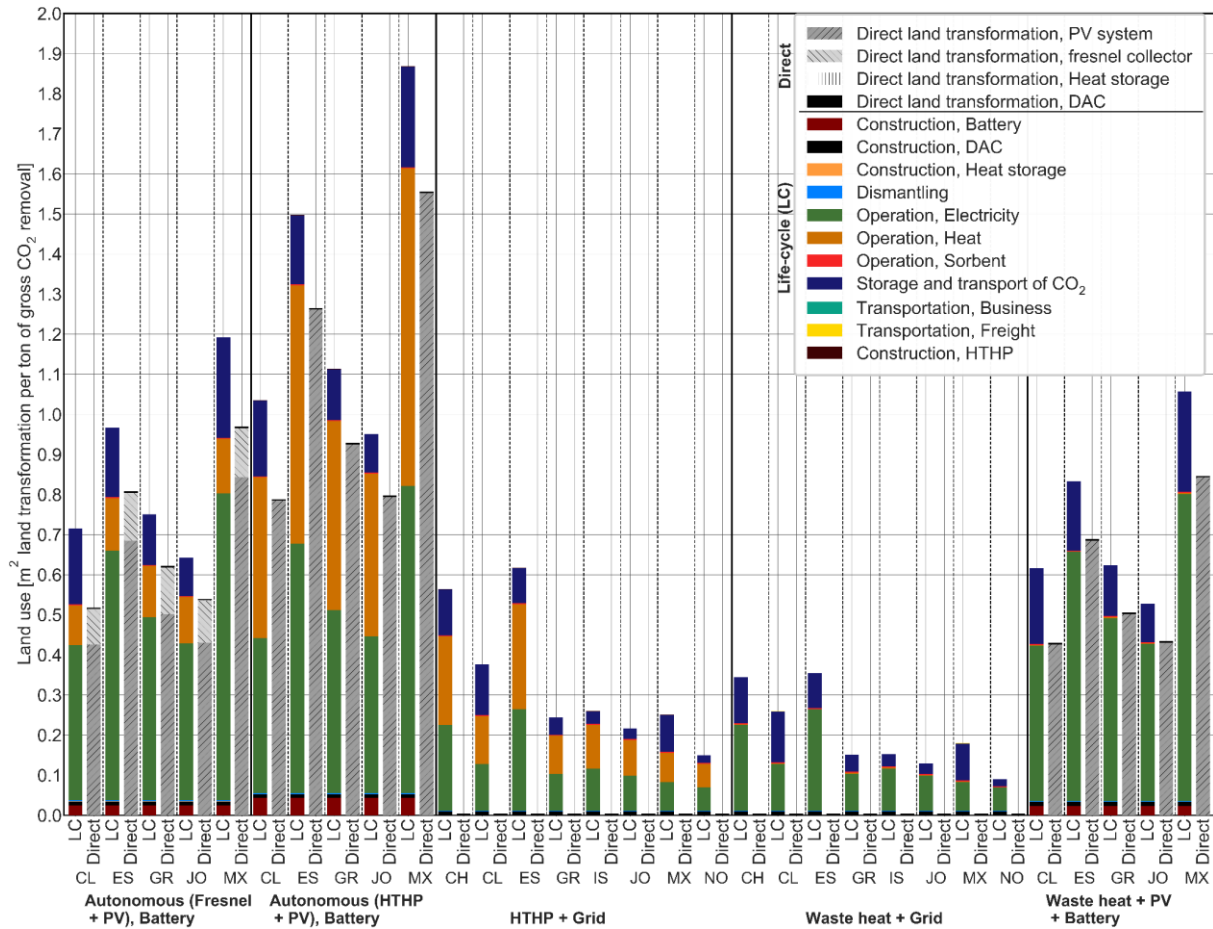


Figure E. Land transformation results for all considered DACCS configurations and countries of our main analysis. For each country, the total life-cycle land transformation (including indirect land transformation) is represented by the colored stacked bars. The direct land use transformation at the DAC 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 CO₂ capture

Figure F shows the sensitivity analysis regarding electricity consumption of the DAC unit and the effects on life-cycle GHG emissions per ton of CO₂ captured.

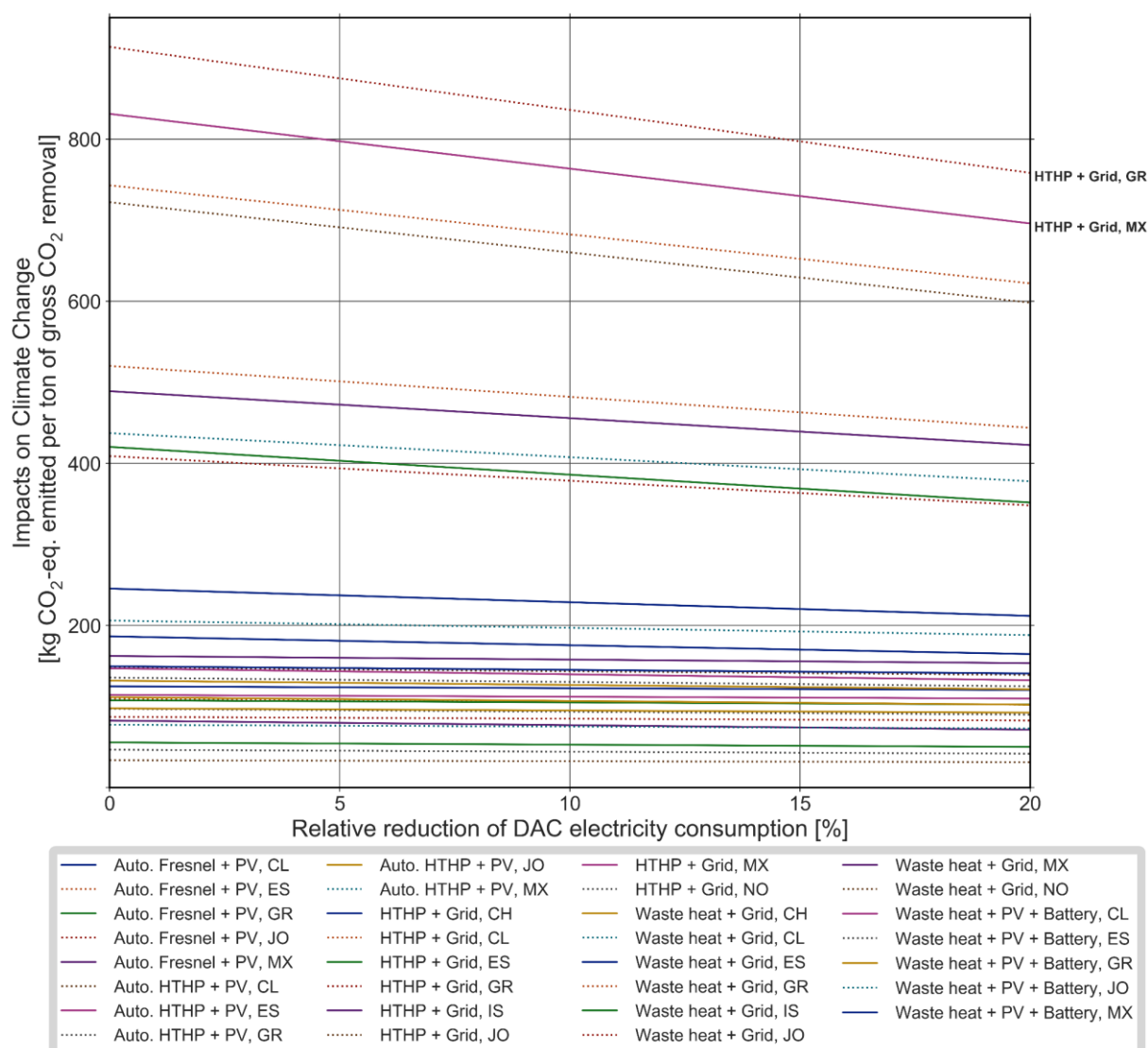


Figure F. Sensitivity analysis on the Climate Change impact category with a reduction of electricity consumption for CO₂ capture.

S9. Ecoinvent 3.6 datasets used for Figure 3.

Table 9 shows ecoinvent datasets used – represented on the x-axis – in Figure 3 of the main article.

Table 9. 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

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

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Abstract

Direct air carbon capture and storage (DACCS) is an emerging carbon dioxide removal technology, which has the potential to remove large amounts of CO₂ from the atmosphere. However, DACCS systems have hardly been evaluated regarding their environmental life-cycle performance. We present a comprehensive life cycle assessment (LCA) of different DACCS systems with low-carbon electricity and heat sources required for the CO₂ capture process - both stand-alone and grid-connected system configurations. The results demonstrate negative greenhouse gas (GHG) emissions - *i.e.* a net removal of CO₂ from the atmosphere - for all eight selected locations and five system layouts. Highest GHG removal potential is found for Norway with a grid-coupled system layout and waste heat usage with a GHG removal efficiency of almost 97%. Autonomous system layouts - entirely supplied by solar energy - prove to be a promising alternative at locations with high solar irradiation to avoid the consumption

of fossil fuel based grid electricity and heat: Their GHG removal efficiency (79%-91%) is at a similar - or even higher - level as grid-connected DAC in countries with rather low-carbon electricity supply and available waste heat, such as Switzerland with a GHG removal efficiency of 87%. The analysis of environmental burdens other than GHG emissions shows some trade-offs associated with CO₂ removal - especially land transformation for system layouts with PV electricity supply - and confirms the need for a comprehensive LCA approach. Further, the sensitivity analysis reveals the importance of selecting appropriate locations for grid-coupled all-electric system layouts, since the deployment of DACCS at geographic locations with CO₂-intensive grid electricity mixes leads to net GHG emissions instead of GHG removal today. However, a prospective global analysis with the integration of two future energy scenarios shows net-negative GHG emissions for the all-electric system layouts on all continents in 2040.

