# Supplementary Information: A Roadmap for Achieving Scalable, Safe, and Low-cost Direct Air Carbon Capture and Storage

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### 1 DACCS Classification

### 1.1 DAC technology descriptions

Table 1 lists all DAC technologies, organized by their corresponding mechanism for  $CO_2$  capture and driver for regeneration.

Technology	Configuration	Description
	All	Absorption with an alkaline solvent followed by a two-step desorption process where the $CO_2$ is mineralized out of the solution and then regenerated by high-grade heat (700-900° C).
1A: Capture by absorption and release by high-grade	NG	NG for natural gas relates to the process outlined in Keith et al. <sup>1</sup> , which relates to the Carbon Engineering process using an oxy-fired calciner in the regeneration cycle.
heat	Electric	In addition to the pure natural gas configuration, Keith et al. $^1$ discuss a process that substitutes parts of the natural gas demand with electricity.
	Syngas	Keith et al. <sup>1</sup> present a third configuration operating on natural gas and syngas.
1B: Capture by absorption	All	Absorption with an amino acid solvent followed by a two-step desorption process where the captured $CO_2$ is crystallized out of a solution and then regenerated by low-grade heat (around 120° C).
crystallization & low-grade heat	PyBIG	This configuration derives from experimental data of Brethomé et al. <sup>2</sup> , who use an amino acid (glycine and sarcosine) solutions as the liquid solvent, and 2,6-pyridine-bisiminoguanidine (PyBIG) as the aqueous compound that reacts with the carbonate containing amino acids.
1C: Capture	All	Absorption with an amine or amino acid solvent followed by a one-step desorption process in which low-grade heat (around 120 °C) is used to separate $\rm CO_2$ from the solvent (similar to a conventional amine-based carbon capture process).
by absorption and release by low-grade heat stripping	MEA	Kiani et al. <sup>3</sup> present a configuration based on conventional amine scrubbing approaches to capture $\rm CO_2$ from flue gases. The authors suggest an alternative liquid recirculation due to the significantly lower concentration of $\rm CO_2$ in atmospheric air.
	Amino acid	In addition to MEA approach, Kiani et al. $^3$ also present a configuration using an amino acid salts solution.
	All	Absorption with an alkaline solvent followed by a one-step desorption process where an electrochemical cell is used to remove $\text{CO}_2$ from the solvent.

Table 1 | Classification of DAC technologies and configurations.

Technology	Configuration	Description
1D: Capture by absorption and release by voltage	BPMED	BPMED stands for bipolar membrane electrodialysis (BPMED), and relates to design of the electrochemical cell. The considered configuration is outlined in Sabatino et al. <sup>4</sup> A bipolar membrane consists of an anion and a cation exchange layer, laminated together. When a sufficient electric field is applied, the membrane dissociates water into OH- and H+, producing a controllable pH difference. The use of the bipolar membrane reduces the thermodynamic minimum voltage needed for water dissociation in comparison to water electrolysis.
2A: Capture	A11	Adsorption onto a solid mineral sorbent followed by a one-step desorption process where high-grade heat (600-1200 °C) is used to remove $\rm CO_2$ from the mineral.
by adsorption and release by high-grade heat	MgO looping	This configuration refers to the magnesium oxide loop as presented in McQueen et al. <sup>5</sup> Heirloom Carbon Technologies pursues this DAC technology commercially, although, according to their white paper, <sup>6</sup> Heirloom switched minerals and outlines a passive DAC approach using CaCO <sub>3</sub> . The process layout remains identical.
2B: Capture by adsorption	All	Adsorption onto a solid sorbent followed by a one-step desorption process where a swing in humidity (high humidity for regeneration) is used to remove $CO_2$ from the sorbent (i.e., a resin).
and release by humidity	Passive air flow	This configuration relates to a natural flow process presented by Fasihi et al. <sup>7</sup> and used within MechanicalTrees <sup><math>TM</math></sup> . <sup>8</sup> The technology uses a passive flow adsorption column design, which has been licensed to Carbon Collect Limited. <sup>8</sup>
2C: Capture	All	Adsorption onto a solid sorbent followed by a one-step desorption process where temperature and/or pressure swings are used to remove $\rm CO_2$ from the sorbent.
and release by low-grade heat	Waste heat	This configuration mimics the Climework's process of a temperature vacuum swing using waste heat as energy input. The data originates from Young et al. <sup>9</sup>
and/or vacuum and/or steam	Heat pump	The heat pump configuration differs from the waste heat one in the aspect of the energy supply, where instead of waste heat, low-grade temperature heat pumps supply the heat.
	All	Adsorption onto a solid sorbent followed by a one-step desorption process where electricity is used to remove $\text{CO}_2$ from the sorbent.
2D: Capture by adsorption and release by voltage	Bed100	The fundamental working of the process is well documented in the 2019 paper by Voskian and Hatton. <sup>10</sup> Air is pushed through narrow channels lined with electrode substrate coated with a redox active compound, such as e.g. quinone-carbon nanotubes. <sup>11</sup> The CO <sub>2</sub> binds with the electrode when charged (i.e., a specific voltage is applied), and is released when discharged (i.e., a lower specific voltage is applied). The process is fully electrically driven, modular, requires minimal ancillary equipment, and can be used in capturing $CO_2$ from a range of concentrations.
3A: Membrane separation by pressure	All	In polymeric membrane separation, the $\rm CO_2$ is separated from other gasses via differences in the molecules' ability (i.e., permeability) to pass through the polymer membrane. Multiple capture stages (several membranes/units stacked onto each other) are required to achieve $\rm CO_2$ concentrations of several tens of percentages.
gradient	DeltaP50	Fujikawa et al. $^{12}$ suggest 3 to 4 stages and operate them at a pressure ratio of 50 to yield a 40-60% concentrated $\rm CO_2$ stream for organic polymer membranes.
	All	Ion-exchange membrane separation where the $CO_2$ is separated from other gasses in an electrochemical cell by the means of a membrane.
3B: Membrane separation by voltage	Shorted membrane	The considered configuration for this technology comes from the group of Yushan Yan, <sup>13</sup> who present an electrochemical membrane in a spiral-wound module, initially developed to be used in hydrogen fuel cell cars. This process is powered by hydrogen, which releases the electrons at the anode side, H <sup>+</sup> passes the membrane, and reacts with the $CO_3^{2^-}$ ion to form $CO_2$ and water. Shi et al. <sup>13</sup> label this as a shorted membrane, because the external voltage is zero, meaning there is no external power circuit needed. Yushan Yan is a co-founder and board member of the company RepAir, <sup>14</sup> which holds patents for an electrically driven separation process. <sup>15</sup>