Keywords

Life cycle assessment (LCA), Direct air carbon capture and storage (DACCS), Carbon dioxide removal (CDR), Negative emission technologies (NETs).

Synopsis

We provide a comprehensive life cycle assessment of different direct air carbon capture and storage configurations to evaluate the environmental performance of this supposedly decisive technology in future low-carbon energy systems.

1 Introduction

Carbon dioxide removal (CDR) technologies, or negative emission technologies (NETs), are expected to play a crucial role in the decarbonization of the global energy system, with carbon removal potentials of more than 20 gigatonnes year⁻¹ in 2050.^{1,2} Prospective energy

scenarios, generated by integrated assessment models (IAMs), demonstrate that the 1.5°C target of the Paris Agreement is likely to be infeasible without the large-scale deployment of CDR technologies, and most IAM scenarios rely on the large-scale deployment of CDR technologies to have a chance of more than 50% to reach the 2.0°C target.^{3,4}

Further, CDR technologies are required to a greater extent when climate mitigation is postponed, to compensate for an overshoot of GHG emissions.⁵ A wide portfolio of CDR technologies has been proposed, such as the application of biochar, enhanced weathering (EW), ocean fertilisation (OF), bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).^{1,2,6} However, CDR technologies can have substantial environmental side-effects, such as impacts on land, water and/or soil.^{4,6} For example, CDR technologies associated with biomass feedstock (*e.g.* BECCS and biochar) typically result in intensive land use, soil quality changes and water consumption, while potential unintended side-effects of other CDR technologies (*e.g.* OF) still need to be investigated.^{4,6,7} DACCS systems could largely avoid impacts on the water and food security nexus and can be considered as technology ready for small-scale deployment.^{4,6,8,9} DACCS systems aim to extract CO₂ from ambient air and permanently store the captured CO₂ in a geological storage medium.⁶

Direct air capture (DAC) usually includes two steps, the adsorption (or absorption) step and the desorption (regeneration) step. During the former process, sorbents with strong absorption characteristics are used in a contacting area to bind CO₂, which is challenging due the extreme dilute concentration of CO₂ in ambient air.⁸ The regeneration process aims to regenerate the sorbents and to separate CO₂. The latter process is energy-intensive due to the requirement of heat at relatively high temperature levels.⁸

DACCS systems offer some flexibility compared to other CDR technologies, since they can remove CO₂ independently from point sources, both in time and space.^{6,10} Consequently, optimal locations can be selected, considering CO₂ storage potential and local costs for energy supply.¹¹ DAC systems are usually based either on aqueous solutions with high temperature

regeneration (HT DAC), or on solid sorbents with low temperature regeneration (LT DAC).⁸ This distinction is established based on the temperature level and the sorbent used in the CO₂ capture process.⁸ Few companies currently offer such DAC systems. Carbon Engineering (Canada) implemented HT DAC systems on the North-American market.^{8,12} Climeworks (Switzerland) installed pilot LT DAC plants in Europe and realized the first DACCS project with negative CO₂ emissions in Hellisheiði (Iceland) in 2017.^{8,13} Global Thermostat recently deployed pilot and demonstration plants based on LT DAC in the United States.⁸ Other DACCS initiatives and pilot plants usually apply the LT DAC approach.¹⁴ Generally, not all current DACCS demonstration or pilot plants are designed as DACCS - *i.e.* with permanent storage of captured CO₂ - but rather connect to an industrial carbon utilisation process to reach carbon neutrality.

As emerging technology with a supposedly decisive role in future low-carbon energy systems, DACCS systems must be thoroughly evaluated regarding their environmental performance in a transparent and consistent way over their entire lifetime.⁶ Life cycle assessment (LCA) is a suitable and flexible assessment tool to identify environmental hotspots (*i.e.* the main contributors to environmental burdens) and to evaluate the total life-cycle environmental performance of a product or service.^{15,16} Only few DACCS LCA studies - with mostly limited scopes - have been conducted so far.

De Jonge *et al.*¹⁷ assessed the life-cycle carbon removal efficiency of a HT DAC system and determined the main environmental contributors to overall LCA scores. The contribution analysis revealed a high environmental impact due to energy needed for the CO₂ capture process. A recent DACCS LCA study conducted by Deutz and Bardow¹⁸ showed that two commercial LT DAC(CS) plants - in Hinwil (Switzerland) and Hellisheiði (Iceland) produced and operated by Climeworks - achieved GHG removal efficiencies of 85% and 93%, respectively. The latter study also determined the environmental impacts of six different adsorbents and concluded that climate benefits are mainly influenced by energy sources used for CO₂ capture.

To the best of our knowledge, no comprehensive LCA of DACCS has been published in the scientific literature. We acknowledge that the study of Deutz and Bardow¹⁸ is comprehensive for the DAC system and the associated supply chains, but lacks a detailed assessment of the CO₂ storage stage, since their work only considered electricity demand for CO₂ injection. However, the CO₂ storage stage includes for example environmental impacts from infrastructure (*e.g.* pipelines, injection wells and the compression station), the drilling of injection wells and CO₂ leakage during the transportation of CO₂.^{19,20} Besides, the latter study excludes energy storage when intermittent (renewable) energy sources are integrated and claim that their energy system layouts can be installed at remote locations, while we believe that appropriate energy storage units need to be considered when (renewable) intermittent energy sources are used for the CO₂ capture process - which inevitably leads to additional environmental impacts. Further, the DACCS study of de Jonge *et al.*¹⁷ only focused on the life cycle carbon efficiency, hence excluded other potentially important environmental impacts. In addition, the latter study reported limitations regarding the quality of their life cycle inventory (LCI) data for the DAC infrastructure.

Other available LCA studies mainly focus on DAC, thereby excluding the carbon storage stage required for permanent CO₂ removal from the atmosphere. In addition, these LCAs are simplified regarding LCA modelling choices, such as the exclusion of life-cycle phases and of environmental impact categories besides climate change.⁶ Further, some studies do not consider a certain amount of CO₂ equivalents removed from the atmosphere as functional unit, which impedes the comparison of different CDR technologies.⁶ Essentially, a comprehensive LCA on the entire DACCS supply chain, which assesses multiple environmental impact categories, uses an appropriate functional unit, is transparent in the methodology used, thoroughly assesses all life-cycle stages and examines a wide set of energy sources for CO₂ capture including autonomous system designs, is missing.

In this context, the contributions of this paper can be summarized as follows:

- We present a detailed and transparent LCA of a LT DACCS system - based on Clime-

works' technology and verified with available data on LT DAC - with different electricity (*i.e.* grid and photovoltaics (PV) power) and heat sources (*i.e.* electricity, waste and solar heat) for CO₂ capture.

- Different innovative and autonomous system layouts are included, namely the integration of high temperature heat pumps (HTHPs), the integration of a fresnel solar heat plant at locations with high solar irradiation and system layouts with electricity and heat storage.
- We include several processes needed for CO₂ storage - parameterized on transportation distance, geographical storage location and storage depth: energy needs for compression, infrastructure requirements (*e.g.* pipelines and compression stations), drilling of boreholes, country-specific electricity for the injection of CO₂, and CO₂ leakage resulting from the transportation in pipelines.
- We address land transformation in detail: while grid-connected DACCS systems could exhibit low land requirements compared to other CDR technologies,⁶ direct solar electricity and heat supply for the DAC unit might result in substantial land transformation.^{4,14}
- A global analysis is included for all-electric grid connected DACCS systems.
- We integrate two future IAM scenarios^{21–23} and modify the ecoinvent background LCA database to determine the future global carbon removal potential of grid connected DACCS systems.

The structure of the paper is as follows. Section 2 describes the methodology, where LCA modelling steps and different DACCS system layouts are discussed. Section 3 presents the LCA results, discussions and limitations. Finally, conclusions are drawn in Section 4.

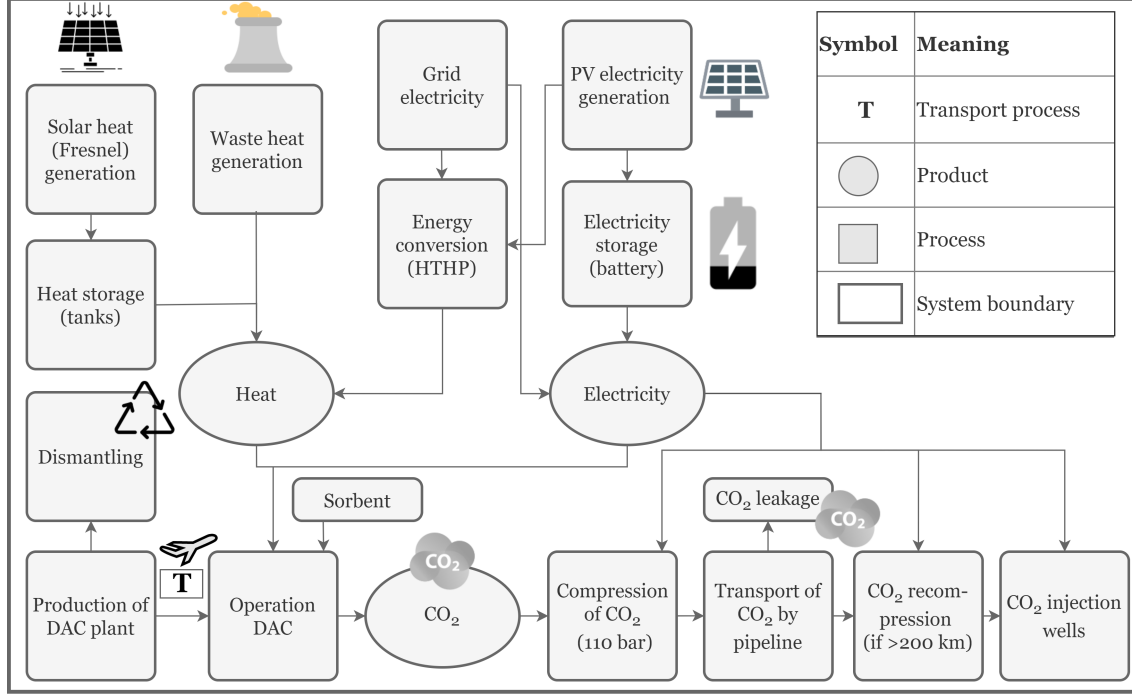


Figure 1: System boundaries of the DACCS product system. Note the different electricity and heat system layouts in the upper part of the figure. All upstream and downstream materials, services and emission flows are included, but are not shown in this figure to reduce complexity. HTHP = high temperature heat pump, DAC = direct air capture.