Technology	Configuration	Description
4A: Cryogenic	All	Cryogenic separation where very low temperatures induced by heat exchangers enable the separation of solid (frozen) $CO_2$ from other gasses.
separation by phase change (vapor-solid)	Heat exchanger	von Hippel <sup>16</sup> conceptualized the capture process using heat exchangers and a passive pre-cooling step. The configuration used in this study relates to the region of Yukon in Canada, with an average ambient temperature of -20 $^{\circ}$ C from November through February.

Table 1 also provides a description of the DAC configurations that exist and are classified by material, equipment, process layout, and energy vector.

#### 1.2 Process maps

In this section, the developed 11 DAC technology process maps are presented. These process maps are separated into 3 main categories: (i) capture, (ii) release, and (iii) conditioning and storage. For each category all the key process steps, system components, system intermediary inputs and outputs, and input and output flows are illustrated and a short description is also provided.

#### 1A. Capture by absorption and release by high-grade heat



Notes and sources: Keith et al.<sup>1</sup>, National Academy of Sciences, Engineering, and Medicine<sup>17</sup>



#### 1B. Capture by absorption and release by crystallization and low-grade heat

This first step is common for all absorption-based DAC technologies. Fans blow atmospheric air into a contacting module where the  $CO_2$  is moved from the gas phase into the liquid solvent (absorbed). What differentiates absorption-based DAC technologies from each other are the choice of solvent and the way the captured  $CO_2$  is released in the second step. In this absorption technique the liquid solvent (e.g., an amino acid solution) chemically binds with  $CO_2$  to form bicarbonate and glycinate. The resulting compounds are then reacting with a guanidine compound forming carbonate salts. Thereby,  $CO_2$  is released from the solvent. The  $CO_2$ -free amino acid solution is looped back to the absorption step whereas  $CO_2$  is released in the heating step. The main difference between technologies 1A and 1B is that 1B makes use of low-grade heat.

Notes and sources: Brethomé et al.<sup>2</sup>

#### 1C. Capture by absorption and release by low-grade heat stripping



This first step is common for all absorption-based DAC technologies. Fans blow atmospheric air into a contacting module where the  $CO_2$  is moved from the gas phase into the liquid solvent (absorbed). What differentiates absorption-based DAC technologies from each other are the choice solvent and the way the captured  $CO_2$  is released in the second step.

In this technology the liquid solvent (e.g., monoethanolamine (MEA) a benchmark solvent used in conventional  $CO_2$  capture processes) chemically binds with  $CO_2$  to form a  $CO_2$ -rich solvent. The solvent is then heated in a stripper via low-grade heat for solvent regeneration.  $CO_2$ is then released as gas while the  $CO_2$ -lean solvent is looped back to the absorption step. The nearly pure CO<sub>2</sub> generated by heating up the rich solvent is further treated (if required) to reach requirements of a particular storage option (e.g., compressed so it can be transported to sites for long-term geological storage or to plants where it is integrated into durable products).

the carbonate salt is further treated (if

durable products).

required) to reach requirements of a particular

storage option (e.g., compressed so it can be

storage or to plants where it is integrated into

transported to sites for long-term geological

Notes and sources: Sabatino et al.<sup>18</sup>, Kiani et al.<sup>3</sup>, Spietz et al.<sup>19</sup>



#### 1D. Capture by absorption and release by electricity

Notes and sources: Sharifian et al.<sup>11</sup>, Sabatino et al.<sup>4</sup>, Shu et al.<sup>20</sup>, Prajapati et al.<sup>21</sup>

#### 2A. Capture by adsorption and release by high-grade heat



either chemically or physically bound to the surface of a solid (adsorbed). What generally differentiates adsorption-based DAC technologies from each other are the choice of sorbent and the way the captured CO2 is released in the second step.

calcined to release a pure CO. steam. Then the MaO is looped back to the adsorption step.

transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: National Academy of Sciences, Engineering, and Medicine<sup>17</sup>, McQueen et al.<sup>5</sup>



#### 2B. Capture by adsorption and release by humidity

This DAC technology differs from other absorption- and adsorption-based DAC technologies during the capture step as it makes use of natural air flow to bring atmospheric air into a contacting module (in contrast to using fans). What is common to all adsorption-based DAC technologies, however, is that in the contactor CO, is either chemically or physically bound to the surface of a solid (adsorbed). What generally differentiates adsorption-based DAC technologies from each other are the choice of sorbent and the way the captured CO2 is released in the second step.

In this technique the CO, binds to the surface of an ion-exchange resin and is released in the presence of water in the desorption (or regeneration) step. The resin can then be used again to adsorb CO, in a dry environment. A slightly concentrated CO2 stream (i.e., approx 50,000 ppm) is produced after resin regeneration Further processing of the captured CO2 is needed to achieve high CO2 purities. This can be, for example, achieved by condensing water in the condensation step

The nearly pure CO<sub>2</sub> generated by condensation is further treated (if required) to reach requirements of a particular storage option (e.g., compressed so it can be transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: McQueen et al.<sup>22</sup>, Wang et al.<sup>23</sup>, Infinitree<sup>24</sup>, Shi et al.<sup>25</sup>

#### 2C. Capture by adsorption and release by low-grade heat and/or vacuum and/or steam



differentiates adsorption-based DAC technologies from each other are the choice of sorbent and the way the captured CO2 is released in the second step.

dilution of the CO, stream, the temperature vacuum swing adsorption process might be tailored for achieving the required process performance. A pure CO, can be produced either after the desorption or the condensation steps (i.e., if steam is used in the desorption step).

transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: National Academy of Sciences, Engineering, and Medicine<sup>17</sup>, Sabatino et al.<sup>18</sup>