2 Methodology: Life Cycle Assessment

LCA is a methodology which aims to quantify environmental impacts of a product or service over its entire life-cycle.^{15,16} LCA is standardized by the international organization for standardisation (ISO), where ISO 14040 describes the general principles and framework of LCA²⁴ and ISO 14044 presents guidelines and general practices for LCA.²⁵

2.1 Goal and Scope

Our goal is to quantify the environmental impacts and to determine environmental hotspots (*i.e.* main drivers and processes determining the environmental performance) along the DACCS life-cycle considering low-carbon energy sources for CO₂ capture in different DACCS system layouts. Our work focuses on innovative low-carbon energy sources and electrification

of DACCS systems for the following reasons. Previous analysis of DAC(CS) demonstrated that impacts on climate change mainly depend on the carbon-intensity of electricity and heat sources.^{17,18,26} However, the overall environmental impact of the integration of low carbon energy sources - using a wide set of environmental impact categories - has not been well examined until now. Further, we expect that the penetration of low carbon energy sources and the electrification of energy systems will expand further in the future.²² And finally, site dependent boundary conditions - such as the lack of waste heat, geological CO₂ storage sites or low-carbon electricity from the grid - might require novel system designs including heat and electricity storage allowing for autonomous DAC operation in proximity of geological CO₂ storage sites.

In our analysis, we consider the following countries, which exhibit different climates: Greece, Mexico, Jordan, Spain and Chile are included as (semi)-arid countries with high annual solar irradiation. Besides, cooler and temperate climate regions are covered with Norway, Iceland and Switzerland. We have selected these countries based on their geological storage potentials,²⁷ difference in grid electricity mix,²⁸ climate variations and data availability for the fresnel solar collector. A comprehensive argumentation for the selection of these countries is provided in the supplementary information (SI) Note S2.

Our functional unit is defined as '*Gross removal of 1 ton CO₂ from the atmosphere via the use of a DAC plant combined with geological CO₂ storage*', with a reference flow of a DAC unit removing 100 kt CO₂ year⁻¹ with varying system layouts and electricity and heat inputs as specified in the individual scenarios (see Section 2.2.1). Consequently, total GHG emissions produced from all upstream and downstream DACCS activities should be less than 1 ton CO₂-eq. to result in net negative GHG emissions, *i.e.* net CO₂ removal from the atmosphere.

We identify no multi-functionality of our DACCS system, since the main purpose is to remove CO₂ from the atmosphere in a permanent way. Hence, allocation or system expansion is not required.²⁹

We use the ILCD 2.0 (2018) life cycle impact assessment (LCIA) method³⁰ to assess the environmental performance of the proposed DACCS system layouts. We adopt 16 midpoint categories from ILCD in the protection areas climate change, ecosystem quality, human health, and resources. Further, we add one additional impact category to capture water consumption with the Water Depletion impact category of the ReCiPe 2016 LCIA methodology (1.1 (20180117)).^{31,32} Finally, we are interested in the total amount of land transformed associated with different DACCS configurations, since we include different PV-coupled DACCS configurations which could be land-intensive.^{4,14} Therefore, we aggregate all life cycle inventory flows associated with land transformation (in m²), since the considered environmental impact category 'land use' of the ILCD 2.0 LCIA method represents land use impacts in terms of points and as such does not lead to meaningful land transformation surface areas. Results are shown for impacts on climate change in the main text, while the complete set of results is shown in SI Note S6.

An attributional LCA perspective with the ecoinvent database (v3.6, system model *Allocation, cut-off by classification*^{33,34}) as source of background inventories is applied. The open-source Python package Brightway2 is used to conduct our LCA.³⁵ Our LCIs and corresponding assumptions will be discussed in Section 2.2 and Section 2.2.1. In addition to the analysis for the specific countries listed above, a sensitivity analysis shows GHG emissions of an all-electric system layout for 144 countries on a world map, see Section 3.3.2.

2.2 System Boundaries and Technical Description

We evaluate five different DAC configurations with specific supply of heat and electricity for CO₂ capture:

- (1) Electricity from the grid, heat from a waste heat source.
- (2) Electricity from the grid, heat from a HTHP operated with electricity from the grid.
- (3) Electricity from a PV installation, heat from a fresnel solar-thermal heat collector.

- (4) Electricity from a PV installation, heat from a HTHP operated with electricity from the PV installation.
- (5) Electricity from a PV installation, heat from a waste heat source.

These configurations are detailed in subsequent sections. A simple representation of our system boundaries is shown in Fig. 1. The DACCS product system includes - depending on the specific system configuration - the production and transportation of system components, energy generators and storage units, such as the DAC plant, a fresnel heat plant, PV systems, heat storage tanks and batteries as well as transport and injection of CO₂ and business flights (the so-called "foreground processes"). Detailed assumptions regarding the infrastructure and dismantling of the DAC plant (based on Climeworks' technology), sorbent used for CO₂ capture, business trips as well geological storage of CO₂ are provided in the SI Note S5.

Energy requirements for CO₂ capture are estimated on 500 kWh t_{CO₂}⁻¹ for electricity (without electricity consumption for CO₂ compression) and 1500 kWh t_{CO₂}⁻¹ for heat (at around 100°C).¹⁸ Earlier DAC(CS) LCAs showed that energy consumption for the CO₂ capture can be perceived as the crucial process in terms of environmental impacts.^{17,18,26} Therefore, we evaluate system layouts with different energy sources for the CO₂ capture process. We focus on solar energy, waste heat and all-electric system layouts for the following reasons. First, solar energy is one of the fastest growing renewable energy sources with large potential for further expansion and comparatively low costs and can be used for both heat and electricity production.³⁶ Second, waste heat - if available - can be considered as the optimal heat source due to its low cost and the fact that it comes (almost) burden-free in terms of environmental impacts.^{8,34} Third, further low-carbon electrification of future energy systems can be expected.²²

Large-scale and economically attractive implementation of DACCS might, however, require remote installations close to proper sites for geological CO₂ storage. Therefore, we introduce two autonomous off-grid system layouts entirely based on solar energy. Besides,

three grid-coupled alternatives are considered. DAC operators generally aim for renewables-based energy sources and low-carbon DAC operation, so that exclusively low-carbon grid electricity is an option for them. An overview of the different system layouts (system components, capacities, lifetimes) is given in SI Note S3. The common system lifetime is indicated as 20 years - which is the lifetime of the DACCS unit. In case of a longer lifetime of a system component, we assign a proportional fraction of the inventory of the system component to the DACCS system by dividing the common system lifetime with the lifetime of the system component. An overview of the main parameters used in the DACCS system configurations is provided in Table 1.

Table 1: Main parameters per DACCS configuration. More information per system configuration is provided in SI Note S3.

Main parameters <i>Storage medium(s)</i>	Autonomous (Fresnel + PV) <i>Heat + Battery</i>	Autonomous (HTHP + PV) <i>Battery</i>	HTHP + Grid	Waste heat + Grid	Waste heat + PV + Battery <i>Battery</i>	Unit
Capture capacity	100	100	100	100	100	kt CO ₂ year ⁻¹
Lifetime	20	20	20	20	20	Years
Electricity consumption (for CO ₂ capture, HTHP and compression)	690	1271	1132	614	690	kWh/t CO ₂ captured
Waste or fresnel heat consumption (for CO ₂ capture)	1500	0	0	1500	1500	kWh/t CO ₂ captured
Sorbent consumption	3.0	3.0	3.0	3.0	3.0	kg/t CO ₂ captured

2.2.1 Autonomous (Fresnel + PV)

The *Autonomous (Fresnel + PV)* system layout is supposed to allow for an autonomous off-grid DAC system operation entirely based on solar energy. However, solar energy is intermittent, resulting in fluctuations in power and heat output of the PV and fresnel units.³⁷ These fluctuations are mitigated by two storage media: heat storage tanks and battery electricity storage. This system design enables an assessment based on the common functional unit with the same goal, *i.e.* to capture 100 kt CO₂ annually from the ambient air. Less CO₂ would be captured without a storage medium when the same DAC capacity is installed, since fluctuating electricity and heat supply would not allow for continuous DAC operation.

Solar heat can be generated with fresnel solar collectors when sufficient solar irradiation is present.³⁸ Steam temperatures up to 400°C can be achieved with fresnel solar collectors,

which makes fresnel solar heat an appropriate heat source for industrial applications as well as for DAC systems.³⁹ For the desorption of CO₂ heat at a temperature of 100°C is required.⁸ LCI of the fresnel solar collector has been generated in collaboration with Industrial Solar (Freiburg, Germany), based on an existing fresnel plant in Jordan. Detailed information and LCI of the fresnel system is provided in SI Note S4.

Site-specific annual solar irradiation is a key factor for the design and heat output of fresnel units and therefore, location specific plant designs are required.³⁸ We use data received from Industrial Solar for eight locations in five countries with a direct normal irradiance of more than 2000 kWh/m² year⁻¹, which were comprehensively modelled regarding their techno-economic performance. The sites considered are located in Chile (Antofagasta), Greece (Creta), Jordan (Amman), Mexico (San luis Potosí) and Spain (Tabernas).