#### 2D. Capture by adsorption and release by voltage



Notes and sources: Verdox<sup>26</sup>, Voskian and Hatton<sup>10</sup>

#### 3A. Membrane separation by pressure gradient



In this first and only step fans are used to blow atmospheric air through a unit with membrai stacks. Unlike absorption- and adsorption based DAC technologies, membrane separation does not require a solvent or sorbent to bind the CO2 from the air. Instead, separation happens due to the differences in the molecules' ability (i.e., permeability) to pass through the polymer membrane. Multiple capture stages (several membranes/units stacked onto each other) are required to achieve similarly high CO2 concentrations as for absorption- or adsorption-based DAC technologies. The produced  $CO_2$  stream can be further treated (if required) to reach requirements of a particular storage option (e.g., compressed so it can be transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: Fujikawa et al.<sup>12</sup>, Rahaman et al.<sup>27</sup>

#### 3B. Membrane separation by voltage



In this first and only step fans are used to stream atmospheric air into an electrochemical cell. Unlike absorption- and adsorption based DAC technologies, membrane separation does not require a solvent or sorbent to bind the CO2 from the air. Instead, separation happens due to the differences in the molecules' ability to pass through a membrane. In this technology a ion-exchange membrane is used for separation. Ion-exchange membranes transport certain dissolved ions (electrically charged molecules) while blocking other charged or neutral molecules. In this specific setting, CO2 passes the membrane in the form of carbonate and bicarbonate ions ( $CO_3^{2^-}$ and  $HCO_3^-$ ). The displayed process is fully powered by electricity, but alternative settings also consider the use of hydrogen as a source of energy. The produced  $CO_2$  stream can be further treated (if required) to reach requirements of a particular storage option (e.g., compressed so it can be transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: RepAir<sup>14</sup>, Shi et al.<sup>13</sup>, Yan et al.<sup>15</sup>

#### 4A. Cryogenic separation by phase change (vapor-solid)



In this first step, this DAC technology makes use of natural air flow to bring atmospheric air into a heat exchanger where it is pre-cooled. Then it is fed into a desublimation heat exchanger where it is further cooled until the gaseous  $CO_2$  solidifies as dry ice on the surface of the heat-exchanging metal areas (e.g., aluminium). In the second step the frozen  $CO_2$  is removed from the heat exchanger and defrosted resulting in a pure stream of  $CO_2$ . Von Hippel conceptualizes this technology as a land-based DAC technology operating in some of the coolstest and remote regions in the world to lower energy consumption for cooling. The start-up High Hopes presents an alternative approach using gas-filled balloons derived from weather balloons to launch their capture device to altitudes of 15 kilometers to use naturally occurring low temperatures of around minus 60°C. The produced  $CO_2$  stream can be further treated (if required) to reach requirements of a particular storage option (e.g., compressed so it can be transported to sites for long-term geological storage or to plants where it is integrated into durable products).

Notes and sources: von Hippel<sup>16</sup>, Font-Palma et al.<sup>28</sup>

### 2 TEA methodology

As a functional unit for the techno-economic assessment, we choose the amount of  $CO_2$  captured and removed from the air, expressed in metric tonnes. Figure 1 in the main text schematically illustrates the system boundary of a DAC process, the energy and material flows across the boundary, and the upstream energy supply. It is an abstract representation – a harmonization approach – that allows us to compare configurations on a process level by quantifying the arrows in and out of the DAC plant boundary.

This paper presents two cost approximations: (i) operational energy cost on '*DAC process level*' and (ii) a full TEA for a first-of-a-kind plant on '*DAC plant level*'. Figure 1 illustrates the methodology, which is explained in detail in the following subsections.

#### 2.1 Estimation of process level costs and emissions

In accordance with Figure 1, the variable operation costs are the costs for energy and material to run the DAC process. In this assessment, we neglect the cost for continuous material input such as water, due to the poor and inhomogenous data quality. Instead, the variable operation and maintenance costs only include the energy cost from natural gas and electricity (see equation 1). Waste heat is considered free.

$$O\&M_{variable} = e_{el} \cdot \pi_{el} + e_{NG} \cdot \pi_{NG} \qquad [USD/tCO_2] \quad (1)$$

With  $e_{el}$  the total amount of electricity,  $\pi_{el}$  the price for electricity,  $e_{NG}$  the total amount of natural gas, and  $\pi_{NG}$  the price for natural gas.

The values presented in Figure 3 of the main text are the  $O\&M_{variable}$  values, based on the energy data of Table 2 and the cost values of Table 3 (in the main text). Table 2 lists publicly reported energy values for different configurations. These configurations and values are directly taken from the literature. The natural gas and electricity demands follow from:



Figure 1 | The four primary separation mechanisms in DAC processes. TEA methodology of the two cost approximations: 'DAC process level' and 'DAC plant level' analyses. The 'DAC process level' (presented in Section 2.1) analysis accounts for operational energy and material costs and defines the process (Scope 1 and Scope 2) emissions, while the 'DAC plant level' assessment (presented in Section 2.2) incorporates CAPEX from equipment, installation, indirect costs, owner costs, and contingencies, and discounts them over the plant lifetime.

$$e_{NG} = e_{NG,oxy} + e_{NG,non-oxy} \qquad [GJ/tCO_2] \quad (2)$$

$$e_{el} = \frac{e_{heat \ pump}}{COP} + e_{joule \ heating} + e_{direct} \qquad [GJ/tCO_2] \quad (3)$$

With  $e_{NG,oxy}$  and  $e_{NG,non-oxy}$  as the natural gas demand of Table 2, and  $e_{el}$  the total amount of electricity, derived from the parts of the heat pump (converted by the COP), the joule heating, and the direct use.

Scope 1 and Scope 2 emissions are combined in an emission factor (EF) and used to determine the net capture cost. Figure 3 of the main text summarizes the energy prices and assumptions for Scope 2 emissions. The global warming potential (GWP) of the Scope 2 methane leakage is expressed in CO<sub>2</sub>-equivalent and assessed against a 100-year time horizon. The net energy costs follow from gross costs by dividing it by the emission factor:

$$net O\&M_{variable} = O\&M_{variable} / (1 - EF_{GWP100})$$
(4)

Scope 1 and Scope 2 emissions from electricity and natural gas are combined in an emission factor (EF) and used to determine the net capture cost.

$$EF_{GWP100} = EF_{NG} + EF_{el} \qquad [tCO_2 e/tCO_2] \quad (5)$$

$$EF_{el} = e_{el} \cdot CI_{el} \tag{6}$$

$$EF_{NG} = EF_{NG,leakage} + EF_{NG,combustion} \tag{7}$$

$$EF_{NG,leakage} = (e_{NG,oxy} + e_{NG,non-oxy}) \cdot GWP \tag{8}$$

$$EF_{NG,combustion} = e_{NG,non-oxy} \cdot (1 - r_{capture}) * CI_{NG}$$
(9)

With  $CI_{el}$  as the carbon intensity of the electricity (see Table 3 of the main text),  $e_{NG,oxy}$ and  $e_{NG,non-oxy}$  as the energy demand of Table 2, GWP the global warming potential of methane (Table 3),  $r_{capture}$  the CO<sub>2</sub> capture rate, and  $CI_{NG}$  the carbon intensity of combusting natural gas (assumed to be the stoichiometric value of 198 gCO<sub>2</sub>/kWh for all case studies).

Configuration			NG		Waste Electr	Electricity	Electricity		
			Non-oxy	Oxy	heat	Heat pump*	Joule heating	Direct	Capture rate
				[GJ/tCO2]					
	NG	[1]	3.1	6.7	_	_	_	_	75
1A	Electric	[1]	5.3	_	_	_	_	1.3	75
	Syngas	[1]	5.3	_	_	_	_	0.3	75
1B	PyBIG	[2]	-	_	_	6.5	-	_	_
10	MEA	[3]	_	_	_	_	10.7	5.2	_
	Amino acid	[3]	-	_	_	_	12.6	4.0	_
1D	BPMED	[4]	-	_	_	_	-	22.4	_
2A	MgO looping	[5]	-	5.9-8.0	_	_	-	0.3	_
<b>2</b> B	Passive air flow	[7]	_	_	_	_	-	1.2	_
20	Waste heat	[9]	_	_	9.8	_	_	0.99	_
20	Heat pump	[9]	_	_	_	9.8	_	0.99	_
2D	Bed100	[10]	_	_	_	_	_	1	_
<b>3</b> A	DeltaP50	[12]	-	_	_	_	_	44.2	_
3B	Shorted membrane	[13]	_	_	_	_	_	41	_
<b>4</b> A	Heat exchanger	[16]	-	_	_	_	_	5	_

Table 2 | Detailed energy demand values used in the harmonized TEA.

\* Values represent demand for low-grade heat. Electricity demand follows from COP of heat pump (assumed COP of 2 for this study).

#### 2.2 Methodology for the estimation of first-of-a-kind plant costs

We perform a complete TEA for the configurations '1A: NG', '1A: Electric', '1C: MEA', '1C: Amino acid', '2A: MgO looping', and '2C: TVSA'. We calculate the costs based on a series of assumptions, as graphically illustrated in Figure 1. By using the same approach for different configurations, we harmonized the TEA results for FOAK plants.

The methodology follows the National Energy Technology Laboratory (NETL) costing methodology.<sup>29</sup> Equipment cost, DAC plant capacity, plant lifetime, and fixed Operational and Maintenance costs (O&M) for each configuration are taken from literature (see Table 2 for references) and form the basis of the capital cost calculations. The variable O&M as well as the Scope 1 and Scope 2 emissions follow from the consideration described in the previous section. The equipment cost is corrected to USD in the year 2019 using the Chemical Engineering Cost Plant Index (CEPCI) annual average.<sup>30</sup> We use an installation factor of 80% to incorporate the cost of installing equipment on site. Subsequently, we calculate an indirect cost of 13% based on the Total Direct Plant Cost (TDPC). This accounts for costs not associated with processing units (i.e., buildings, additional overheads, roads, other infrastructure, etc.). The sum of the indirect costs and the Total Direct Plant Cost represent the Engineering, Procurement, and Construction (EPC) costs.

Contingencies for process and project are then added (see Table 3 and Table 4). These allow for anticipated cost escalation due to lack of complete project definition and engineering. The process contingency compensates for performance uncertainties associated with the development status of the technology. Process contingencies vary based on the Technology Readiness Level (TRL) of the underlying DAC technology. Table 3 and Table 4 show the guidelines and present contingency ranges. For each DAC configuration, we performed two computations using the low and high values of the respective TRL for the capital cost estimates. The TRL used for assigning contingencies is based on the origin of the data, and not the current status of the DAC technology. For example, it is known that amine scrubbing DAC (Technology 1C) is at a lab scale (TRL 4), but the data we use in our TEA is taken from an Aspen modeling study (TRL 1–2). Hence for technology 1C the contingency is based on TRL 1–2. After including the contingencies, we derive the Total Plant Cost (TPC). An owner's cost of 20% is added which accounts for costs from a range of sources. These may be pre-production (start-up) costs, working capital, inventory capital, land, financing costs, technology licensing fees, permitting costs, legal fees, etc. For a more detailed description of owners cost see the example given by the NETL cost estimation methodology.<sup>29</sup> The owner's cost applied to the TPC gives the Total Overnight Cost (TOC).

Table 3 | Guidelines for process contingency costs.<sup>31</sup>

contingency	TRL
40+	3
30-70	4
20-35	5-6
5-20	7-8
0-10	9

Table 4 | Guidelines for project contingency costs.<sup>31</sup>

Contingency	Design effort	Cost classification
30-50	simplified	Class I (AACE Class $5/4$ )
15-30	preliminary	Class II (AACE Class 3)
10-20	detailed	Class III (AACE Class 3/2)
5-10	finalized	Class IV (AACE Class 1)

The TOC is discounted based on the discount rate and the lifetime of the plant to incorporate the cost of capital (i.e., repayment of loans). This is done by multiplying with the Capital Recovery Factor (CRF)

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{10}$$

where i is the discount rate and n is the plant lifetime. We apply discount rates of 7.5% for the low capital cost estimate, and 12.5% for the high discount value.