Electricity is supplied by large scale ground mounted PV arrays. Therefore, country-specific LCI datasets are generated and used to represent multi-Si PV modules (see SI Note S5). Further, we use a stationary battery system to store excess PV electricity during daytime in order to be consumed during night-time. We include a lithium Nickel-Manganese-Cobalt oxide (NMC) battery, representing mainstream technology for stationary electricity storage today.⁴⁰

We assume that the NMC battery is able to store 12 hours of the electricity load to provide sufficient electricity during night for CO₂ capture and compression, in line with the heat storage sizing and the aim to capture 100 kt CO₂ year⁻¹. The minimum battery storage capacity requirement ($C_{\text{bat,req}}$) is calculated to capture 100 kt CO₂ year⁻¹ considering 12 hours of storage. We oversize the NMC battery to consider battery degradation.⁴¹ Hence, the battery capacity (C_{bat}) is determined by considering the Depth of Discharge (DoD), the discharge efficiency (η_{dis}) and the percentage of the original storage capacity left, required at the end of its lifetime (EoL). We use a DoD of 93%, a discharge efficiency of 94.3% and an EoL capacity percentage of 80%.³⁷ Equation 1 is used to size the energy capacity of the

NMC battery.³⁷

$$C_{\text{bat}} = \frac{C_{\text{bat,req}}}{\eta_{\text{dis}} \cdot \text{DoD} \cdot \text{EoL}} \quad (1)$$

Besides, we assume a C-rate of 0.5 C (*i.e.* two hours for battery charge or discharge) as most appropriate, since the NMC battery is installed in (semi)-arid locations with high PV power peaks. Consequently, a high power capacity could be beneficial to charge during PV power peaks in order to avoid curtailment of PV electricity. Further, we consider additional electricity needed for system layouts with battery deployment to compensate for the Roundtrip Efficiency (RE) related losses of the battery. Hence, the required PV electricity is divided by the RE (*i.e.* 89%) of the NMC battery to function as a safety factor.³⁷ The latter assumption can be perceived as a worst case scenario in order to be conservative, assuming that all produced PV electricity will go through the NMC battery to be used for electricity for the DAC plant.

2.2.2 Autonomous (HTHP + PV)

The *Autonomous (HTHP + PV)* system layout is an all-electric off-grid system entirely supplied by PV electricity, including a HTHP to deliver high temperature heat for the CO₂ capture process. Hence, the difference with our previous system layouts is the replacement of solar heat with heat produced by a HTHP. Further, an NMC battery is used to store PV electricity during the night; the storage capacity of the battery is calculated using equation 1. Note that the battery storage capacity is larger compared to *Autonomous (Fresnel + PV)*, due to the larger electricity requirement for this all-electric system layout. We assume a coefficient of performance (CoP) of 2.9 for the HTHP, which is conservative and at the lower range of presented CoPs of HTHPs.⁴² CO₂ capture via DAC requires heat at relatively high temperatures (100°C), compared to heat temperatures provided by HTHP on the market today, hence a CoP at the lower end of the range seems reasonable.⁴² LCI of the HTHP has been generated by linearly scaling up a 10 kW heat pump from the ecoinvent database, to the appropriate heat pump size (17 MW) to deliver sufficient instant heat for CO₂ capture. We

modify the LCI of the heat pump and use CO₂ (R744) as refrigerant - instead of R134 - based on information from MAN Energy Solutions (Zürich, Switzerland), to represent current and future industrial practices of the HTHP industry.⁴³

2.2.3 HTHP + Grid

The all-electric *HTHP + Grid* system layout contains a HTHP connected to the electricity grid. The same assumptions for the HTHP are used as in the previous system layout. Other energy sources are not required, since grid electricity is available in all selected countries. Consequently, the environmental impact of energy consumption (predominantly) depends on the national grid electricity mix and the performance of the HTHP. Country-specific LCI datasets of the ecoinvent database are used for grid electricity.³⁴ We conduct a sensitivity analysis for future electricity mixes, see Section 2.3.2.

2.2.4 Waste heat + Grid

The *Waste heat + Grid* system layout consumes (industrial) waste heat and is connected to the electricity grid. Note that waste heat comes (almost) burden-free in the *Allocation, cut-off by classification* system model of ecoinvent.³⁴ The *Waste heat + Grid* system layout is only applicable when waste heat at the correct temperature level is available for example generated from industrial processes. Therefore, a location specific assessment is required to identify the potential of waste heat. For simplicity, we decided to include all 8 countries with country-specific LCI from the ecoinvent database for waste heat and grid electricity.³⁴

2.2.5 Waste heat + PV + Battery

The *Waste heat + PV + Battery* system layout consumes PV electricity and waste heat as energy sources for CO₂ capture. For waste heat, the same assumptions are used as in the previous system layout. Assumptions for the provision of PV electricity and battery storage are adopted from the *Autonomous (Fresnel + PV)* layout. Complete LCIs of all system

layouts are provided in SI Note S5.

2.3 Sensitivity Analysis

2.3.1 Reduced electricity consumption

DACCS is an emerging technology and will profit from technological improvements.⁸ This could result in a reduction of energy consumption during the CO₂ capture process. Current figures used for energy consumption (500 kWh t_{CO₂}⁻¹ electricity and 1500 kWh t_{CO₂}⁻¹ heat¹⁸) are based on a very high CO₂ purity in the resulting CO₂ stream.⁸ However, a lower CO₂ purity seems to be compatible with carbon capture and storage (contrary to carbon capture and utilization applications), which might result in lower energy requirements. Therefore, we examine the performance of the proposed system layouts with an electricity consumption of the CO₂ capture process reduced by 20%.

2.3.2 Electrification: HTHP + Grid alternative

The all-electric *HTHP + Grid* system layout is further examined on a global scale to determine GHG emissions (*i.e.* *Climate Change*) of DACCS in 144 countries. We specifically focus on this all-electric system layout in our geographical sensitivity analysis, since energy system models predict an increase of low-carbon electrification in future energy systems.²² Besides, this system layout is the simplest and (theoretically) could be implemented in all locations with a (low-carbon) grid connection providing sufficient electricity, as grid electricity is the only energy source needed. Climeworks has committed - and probably also other DAC suppliers - to only offer carbon dioxide removal services with grid-coupled DAC systems at geographical locations with low GHG intensive grid electricity.

For simplicity, we exclude environmental impacts for transportation and business trips in this sensitivity analysis, since GHG emissions from transportation processes are small according to our results. Further, we use average electricity supply (*i.e.* 'market group for electricity, ..') for countries which are modelled with multiple regional electricity datasets

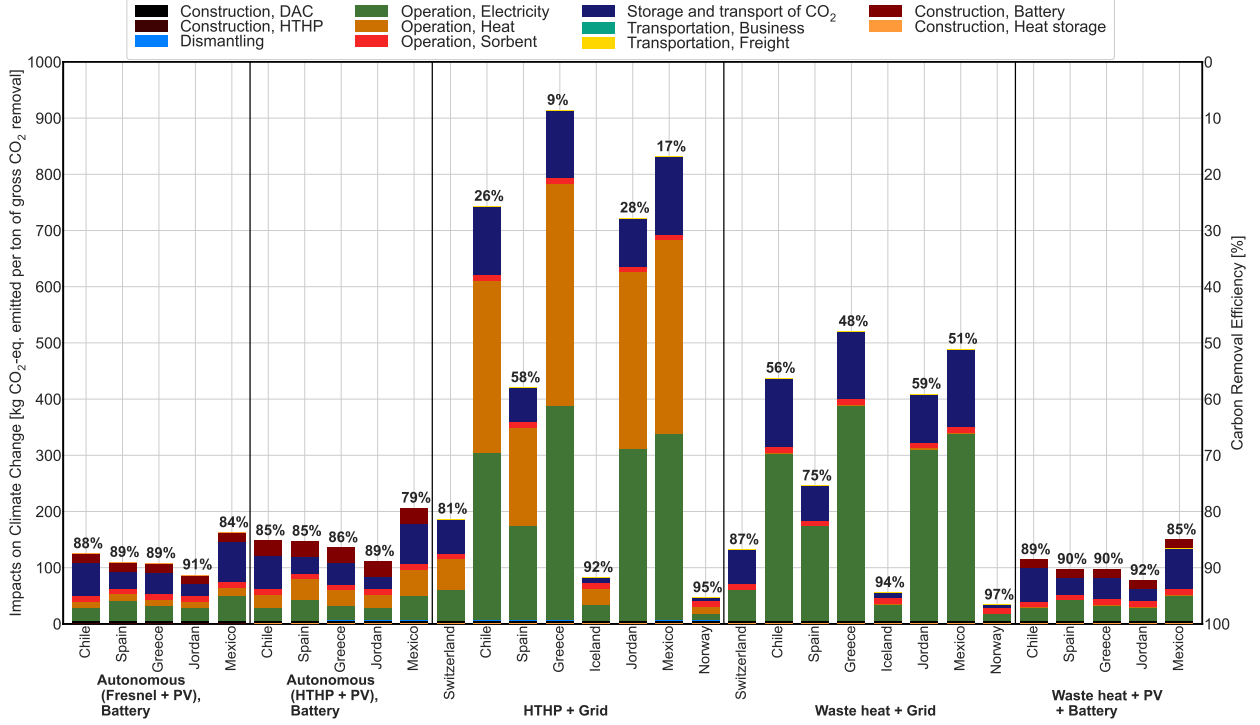


Figure 2: Life-cycle GHG emissions in kg CO₂-eq. per ton of gross CO₂ removal with the DAC plant as well as carbon removal efficiencies [%], for different system layouts in selected countries. The size and colors of the bar segments correspond to the contributions of specific processes to the total life-cycle GHG emissions. Note that 'Storage and transport of CO₂' includes compression, transportation, re-compression, injection and the infrastructure requirements during the CO₂ storage stage.

in the ecoinvent database. In case there is no country-specific electricity dataset available, we use the market (group) for electricity for the geographical area in which this country is located as approximation. Further, we assume a generic transportation distance for CO₂ of 500 kilometers to the injection wells and a generic storage depth of 2000 meters.