The total operation and maintenance cost is the sum of the fixed and the variable part. The fixed part is based on literature data for the respective configurations (usually a fixed percentage of the TOC) and includes labor, insurance, and maintenance.

$$O\&M = O\&M_{fixed} + O\&M_{variable} \tag{11}$$

The levelized gross carbon capture cost (in  $USD/tCO_2$ ) is calculated by the addition of the total O&M to the discounted Total Overnight Cost (TOC multiplied by CRF). The levelized net carbon capture cost follows by incorporating the emissions produced due to the gas and/or electricity usage.

$$LCOC = TOC \cdot CFR + O\&M \tag{12}$$

$$net \ LCOC = LCOC/(1 - EF_{GWP100}) \tag{13}$$

There are a couple of exceptions for Technologies 1C and 2A. Technology 1C is described in Kiani et al.<sup>3</sup> where the authors have performed a TEA and provided an equipment list with each unit's costs and installation costs. Since the installation cost has already been incorporated into the equipment cost, we have not applied an installation factor of 80% to this equipment list. Additionally, the TEA described in Kiani et al.<sup>3</sup> is produced based on Aspen modeling (i.e., data produced from a TRL of 1–2), the process contingencies for low and high values is set to 40%.

Technology 2A is based on McQueen et al.<sup>5</sup>, where a TEA has been conducted for two

plant capacities. As such, there are low and high equipment costs as well as low and high energy costs. Additionally, McQueen et al.<sup>5</sup> has incorporated an installation factor, hence no additional installation factor is added.

### 3 List of obstacles to safe, low-cost, and scalable DACCS

Table 5 lists all obstacles which were identified and presents them aggregated in five categories: (i) material, (ii) process, (iii) equipment, (iv) system integration, and (v) infrastructure. Some pertain to specific DAC technologies; some pertain across DAC technologies. Note these obstacles were identified from the public literature, meaning some obstacles may have been addressed behind company walls already. Cryogenic technology is not considered as we don't consider this technology viable at scale due to geographical and seasonal limitations, explained in the main manuscript.

Material Obstacles					
#1 Unexplored materials			erials		
	There are nu generated in	There are numerous existing materials and millions of hypothetical ones that can be			
	applications.	Their	properties (e.g., density, solubility, permeability, volatility,		
	viscosity, por	osity,	heat of absorption, heat of adsorption, thermal conductivity)		
	cover a broad	l desig	n space, which makes their exploration challenging.		
	Unexplored material benefits				
	Even for existing materials, optimal trade offs between material properties are				
	largely unexplored. There are many open questions:				
	- How material properties relate to energy requirements of a DAC technology				
	– How material choices affect the $\mathrm{CO}_2$ removal efficiency of a DAC unit				
# <b>2</b>	- Lack of established frameworks for guiding the selection of materials				
			- Unknown optimal concentrations of alkaline solutions		
		1A	- Unknown optimal caustic for removal loop		
	Abcomption		- Unknown optimal minerals for regeneration loop		
	Absorption		- Moderate loading capacity and very slow kinetics for BIG (bis-		
		1B	imino guanidinium) materials (the materials currently proposed)		
			- Unknown material behavior at ranges of temperature and pressure		
		10	- Undefined optimal amino acid concentrations		
			- Unexplored potential of alternative solvents		

Table 5 | Identified obstacles to safe, low-cost, and scalable DAC.

		1D	<ul> <li>At voltages above 1.23V, water splitting occurs and the efficiency reduces significantly (trade-off between CO<sub>2</sub> removal rate and applied current density)</li> <li>Resistance of membrane (to be lowered) and activity of electrocatalyst (to be increased)</li> <li>Slow kinetics in a narrow pH-swing (~2 pH units) versus high energy use in a wide pH-swing, enzyme loss if used as sorption promotor, deactivation or degradation might result from wider pH-swing range</li> <li>Lack of solvent promoters/activators development to increase absorption kinetics and CO<sub>2</sub> loading</li> </ul>		
		2A	- Lacking comparison of different minerals MgO vs CaO vs Na2O (and optimal particle size)		
	Adsorption	2B	<ul> <li>Produced solution of 5 vol% CO<sub>2</sub> and H<sub>2</sub>O requires post-processing to achieve higher CO<sub>2</sub> purities</li> <li>Lacking comparison of different moisture swing sorbents (and nanoporous structure)</li> <li>Lacking detailed understanding of the molecular mechanisms and most important material properties that can reduce CAPEX and OPEX.</li> </ul>		
		2C	<ul> <li>Lacking detailed understanding of the chemical reactions of the gasses with the amine and carbonate functionalized adsorbents and how these vary with temperature and humidity</li> <li>Lacking analysis of heat transfer in materials and its impact on process productivity</li> </ul>		
		2D	- Slow kinetics and relatively low capacity		
	Membranes	3A	- Low selectivity of $CO_2$ over $N_2$ and $O_2$ for polymer membrane, require more than selectivity of 70 and permeance of 40,000 GPU.		
		3B	<ul> <li>High mass transfer resistance for CO<sub>2</sub> diffusion into cathode</li> <li>Expensive catalyst needed (Pt)</li> <li>Optimal ionomer loading unknown</li> </ul>		
#3	Unknown/unreported stability and recyclability				
	<ul> <li>Lack of a reported long-term material performance under realistic conditions</li> <li>Lack of fundamental studies on DAC materials for understanding the mechanisms that cause material aging, degradation, and loss to the atmosphere</li> <li>Unexplored effects of local/regional climates and harsh operational conditions</li> </ul>				
#4	Missing independent validation of reported performance				
	Current reported material performance might be biased and has not been validated by independent studies.				
Proce	ess Obstacles				
#5	Lack of detailed process designs and evaluation				

	<ul> <li>Lack of detail process design, evaluation and optimization</li> <li>Reliance on traditional performance indicators: Traditional performance indicators such as selectivity and energy consumption can lead to incorrect conclusions in assessing the suitability of a material and a process.</li> <li>Thermodynamic models that exclude mass and heat transfer effects cannot be used to predict productivity and simple metrics such as working capacity may fail to indicate towards the right material and process.</li> <li>Other studies have shown that metrics beyond material and process design, such as capital and operational expenditure and climate change, may lead to different conclusions on the suitability of a material and/or a process.</li> </ul>						
<b>#6</b>	Unexplored	l syne	rgies between material and process development				
	- Missing ma - Missing exp - Missing dev	terial perime velopm	and process optimization tailored to a specific technology ntal validation of material and process performance ent of advanced process evaluation models for scaling up				
#7	Unexplored	l proc	ess potential				
	<ul> <li>Lack of exploring the details of cycle steps and sequences</li> <li>Lack of exploring alternative regeneration methods (e.g., indirect heating, electric calciner, joule heating, microwave)</li> <li>Lack of exploring bed configurations (e.g., fixed beds, moving beds, fluidized beds) and/or packing</li> </ul>						
#8	Missing validation of process operation at scale						
<ul> <li>Lack of piloting beyond lab-scale (&gt;TRL 5) for technologies other than 1A, 2 and 2C</li> <li>For 1A, 2A, 2C: lack of reporting of process operation at pilot and demonstration scale, which is critical to public understanding of obstacles that surface at larger scale, but not in lab (e.g., mass and heat transfer resistances, material perform and degradation, ramping up/down rates, CO<sub>2</sub> production rate, emissions and wastes produced)</li> <li>For 1A, 2A, 2C: lack of independent corroboration of process operation at pile and demonstration scale</li> <li>Unknown performance in CO<sub>2</sub> concentrations &lt;400 ppm, therefore lacking understanding of potential spacing of DAC units (what is minimal distance between units, et cetera)</li> </ul>							
<b>#9</b>	Lack of public data and independent performance assessment						
	Current reported process performance may be biased and not have been validated by independent studies.						
Equip	lipment Obstacles						
	Lack of fit-	for-pı	rpose equipment				
#10	<ul> <li>(Air contactors, calciners, fans/blowers, CO<sub>2</sub> compressors and energy equipment, such as heat pumps, heat exchangers, or energy storage layouts)</li> <li>Unexplored optimal (e.g., low cost, low pressure drop, low footprint, fast mass and heat transfer) designs for air contactors</li> <li>Missing data availability of performance testing of existing air contactor designs</li> </ul>						
	Aboutin	1A	- Lack of development of different calcination methods (e.g., oxy-fired, post-calcination $CO_2$ capture, electric calcination, solar calcination)				
	Absorption	1B	- Lack of testing large-volume crystallizers and solid-liquid separators				

			- Conventional solvents require additional equipment (e.g.,				
			water washing column, acid column) to prevent solvent				
		1C	losses into the atmosphere				
		10	- Absorbers and absorber packings have been extensively				
			used for carbon capture from concentrated streams but not				
			for DAC, need adjustment				
		1D	- High-pressure electrochemical cell designs for DAC lacking				
			- Low pressure drop adsorbent structure/bed development				
		2A	lacking				
			- Missing design of contacting equipment for mineral				
	Adsorption		adsorbents with subsequent thermal regeneration				
			- Low pressure adsorbent structure/bed needed				
		2B	- Required preprocessing of CO2 for the removal of excess				
			water				
			- Low pressure drop adsorbent structure/bed development				
			needed				
		20	- Requires industrial heat pumps to provide heat at 100-120°C				
		20	that can switch on and off flexibly and rapidly at high				
			emciency Descrives an effective transmission for higher CO				
			- Requires more efficient vacuum pumps for higher $CO_2$ recovery				
			- Low pressure drop adsorbent structure/bed				
			- Contactor and sorbent are both novel and developed for the				
			purpose of $CO_2$ capture				
		2D	- Capacity and kinetics yet to be seen for DAC conditions				
			(and will largely dictate capital costs)				
			- Durability and lifetime of sorbent yet to be seen for DAC				
			conditions (will also largely impact the capital costs)				
	Membranes	3A	- Optimal designs for modules unexplored				
		3B	- Pretreatment of $CO_2$ product stream may be required to				
			achieve high purity				
<b>#11</b>	Unexplored process intensification						
	Unexplored synergistic effects between different unit operations/processes for						
	an efficient performance and low energy consumptions.						
	Lack of con	ipara	tive studies in DAC settings				
	Lack of data and comparative studies (both experimental and computational) on						
	existing or no	ovel co	ntactor designs in a DAC specific setting.				
			- Unknown performance (and comparison) of alternative				
#12		1 4	regeneration technologies (e.g., solar or electrical calciner)				
		IA	- Unknown (comparative) performance of different contactor				
	Absorption		designs (e.g. conventional, cross-flow columns, membrane)				
			- Amino acids may require completely different column				
		$1\mathrm{B}$	designs (to conventional ones applied to fuel gasses) for				
			optimal operation				
		$1\overline{C}$	- Conventional columns are not optimal for amino acids				
			- Lack of comparative studies on different electrochemical				
		1D	regeneration equipment, e.g., electrolyzers versus bipolar				
		-	membrane electrodialysis, higher (than ambient) pressure				
			and temperature operation.				

	Adsorption	2A	<ul> <li>Little public information on different passive air contacting methods</li> <li>Lack of rigorous comparison and development of different calcination methods (oxy-fired, post-calcination CO<sub>2</sub> capture, solar calcination, electric calcination, alternate fuel calcination, i.e., biogas)</li> </ul>		
		2B	<ul> <li>Lacking comparative assessment of different resins in scaled up systems</li> <li>Lacking comparative assessment of different contacting configurations in public literature</li> </ul>		
		2C	<ul> <li>Detailed comparison of alternative regeneration methods:</li> <li>conventional heat exchange, steam stripping, joule heating, microwave regeneration, or any other</li> <li>Study of feasibility and performance of different contactor designs such as monolithic structures or laminates fitted into fixed beds, moving beds, or rotating wheels</li> </ul>		
		2D	<ul><li>No public comparative studies of this technology in a DAC setting</li><li>Novel sorbent and novel contactor with little academic literature</li></ul>		
	Membranes	3A	<ul> <li>No comparative studies of different contactor designs (hollow fiber, spirally wound, et cetera)</li> <li>Lack of testing different connected membranes, in series, parallel, both to identify optimal low energy configurations</li> </ul>		
		3B	- No comparative studies of different contactor designs (flat plate, spirally wound, et cetera) that minimise pressure drop and maximise $CO_2$ diffusion into electrode		
#13	Designs for crucial DAC equipment are proprietary				
	Patented equipment designs increase the CAPEX for DAC systems.				
#14	Lack of specialized supply chains				
	A specialized equipment supply chain is required to enable DAC deployment at scale. However, the current stage of equipment development and low TRL of most DAC technologies serve as barriers to enable the development of such a supply chain.				
System	m Integration	ı Obs	tacles		
#15	Lack of TEA and LCA studies				
	<ul> <li>There is a lack of sound and independent TEA and LCA studies on most DAC technologies, including those at laboratory, pilot, and commercial scale. There is also a lack of independently measured/modeled/reported process data (e.g., full material and energy balances) to enable such assessments.</li> <li>TEAs are missing for half of the technologies</li> <li>Measured data on TRL 6+ exists only for Climeworks technology. For other technologies, TEA data relies on modeled or lab-observed performance estimates.</li> </ul>				
#16	Lack of stu	dies o	on DAC integration into local/regional climates		
Local/regional climate sensitivity and environmental impact studie missing for all DAC technologies, except 1A and 2C.			ate sensitivity and environmental impact studies are currently C technologies, except 1A and 2C.		
#17	Lack of ups	caling	g studies		