2.3.3 Future electrification: HTHP + Grid alternative

Projections of IAMs show that electricity grid mixes will become less CO₂-intensive, even in the most carbon intensive energy scenarios.^{21,22} Therefore, we examine GHG emissions of the *HTHP + Grid* system layout based on future grid electricity mixes for 2040. To achieve this, we use these future grid mixes for electricity supply for the DAC unit by modifying the

ecoinvent background database with the `rmnd-lca` Python package,⁴⁴ adapting future electricity mixes in our background database, based on the output figures of the REMIND model scenarios.²¹ Note that this results in geographically aggregated future electricity datasets, since the REMIND model subdivides the world into only 11 regions.

Firstly, we use the *SSP2-Base* energy scenario to determine future GHG emissions of the *HTHP + Grid* system layout. The *SSP2-Base* scenario is a scenario with no additional climate policy.^{21,44} Secondly, we include a more ambitious future climate policy with the *SSP2-PkBudg1300* energy scenario, which corresponds to a maximum average temperature increase of 2°C.⁴⁴

3 Results and discussion

3.1 Assessment of Climate Change impact

The outcome of the assessment of the "Impacts on Climate Change" of DACCS technologies for the different system layouts and countries considered is illustrated in Fig. 2 and 3. The former figure is a bar chart plotting the climate change impact in kilograms of CO₂ emitted per gross removal of 1 ton CO₂ from the atmosphere via the use of a DAC plant (left vertical axis) as well as the net carbon removal efficiency (right vertical axis, increasing from top to bottom, and figure reported above each bar); each bar consists of the overall impact, whereby the life-cycle contributions of eleven different upstream and downstream components of the value chain are identified with different colors. The latter figure plots the (linear) dependence of the climate change impact (and of the carbon removal efficiency) on the GHG intensity of electricity generation for the different system layouts; the different slopes of these lines reflect the electricity demand of each specific system layout (and its corresponding impact on Climate Change), whereas the vertical gray dashed lines indicate the GHG intensities of different electricity generators and national grid electricity mixes according to the ecoinvent 3.6 database.³⁴

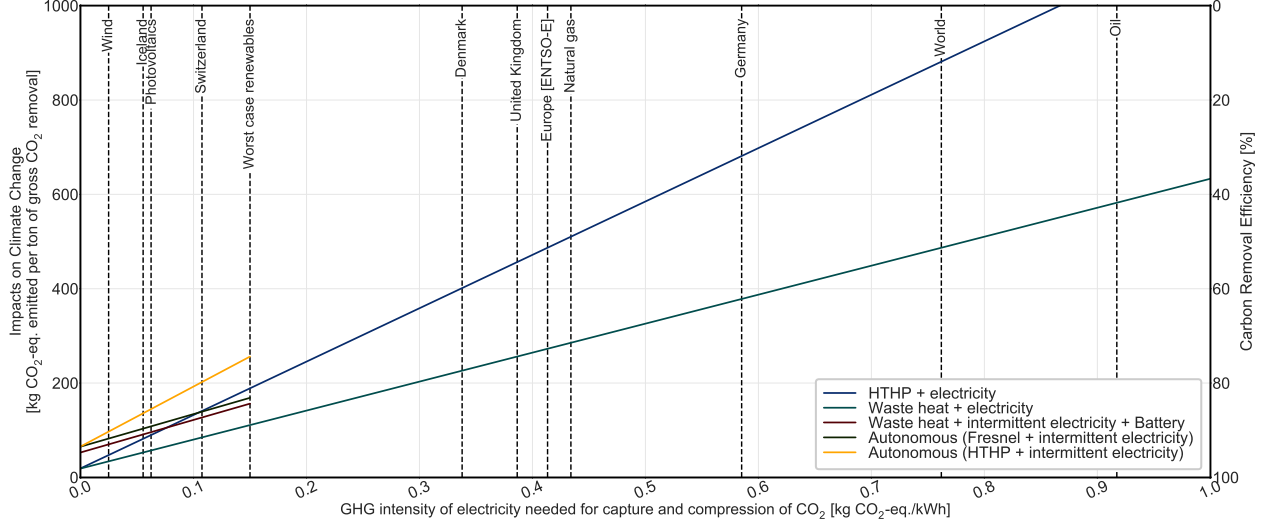


Figure 3: Effect of the GHG-intensity of electricity used - needed for capture and compression of CO_2 - for all alternatives on the overall GHG emissions of DACCS systems. We use the LCI of Norway as proxy for *HTHP + electricity* and *Waste heat + electricity*. Further, LCI of Spain is used for the following configurations: *Waste heat + intermittent electricity + Battery*, *Autonomous (Fresnel + electricity)* and *Autonomous (HTHP + intermittent electricity)*. Note that the *Autonomous (Fresnel + intermittent electricity)* alternative can only be installed in (semi)-arid locations due to the requirement of high annual solar irradiation. Besides, the waste heat alternatives can only be installed with sufficient supply of waste heat. The DAC configurations operated with intermittent electricity are shown up to a GHG intensity of electricity supply of 0.15 $\text{kg CO}_2\text{-eq./kWh}$, which represents a worst case for renewables. The countries and specific power generation technologies on the x-axis represent the GHG-intensities of national electricity grids and technologies according to ecoinvent, see SI Note S9.³⁴

Note that for all cases - considered in Fig. 2 - the climate change impact is smaller than the amount of CO_2 removed and stored, *i.e.* negative emissions are indeed generated in all cases. However, the range of carbon removal efficiencies is large, going from only 9% all the way to 97%. It is worth noting that carbon removal efficiency has a strong impact on unitary costs per net CO_2 removed. If we assumed that the two value chains leading to 9% and to 97% removal costed the same per ton CO_2 removal, say 100 monetary units, then the unitary cost per net CO_2 removed would be 1,111 and 103 monetary units, respectively. Besides, the carbon removal efficiency can be strongly dependent on the GHG footprint of electricity generation, as illustrated in Fig. 3. The main findings can be summarized as follows.

Energy supply - heat and electricity used for CO₂ capture - is the key factor driving GHG emissions of DACCS configurations. Waste heat is environmentally attractive as heat supplier when available, as waste heat comes (almost) burden-free in the *Allocation, cut-off by classification* system model. GHG emissions generated from energy consumption can be reduced by using renewable energy: in our analysis solar energy in countries with high annual solar irradiation.

The GHG-intensity of the grid electricity mix is a crucial factor for grid-coupled DACCS configurations and is very country-specific. Consequently, countries with low GHG intensive electricity mixes in combination with waste heat exhibit lowest GHG emissions, with GHG removal efficiencies of almost 97% and 94% for Norway and Iceland, respectively. On the contrary, high GHG emissions are generated - almost approaching net-positive GHG emissions in Greece with 0.91 ton CO₂-eq. per ton of gross CO₂ removal - for grid-coupled DACCS configurations when the national electricity grid relies on a large share of fossil fuels. Fig. 3 shows that the break-even point - in terms of net-negative GHG emissions for the grid-coupled HTHP DACCS configuration (*HTHP + Grid*) - is on ~ 0.87 kg CO₂-eq. kWh⁻¹ electricity used for the capture and compression of CO₂.

In absolute terms, minor GHG emissions are generated from the DAC construction (6 kg CO₂-eq. per ton of gross CO₂ removal) and sorbent consumption (10 kg per ton of gross CO₂ removal). However, these components can be substantial in relative terms, if energy supply for CO₂ capture is clean in terms of GHG emissions. The relative Climate Change impact of transportation processes directly related to DAC (*i.e.* business and freight transport, for the collectors and process units) can be considered small, with contributions of less than 1%.

GHG emissions from the storage and transport of CO₂ are significant - and their relative contribution fluctuate between 11-52% - mainly driven by electricity requirements for the compression, recompression and injection of CO₂ as well as CO₂ leakage during long distance CO₂ transport, respectively. Note that we included the Medium scenario presented in Holloway *et al.*²⁰ for CO₂ leakage during transportation. The contribution of CO₂ leakage