	- Testing, reporting and verification of large-scale DACCS systems is currently missing for all DACCS systems. This obstacle is crucial for large-scale DAC implementation.						
	- Lack of demonstration projects (apart from technology 2C)						
	- Unknown performance in $\mathrm{CO}_2$ concentrations ${<}400$ ppm, therefore lacking						
	understanding of potential spacing of DAC units (what is minimal distance						
	between units, etc.)						
	- Lack of validation of the different unit operations of a technology working						
	together at scale						
#18	Lack of studies on regional environmental and socio-economic impacts						
	socio economic pathway scenarice) for accessing regional antironmental and						
	socio-economic impacts (in contrast to global ones) on local energy systems						
	from large-scale DACCS deployment.						
<b>#19</b>	Lack of DAC integration into industrial clusters						
	Studies on how to integrate DACCS into existing industrial clusters to benefit						
	from waste heat availability, and de-risk $\mathrm{CO}_2$ storage (by integrating DACCS						
	with CCS), and accelerate learnings for a large-scale DAC deployment.						
Infras	tructure obstacles						
<b>#20</b>	Competition for access to low-carbon energy						
	Global availability of low-carbon energy is insufficient for DAC deployment						
	at scale. Without an increase of global low-carbon energy supply, DAC plants						
	might compete with other industries for available low-carbon energy,						
	undermining the purpose of climate mitigation and slowing the overall energy						
	the polition						
	transition.						
#21	High water footprint						
#21	High water footprint         Local water availability poses an obstacle to water-intensive DAC technologies						
#21	High water footprint         Local water availability poses an obstacle to water-intensive DAC technologies and might limit the technology choice.						
#21 #22	High water footprint         Local water availability poses an obstacle to water-intensive DAC technologies and might limit the technology choice.         Land transformation and high footprint						
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#21 #22 #23 #23	Instruming in purpose of connect integration and booking the order integration and purpose of connect integration and purpose of connect integration and purpose of connect integration and purpose an obstacle to water-intensive DAC technologies and might limit the technology choice.         Land transformation and high footprint         Land availability poses an obstacle to DAC technologies with large footprint limiting their capacity. If land requirements for energy production are taken into account, DAC footprint can be more significant. Exact DACCS footprints are unknown as DAC park spacing studies are lacking. Land footprint is a problem that applies to other CDR technologies as well (and possibly more).         Lack of existing CO <sub>2</sub> transport infrastructure         Availability of high-volume CO <sub>2</sub> pipeline networks is key for the rapid deployment of DAC. The key obstacles to pipeline buildout are permitting timelines, capital costs, and public/political support and the lack of demand for CO <sub>2</sub> transport during initial years of operation (the CO <sub>2</sub> T&S chicken and egg problem).         Lack of existing CO <sub>2</sub> storage sites         - Only a few large-scale storage reservoirs have been developed for CO <sub>2</sub> storage.         - Transport infrastructure, permitting timelines, capital costs, and public/political support require time and are primary obstacles to storage buildout.         - Streamlined permitting regimes for storage reservoirs do not yet exist and						

## 4 List of priority initiatives for safe, low-cost, and scalable DACCS

Table 6 lists all priority initiatives which were identified in response to the observed obstacles identified in Section 3. Some pertain to specific DAC technologies; some pertain across DAC technologies.

	Exploration	of ma	aterial space and identification of optimal materials		
	<ul> <li>Access exist space</li> <li>Build or ad</li> <li>Ensure pub</li> <li>Develop/use</li> </ul>	ting ma vance o lic acce e artific	aterial databases or create hypothetical ones to better understand the material computer models that can evaluate material properties ess to these such models and to materials databases cial intelligence to speed up the exploration of materials (there are millions of in to be compared)		
	Exploration of material benefits				
	For both exis - Predict/me - Relate perfe - Establish fr	sting ar asure A ormanc amewo	ad hypothetical materials, identify optimal trade offs between material propertial. ALL relevant material performance parameters be data to advanced metrics such as energy needs and $\rm CO_2$ removal efficiency orks for selection of optimal materials		
		1A	- Investigate optimal concentrations of alkaline solution, optimal caustic		
	Absorption	1B	for removal loop and minerals for regeneration loop - Obtain fundamental data on amino acid properties such as solubility, viscosity and surface tension		
		1C	- Investigate optimal concentrations of amino acids in air contactor		
		1D	<ul> <li>Identify and test new solvent blends that maximize kinetics and CO<sub>2</sub> solubility, while combining low degradation and volatility with acceptable regeneration energy</li> <li>Develop higher activity electrocatalysts and lower resistance membranes</li> <li>Improve anion exchange membrane selectivity for electrodialysis</li> <li>Improve ion exchange membrane conductivity by roughly a factor of 10 (Sabatino et al. <sup>18</sup>)</li> </ul>		
-	Adsorption	2A	<ul> <li>Examine alternative minerals than calcium and magnesium carbonates including experimental work such as carbonation kinetics, potential catalysts, particle size optimisation, calcination temperature optimisation, and calcination kinetics</li> <li>Quantify climate impact on carbonation for different materials (e.g., ambient temperature and humidity)</li> </ul>		
		2B	- Study the molecular mechanisms in sorbents to correctly assess the optimal material characteristics for humidity swing		
		2C	<ul> <li>Optimize structural adsorbents and their geometry with respect to mass and heat transfer, thermal conductivity, and pressure drop</li> <li>Optimize material to leverage water co-adsorption</li> <li>Develop scientific understanding of amine-functionalized adsorbents particularly with respect to mass transfer (impact of humidity, partial pressures, and temperatures), and co-adsorption equilibrium of CO<sub>2</sub> and H2O</li> </ul>		
		2D	<ul> <li>Improve kinetics and adsorption capacity (through sorbent development)</li> <li>Cyclic studies for many cycles to assess durability, under real DAC conditions (e.g. different impurities, presence of water).</li> <li>Life time of sorbent is to be determined</li> </ul>		
Ē	Membrane	3A	<ul> <li>Improve permeance and selectivity of organic polymer membrane</li> <li>Place tens of membranes in series to produce a high CO<sub>2</sub> purity without significant increase in the pressure drops across the membranes</li> </ul>		
		3B	- Develop and test different cathode materials and catalyst, different spacers, membrane types, and ionomer types and concentrations		