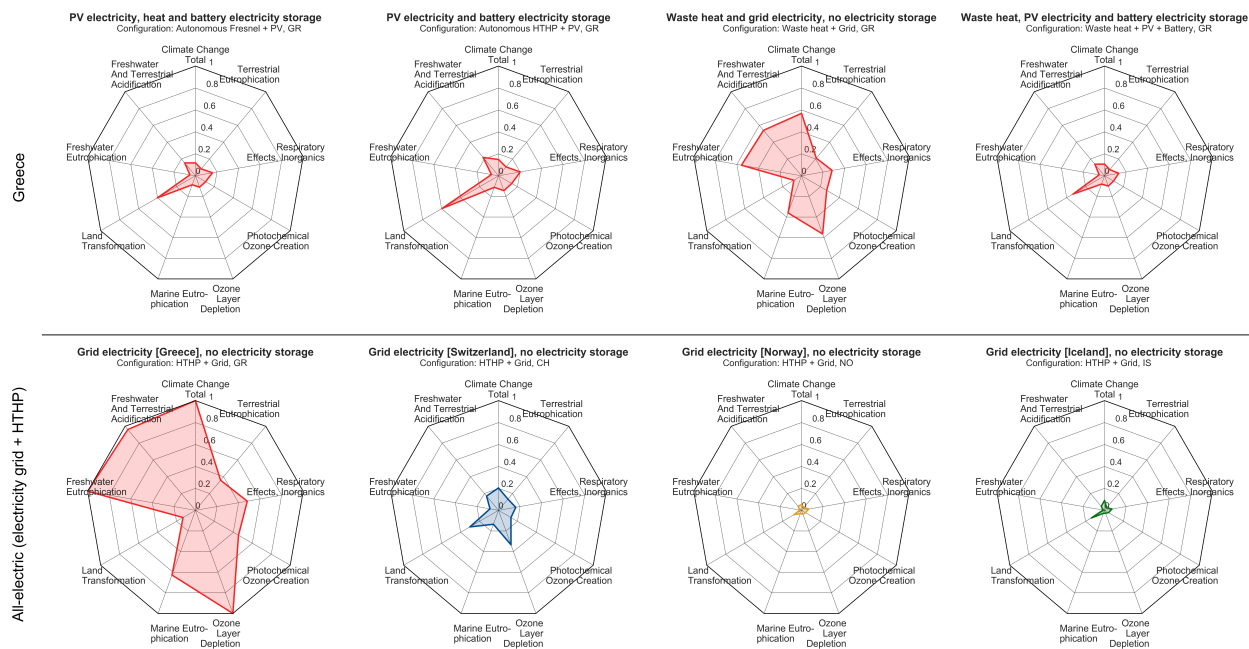


Figure 4: Spider graphs illustrating environmental trade-offs for a selection of DACCS configurations on nine environmental impact categories with a focus on Greece and all-electric DACCS configurations, please refer to the main body of the text for an explanation of this selection. Complete spider graphs considering all DACCS system configurations and environmental impact categories are provided in SI Note S6.

during the transportation of CO₂ in pipelines would increase by a factor of 10 if we used their Pessimistic scenario for CO₂ leakage, which emphasizes the need for a well-designed pipeline network for CO₂ transportation.

DACCS-related GHG emissions in countries with a CO₂-intensive grid electricity mix can be substantially reduced by shifting to renewable energy sources as energy suppliers and can be installed as (nearly) autonomous DACCS configurations. The GHG removal efficiencies of autonomous system layouts - entirely supplied by solar energy - are in between 79-91% and are therefore at a similar - or even higher - level as grid-connected DAC in countries with rather low-carbon electricity supply and available waste heat, such as Switzerland with a GHG removal efficiency of 87%.

Autonomous system layouts with a fresnel solar collector exhibit slightly higher GHG removal efficiencies (84-91% for *Autonomous (HTHP + electricity)*) in comparison with

autonomous DACCS configurations entirely based on PV arrays in combination with a HTHP (79-89% for *Autonomous (HTHP + electricity)*), mainly due to the provision of lower carbon heat with a fresnel solar collector and the requirement of a smaller battery (~ 125 MWh vs. ~ 221 MWh). A bigger battery is required for autonomous configurations with a HTHP as electricity needs to be stored to provide sufficient electricity to the HTHP during night. Further, the production of heat storage tanks (made of low-alloyed steel) causes lower GHG emissions compared to the production of bigger battery energy storage systems, which means lower GHG emissions for DACCS configurations with fresnel heat.

The production of electricity storage (NMC battery) mediums can - in relative terms - have a significant impact on GHG emissions, from 10% to 24%, while that of the production of the heat storage (steel tanks) units is small with a relative contribution of less than 1%. Consequently, GHG emissions from the infrastructure of autonomous systems are comparably higher (see the lower-left part of Fig. 3), due to the impact of the production of energy storage units, such as battery energy storage systems. Fig. 3 illustrates how alternatives with waste heat consumption, and the autonomous system layout coupled with fresnel heat (*Autonomous (HTHP + electricity)*), are less sensitive when using high GHG intensive electricity, due to less electricity consumption required for CO₂ capture. For example, the autonomous DACCS configuration with fresnel heat generates solar heat and therefore less electricity is required for CO₂ capture, although this alternative can only be installed at locations with sufficient annual solar irradiation.

3.2 Assessment of other environmental impact categories

Fig. 4 illustrates the overall environmental burdens and trade-offs for a selection of DACCS configurations and environmental impact categories. The spider graphs show the normalized scores (scores from 0 to 1, visualized with the colored line) of DACCS configurations on nine environmental impact categories, normalized to the system configuration with the highest environmental impact among all configurations (*i.e.* highest score = 1, presented in SI

Note S6) on a specific environmental impact category. A greater colored area therefore demonstrates an overall higher environmental burden for a specific DACCS configuration.

Environmental impact categories - presented in Fig. 4 - are selected based on recommendations by Fazio *et al.*³⁰ We only show impact categories of recommendation level I and II in the main article and add land transformation, since these are important for CDR technologies in general.⁶ Greece is included as a reference and worst-case scenario regarding GHG emissions. All-electric DACCS system configurations - *i.e.* *HTHP + grid electricity* - exhibit a large sensitivity regarding overall environmental impacts between countries. We therefore include three other countries with cleaner electricity mixes in terms of GHG emissions - Switzerland, Norway and Iceland - since Climeworks has committed to only offer carbon dioxide removal services with grid-coupled DAC systems at geographical locations with low GHG intensive grid electricity. The complete set of spider graphs and results for all DACCS configurations and environmental impact categories is provided in SI Note S6.

In general, lowest overall environmental burdens can be achieved with DACCS configurations with waste heat in combination with renewable electricity supply, for example in Norway and Iceland. Fundamental differences between environmental impact categories and countries are found for grid-coupled DACCS configurations in combination with a HTHP. This is illustrated in the second row of Fig. 4. Low overall environmental burdens can also be achieved with grid-coupled DACCS configurations - in combination with a HTHP (*Autonomous (HTHP + electricity)*) - when the national grid electricity mix is based on a large-share of renewables as for example in Norway and Iceland, which both rely on a high share of hydropower. Switzerland has slightly higher overall environmental burdens compared to Norway and Iceland, mainly due to a higher reliance on nuclear power and fossil fuels, respectively.

On the contrary, substantially higher environmental burdens are generated from grid-coupled DACCS configurations when the national grid electricity mix is based on a large share of fossil fuels as for example in Greece (see Fig. 4). This generally results in high

environmental burdens on almost all environmental impact categories.

Autonomous DACCS configurations generate low environmental burdens on almost all environmental impact categories, although several environmental trade-offs occur. The most important one concerns land use, which can be considered as the main "outlier" among all the impact categories: Autonomous DACCS layouts with solar energy supply perform in general worse than grid-connected systems on land transformation (see the first 2 spider graphs in the top row of Fig. 4). Fig. E - in SI Note S7 - presents a detailed contribution analysis on land transformation (in m^2), and reveals that autonomous energy systems exhibit large land transformations (up to 1.87 m^2 per ton of gross CO_2 removal), mainly due to large surface area requirements for ground mounted PV panels and the fresnel heat collector, while the DAC unit as such exhibits very low land transformation impacts (a life-cycle land transformation of 0.01 per ton of gross CO_2 removal). In addition, autonomous energy systems exhibit comparatively high environmental scores on the Minerals and Metals impact category (see SI Note S6), mainly resulting from material requirements for the production of PV arrays and the NMC battery. Note that this impact category is associated with substantial uncertainties and also methodological shortcomings, and is therefore assigned with recommendation level III.³⁰

These examples demonstrate the importance to assess and compare system layouts on a wide set of environmental impact categories to examine environmental trade-offs.

3.3 Sensitivity Analysis

3.3.1 Reduced electricity consumption

Fig. E - in SI Note S8 - demonstrates the absolute change in the Climate Change impact category when the electricity consumption for the CO_2 capture process is reduced by up to 20%. Such an efficiency improvement would result in substantial reductions of impacts on Climate Change for system layouts which consume large amounts of CO_2 -intensive electricity (*i.e.* *HThP + Grid* in Greece and Mexico). In contrast, the environmental impact of such

a electricity reduction is hardly visible for configurations using low-carbon energy sources. Nevertheless, reducing pressure on the electricity grid requires increased efficiency of any technology, including DACCS.

3.3.2 Electrification: HTHP + Grid alternative

Fig. 5 illustrates the performance on the Climate Change impact category for the *HTHP + Grid* system layout for 144 countries. Net-negative GHG emissions can be obtained when life-cycle GHG emissions are lower than 1000 kg CO₂-equivalent per ton of gross CO₂

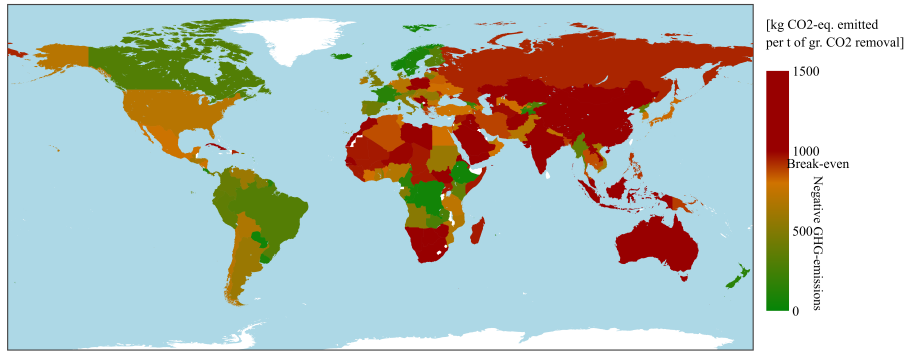


Figure 5: Country-specific results for the Climate Change impact category for the *HTHP + Grid* system configuration. Green and orange indicate net-negative GHG emissions, while dark red shows net-positive GHG emissions of DACCS.

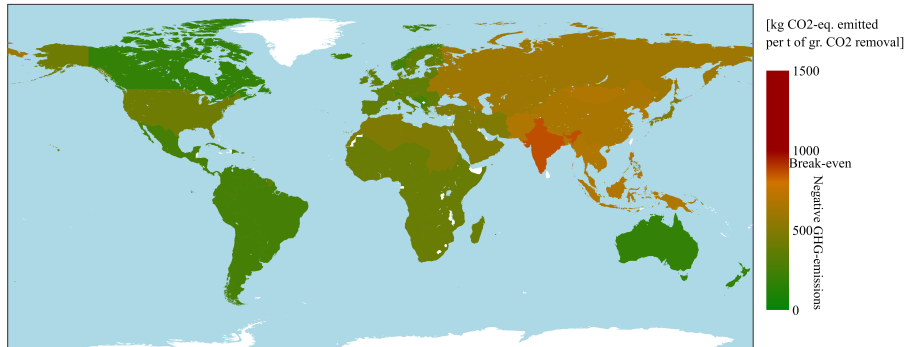


Figure 6: Results for the Climate Change impact category for the *HTHP + Grid* alternative, according to the *SSP2-Base* scenario. Green and orange colors indicate net-negative GHG emissions, while dark red shows net-positive GHG emissions.

removal. Countries which fulfill this requirement are shaded in green and orange (*i.e.* orange meaning higher GHG emissions than green). Net positive GHG emissions are shown in dark red.

Significant variations between countries can (mainly) be explained by the difference of the CO₂-intensity of national grid electricity mixes. For the *HTHP + Grid* system layout, the GHG break-even point is reached with a grid electricity mix GHG intensity of ~ 0.87 kg CO₂-eq. kWh⁻¹ electricity (see also Fig. 3 for the break-even point) - which means that grid electricity mixes with a lower GHG intensity than the GHG break-even point exhibits GHG removal from the atmosphere. It turns out that most countries in Europe, North-America, South-America and central Africa already show large GHG removal potentials with DACCS *HTHP + Grid* system layouts today. However, few countries in these continents exhibit net-positive GHG emissions. In general, Australia and countries in Asia, Southern Africa and Northern Africa are nowadays not (or less) suitable to install DACCS *HTHP + Grid* systems.

3.3.3 Future electrification: HTHP + Grid alternative

Fig. 6 demonstrates the possible future impact (in the year 2040) regarding the Climate Change impact category for the *HTHP + Grid* system layout according to the *SSP2-Base* scenario of the REMIND model,^{21,23} which extrapolates observed trends, but is not particularly ambitious in terms of climate policy. It turns out that the deployment of *HTHP + Grid* DACCS system layouts could result in net-negative GHG emissions in all world regions in 2040. North-America, South America, Europe, Australia and Africa exhibit a large net GHG removal potential, while India and Asia seem to be less suitable due to their still relatively high CO₂-intensive grid electricity mix.

When implementing a more ambitious climate scenario (*i.e.* *SSP2-PkBudg1300*) DACCS in all regions exhibits GHG emissions of less than 230 kg CO₂-eq. per ton of gross CO₂ removal in 2040. Hence, all regions would be green if the world map for this case were drawn

using the same color codes as used for Figures 5 and 6. Therefore, effective climate policy would be very beneficial for all-electric DACCS system layouts connected to the grid.

Note that in these two prospective evaluations we not only use future regional electricity mixes for electricity supply to the DACCS unit, but also populate the scenario-specific development of the electricity sectors throughout the entire background LCA database. This procedure results, for example, in a reduction of GHG emissions due to PV electricity, since the electricity used for PV wafer production exhibits a scenario-specific GHG intensity lower than today's.

3.4 Discussion - limitations and future work

Our analysis shows that within the LCA of DACCS systems, there are few elements and key factors, which determine the results: first of all, energy required for DAC operation and the sources of supply. While we consider data availability and quality regarding energy demand of and supply for, respectively, the CO₂ capture process - the most crucial factor by far driving LCA results - to be high, there are other issues, which call for further analysis in the future. More sophisticated modeling integrating operational experience of DAC units of different scale and at different locations to be gained in the future will allow for a more precise representation of the environmental burdens due to DACCS. We discuss the most important of these elements in the following subsections.

3.4.1 High Temperature Heat Pumps (HTHPs)

We included a HTHP in different DACCS system layouts. Currently, no complete LCA of HTHP has been conducted. We received information regarding potential future refrigerants used in HTHPs from MAN Energy Solutions (Zürich, Switzerland), but had to establish most of our LCI as an extrapolation of a low-temperature HP. Future analysis should consider the utilization of different types of refrigerants, since refrigerants usually exhibit large contributions to environmental burdens caused by heat pumps.^{42,45}

3.4.2 Assessment of fresnel heat plant in other locations

Only five potential locations for the fresnel solar collector were included in the analysis due to the site-specific performance of fresnel solar collectors and limitations on data for further locations. The fresnel performances at these locations in semi-arid climate regions were thoroughly modelled by Industrial Solar (Freiburg, Germany). Since the integration of fresnel solar heat systems turned out to be beneficial from the environmental perspective, especially for autonomous DACCS systems, site-specific assessments and modelling should be expanded to determine the environmental merits in other geographical locations.

3.4.3 Competition between electricity sources

Future energy systems tend to show higher reliance on electricity than current energy systems. Additional electricity will be required by the mobility and heat sector, possibly on top of increased power demand due to population growth and higher electrification rates. Increasing the pressure on the power sector through the installation of grid-coupled DACCS systems competes with other demands of electricity. This was not a topic of our research, but has to be considered.

3.4.4 Battery storage in (semi)-arid countries

We proposed to install NMC batteries in (semi)-arid countries (*i.e.* Chile, Spain, Greece, Jordan and Mexico) with high ambient air temperatures. Temperature levels within these countries could easily reach more than 40°C during warm periods. The acceptable temperature range for lithium-ion batteries is between -20°C and 60°C, with an optimal operation temperature between 15°C and 35°C.⁴⁶ Therefore, location-specific measures should be considered when outside temperatures approach critical temperature levels to avoid battery damage. These measures could result in additional energy and/or material requirements, *i.e.* higher environmental impacts.

3.4.5 Autonomous system layouts

Two autonomous system layouts - entirely based on solar energy supply - were included: *Autonomous (Fresnel + PV)*, and *Autonomous (HTHP + PV)*. Twelve hours of energy storage capacity was assumed for storage mediums for these two system layouts. This led to a large storage capacity needed for both the battery system (~ 125 MWh and ~ 221 MWh, respectively) and the heat storage tanks.

Alternatively, a doubling of the DAC capacity (in order to comply with our functional unit) with discontinued operation over night could be installed to reduce the need for energy storage in the proposed two autonomous system layouts. However, we emphasize that such a system with doubled DAC capacity would still require energy storage for intermittent (renewable) electricity generation, which would result in additional environmental impacts from the production of storage mediums. Further, a doubling of the capacity of the DAC plant would incur large additional capital expenditures for the DAC plant, since capital expenditures of DAC systems are still high.⁸ Therefore, we argue that such a DAC system is currently unrealistic from an economic and technological point of view - and further research is required for a complete assessment of the operation of such an autonomous DAC system.

Further, more sophisticated research is needed to confirm the self-sufficiency - *e.g.* the 12 hours of energy storage - of the proposed autonomous system layouts. For the *Autonomous HTHP + PV*, the environmental and economic performance can possibly be (slightly) improved with the installation of a heat storage medium to reduce the size of the battery. In this way, heat supply - needed for the CO₂ capture process - can be stored in a heat storage medium instead of electricity storage in a battery.

In addition, autonomous system designs with DAC units entirely powered by solar energy require site-specific assessments in terms of land use. The area covered by PV arrays required for electricity supply for a DAC unit removing 100 kt CO₂ year⁻¹ in our most land-intensive case and location (*i.e.* *Autonomous HTHP + PV* in Mexico) amounts to a direct land transformation (for the DAC unit and PV panels considering their lifetimes) of almost 4.7

km². Such a land surface area will not always be available. The scale up of solar PV-coupled DACCS to the gigatonne scale - for example removing 1 Gt CO₂ year⁻¹ from the atmosphere with a GHG removal efficiency of 79% (representing worst case *Autonomous HTHP + PV* for Mexico) - would therefore require a direct land transformation area as large as ~59,000 km²; which is almost 1.5 times the total land surface area of Switzerland.

Land surface area requirements can be significantly reduced by for example using grid electricity sources, although this would result in indirect land use transformations mainly generated from electricity generators. Note that the land transformation for PV panels includes area requirements for the open ground power plant including the space in between the modules as well as some surrounding area,³⁴ and can therefore be considered as conservative. Further, the land between and underneath the PV modules may be used for grazing of small livestock such as sheep or poultry, bee-keeping, or other innovative agricultural uses. Such land use options should already be considered during the design phase of the solar field.

3.4.6 Location-specific limitations

Location-specific assessments are required to identify the availability of waste heat from industrial applications. For example, waste heat could be inaccessible in remote locations, which would limit the design options. Furthermore, decarbonization of the energy system with reduced combustion of fossil energy carriers might result in a reduction of waste heat sources in general, and/or at the required temperature level. However, grid-coupled and autonomous DACCS energy systems provide - in environmental terms - a good alternative for waste heat in these situations.

Another site-specific boundary condition of DACCS is the availability of geological storage sites. We therefore examined different transportation distances from CO₂ capture to the injection wells, although the transportation distance of CO₂ can be minimized - to avoid CO₂ leakages from the transportation of CO₂ - by installing the DAC facility close to geological storage sites. However, the large scale deployment of DACCS requires large geological

storage potentials and therefore CO₂ transportation might be required. This could result in competition for geological storage sites between DACCS and for example carbon capture and storage from conventional power plants, which could limit the large-scale implementation of DACCS.

3.4.7 Future electrification: REMIND regions

We used the outputs of the IAM REMIND²¹ for quantification of future GHG-intensity of electricity supply and to modify our background LCA database to assess the future performance of all-electric DACCS systems. However, the geographical resolution of the REMIND model is limited to 11 world regions. Therefore, the future environmental potential of the electrified system layouts had to be aggregated to those regions, while our results for current systems showed that regional differences can be significant in terms of GHG emissions (see Fig. 5). Further geographical disaggregation would be beneficial for prospective LCA of DACCS, especially for all-electric system layouts. However, our findings demonstrate very well how effective climate policy could improve the environmental performance of all-electric DACCS systems. On the other hand, the decarbonization of the power supply system could lead to additional environmental impacts on other life-cycle environmental impact categories. Luderer *et al.*⁴⁷ investigated benefits and side-effects of the decarbonization of power supply.

3.4.8 Comparison with literature on DACCS

The single purpose of DACCS systems is to remove CO₂ from the atmosphere in a permanent way. Our analysis focused on LT DACCS systems and must not be considered as representative for HT DACCS systems, due to the need of different processes for CO₂ capture and their associated energy requirements.^{8,48}

One recent DACCS LCA study of Deutz and Bardow¹⁸ examined the same LT DAC technology of Climeworks although focused on a smaller DAC plant (with a capture capacity of 4 kt CO₂ year⁻¹), and therefore provided less detailed results for the larger DAC plant

(with a capture capacity of 100 kt CO₂ year⁻¹). Their GHG removal efficiencies are generally slightly higher compared to the reported GHG removal efficiencies in this work. For example, Deutz and Bardow¹⁸ found a carbon removal efficiency of 88.8% for Switzerland - consuming the same amount of grid electricity and waste heat as energy sources for CO₂ capture as our analysis - for the 4 kt CO₂ year⁻¹ DAC facility. The CO₂ removal efficiency can be expected to be higher for the 100 kt CO₂ year⁻¹ DAC facility, due to reductions of sorbent consumption as well as the optimization of the DAC infrastructure (see Section 2.2 and SI Note S1). Reported GHG emissions of the carbon storage phase turned out to have a minor contribution with less than 2% on total GHG removal efficiencies for DACCS configurations with GHG removal efficiencies higher than 86%.

On the contrary, our results show a lower GHG removal efficiency of 86.8% for the waste heat and grid electricity configuration (*Waste heat + Grid*) in Switzerland; (even) for a DAC plant with a capacity of 100 kt CO₂ year⁻¹. First, this can be partly explained by the application of different background LCA data; ecoinvent 3.6 in our analysis vs. both Gabi and ecoinvent 3.5 in Ref.¹⁸ Second, our analysis includes a more thorough (and conservative) analysis regarding the transportation and storage of CO₂, while Ref.¹⁸ expected sufficient CO₂ storage sites close to the DAC facility as well as the utilization of existent infrastructure for CO₂ storage; they therefore excluded CO₂ transportation and infrastructure requirements for geological storage sites. However, the availability of geological storage sites for DACCS can be limited due to geographical availability as well as the competition with conventional CCS and other CDR technologies, such as BECCS (see Section 3.4.6). For Switzerland, CO₂ leakage during transportation (1500 km) reduced the GHG removal efficiency already by more than 2%, while the compression, recompression and injection of CO₂ as well as infrastructure requirements further reduced the GHG removal efficiency to a total of 6% in our analysis.

In addition, the work of Deutz and Bardow¹⁸ reported a generic land use requirement of 4,450 km² (3,683 DAC plants with a capture capacity of 100 kt CO₂ year⁻¹, with 1.21

km² per DAC plant) for PV-coupled DACCS to capture 1% of global CO₂ emissions in year 2019 (0.368 Gt CO₂¹⁸). Our main environmental trade-off was found for land transformation; manifested by the big range of both direct and life-cycle land transformations between DACCS configurations and countries. The worst case land transformation scenario in our analysis demonstrated much higher land use requirements for autonomous PV-coupled DACCS systems; almost 4.7 km² per DAC facility (with a capacity of 100 kt CO₂ year⁻¹), mainly due to lower annual solar irradiation for this specific location (and for the reason given in Section 3.4.5).

Since our analysis and this comparison show that specific DACCS system configurations at different locations exhibit very different environmental performances and that transport and storage of CO₂ can cause substantial burdens, we argue to perform site-specific assessments of DACCS configurations during the design phase, including a thorough analysis of the transportation and storage of CO₂ as well as a location-specific assessment of land use requirements.

3.4.9 Comparison with CDR technologies

Comparison of DAC(CS) LCA results with other CDR technologies or CO₂ sources for carbon capture and utilization should consider the variability of the life-cycle GHG removal efficiency, as demonstrated by our analysis. This is, however, not always the case and the presentation of the GHG removal performance of DAC(CS) as one single number can be misleading (*e.g.* by Müller *et al.*²⁹ for DAC).

Further, DACCS systems should be compared with other CDR technologies on the same functional unit - to evaluate benefits and potential trade-offs of various CDR technology options.⁶ We propose to compare CDR technologies per unit of CO₂-removal from the atmosphere. Unfortunately, we are currently not able to present such a comparison between CDR technologies due to the immature research state of CDR technologies in general.⁶

4 Conclusion

Our paper aimed to determine the life-cycle environmental performance of low temperature DACCS systems with low carbon energy sources for CO₂ capture. The results were presented per ton of gross CO₂ removal with a DAC plant of an annual capture capacity of 100 kt CO₂ year⁻¹ based on Climeworks' technology. We included different energy sources - solar heat, waste heat and electricity by means of a HTHP - to deliver heat to the DAC plant. In addition, different electricity sources - PV and grid electricity - were considered to supply electricity to the CO₂ capture process. The results were presented for different system layouts for eight geographic locations with specific assumptions regarding CO₂ transport and storage after capture.

The results demonstrated that energy supply - heat and electricity used for CO₂ capture - is the key factor driving GHG emissions of DACCS configurations. All eight selected countries exhibited net-negative GHG emissions on all proposed system layouts, meaning that GHG emissions associated with energy supply and material demand for DACCS are below the amount of gross CO₂ removal, equivalent to a net-removal of CO₂ from the atmosphere. However, the level of "net-negativity" showed substantial variation between DACCS layouts and countries of application: while in our best case almost 97% of the captured CO₂ is permanently removed from the atmosphere, our worst case resulted in a life-cycle GHG removal rate of less than 9%. The best climate change-related performances were achieved by system layouts using waste heat - and in countries with low CO₂-intensities of the national electricity grid. The CO₂-intensity of the national grid electricity mix turned out to be the crucial factor for grid-coupled system layouts.

Autonomous DACCS layouts - which consume solar energy - are from an environmental perspective (except for land use considerations) promising alternatives in regions where the grid electricity mix relies on a high share of fossil fuels and at remote locations without grid access (potentially close to CO₂ storage sites). Therefore, we recommend solar-based autonomous DACCS systems for countries with (semi)-arid climates, which have a CO₂-

intensive grid electricity mix and the required land area available. All-electric DACCS system layouts are recommended when the national grid electricity mix relies on low-carbon electricity sources. Further contributions to life-cycle GHG emissions of DACCS - associated to for example DAC infrastructure, CO₂ transport and storage, and energy storage units - can be substantial in relative terms, if energy supply for CO₂ capture is clean in terms of GHG emissions, but absolute GHG emissions due to these contributions are rather small. The assessment of a wide variety of environmental impact categories - in addition to impacts on climate change - showed different trade-offs on a few environmental impact categories, especially regarding land transformation associated with PV-coupled DACCS configurations. This observation confirms the importance of a comprehensive LCA approach not only focusing on climate change.

The sensitivity analysis demonstrated the large variation of GHG emissions between countries for all-electric DACCS systems. Hence, selecting inappropriate locations in countries with CO₂-intensive grid electricity mixes could lead to net GHG emissions instead of GHG removal. Consequently, the operation of all-electric DACCS systems with fossil-fuel based grid electricity mixes should be avoided, and we recommend to assess the suitability of DACCS systems based on site-specific conditions, such as the availability of (renewable) energy sources as well as land, waste heat and the potential of carbon storage sites. Further, our prospective analysis demonstrated that more ambitious climate policy will have beneficial effects on GHG emissions for all-electric DACCS systems.

Finally, we demonstrated significant carbon removal efficiencies of DACCS, although with a large dependency on the energy sources used for CO₂ capture. We therefore argue to utilize low-carbon energy sources for CO₂ capture and to compare alternative DACCS configurations with a comprehensive and transparent LCA approach. Such an approach enables policy-makers to select the most environmentally friendly DACCS configuration under given local boundary conditions. Besides environmental aspects, effective policy is required to facilitate the development of the DAC industry to improve the economic viability of DACCS.

With sufficient geological storage potentials and an economically viable DAC system, we foresee DACCS as a key component in the pathway towards net-zero GHG emissions.

Conflicts of interest

There are no conflicts to declare.

Acknowledgement

This work has mainly been funded by ACT ELEGANCY, Project No 271498, which has received funding from DETEC (CH), BMWi (DE), RVO (NL), Gassnova (NO), BEIS (UK), Gassco, Equinor and Total, and is co-funded by the European Commission under the Horizon 2020 program, ACT Grant Agreement No 691712. This project is supported by the pilot and demonstration program of the Swiss Federal Office of Energy (SFOE). Further financial support was provided by the Kopernikus Project Ariadne (FKZ 03SFK5A), funded by the German Federal Ministry of Education and Research and PSI's ESI platform.

The authors thank Daniel Sutter and colleagues from Climeworks (Zürich, Switzerland), Christian Zahler and Stephan Scherer from Industrial Solar (Freiburg, Germany), and Emmanuel Jacquemoud and Raymond Decorvet from MAN Energy Solutions (Zürich, Switzerland) for the fruitful discussions, feedback and data provision.

Supporting Information Available

The Supporting Information is available free of charge on the ACS Publications website at DOI: ...

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