Table 6 | Identified priority initiatives for safe, low-cost and scalable DAC.

#3	Assurance of stability and recyclability					
	<ul> <li>Conduct long-term degradation studies for carbon capture materials</li> <li>Conduct fundamental studies on DAC materials for understanding the factors that cause material aging, degradation, and loss to the atmosphere (e.g., presence of water, oxygen, or acid gasses)</li> <li>Explore/measure the effects of local/regional climates and harsh operational conditions (e.g.,</li> </ul>					
	system/remo and/or in a s	val per ingle lo	formance sensitivity to humidity and temperature changes across geographies ocation)			
#4	dependently validated performance data					
	Validation of material performance data from commercial players by independent research organizations					
Proce	ss Priority In	itiativ	es			
#5	Conducting detailed process design, evaluation and optimization of DAC solutions					
	<ul> <li>Where missing, conduct detailed process design, evaluation and optimization</li> <li>Move beyond commonly used process performance indicators (e.g., selectivity, CO<sub>2</sub> loading, CO<sub>2</sub> purity, energy requirements) for the selection of both materials and processes.</li> </ul>					
#6	Exploration of synergies between material and process development $\#6$					
	<ul> <li>Conduct synergistic material and process optimization for each technology</li> <li>Validate material and process performance experimentally for each technology</li> <li>Build advanced process simulation/evaluation models to de-risk scaling up</li> </ul>					
#7	Exploration of process potential					
,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	<ul> <li>Optimize cycle steps and sequences</li> <li>Study/develop alternative regeneration methods (e.g., indirect heating, joule heating, electric calciner, microwave)</li> </ul>					
	- Test alterna	ative b	ed configurations (e.g., fixed beds, moving beds, fluidized beds) or packing			
	Technology	valida	tion for large-scale deployment			
#8	- Ensure pub - Develop her	<ul> <li>Increase TRL for a portfolio of DAC technologies to de-risk technology lock-in</li> <li>Ensure public access to measured technology performance data</li> <li>Develop heuristics for optimal spacing of DAC units</li> </ul>				
	Absorption	- Bri - Re base	ng technologies 1B, 1C and 1D to pilot scale (TRL 6+) duce water consumption or develop water recovery systems for solvent- d DAC systems			
	Adsorption	- Bri	ng technologies 2A, 2B, and 2D to pilot scale (TRL 6+)			
	Membrane	Buile	d a pilot DAC membrane system			
#9 Independent assessment of the performance of existing and			ssment of the performance of existing and emerging DAC technologies			
	- Conduct independent performance assessments to corroborate company communications and fill existing caveats					
Equip	ment Priority	/ Initia	atives			
	Besearch, d	evelor	ment and construction of fit-for-purpose equipment			
	- Develop DAC equipment components for DAC systems that can be replicated in a modular					
	fashion (as m	nuch as	possible)			
	- Develop equipment/unit operations that can be used across technologies (where possible) and can be easily replicated, to foster knowledge spillover and learning					
#10	- Develop specific equipment for specific DAC technologies where needed (e.g., because it					
	vastly improv	ves per	ormance) - Develop and test at pilot scale alternative calcination options to			
		1.4	standard natural gas powered calcination (e.g., oxy-fuelled calciners,			
	Absorption	IA	- Explore alternative contactor designs (e.g. shallow contactor designs			
	10001 20001		or membrane contactors) - Develop, test and optimize large-volume crystallizer and solid-liquid			
		1B	separator specific to amino acid capture			
			- OR, explore/test existing large-scale crystallization and solid-liquid separation equipment for use in an amino acid process			
			- Optimize, test and demonstrate absorber (and to lesser extent			
		1C	desorber) design - Tailor absorber and water wash system design to DAC settings			

		1D	<ul> <li>Explore alternative contactor designs (e.g. shallow contactor designs or membrane contactors)</li> <li>Develop new equipment for electrochemical alkaline solvent regeneration that reduces resistances in the electrolyte as a result of CO<sub>2</sub> bubble formation</li> <li>Develop high pressure electrochemical cell to reduce resistance through bubble formation in electrolyte</li> </ul>		
	Adsorption	2A	<ul> <li>Optimize electrochemical cell design, including electrodes and membranes</li> <li>Develop and test at pilot scale alternative calcination options to standard natural gas powered calcination (e.g., oxy-fuelled calciners, solar calciners, electric calciners</li> <li>Design and test at pilot scale contacting equipment for mineral adsorbents with subsequent thermal regeneration</li> </ul>		
		2B	<ul> <li>Develop and test at pilot scale low pressure drop adsorber structure/bed</li> <li>Develop robust and energy efficient industrial heat pumps to provide heat at 100 - 120 °C that can switch on and off flexibly and rapidly</li> </ul>		
		2C	<ul> <li>Improve vacuum pump performance and/or optimize vacuum strategy (constant vacuum serving several unit versus intermittent vacuum serving one unit</li> <li>Develop and test at pilot scale low pressure adsorber structure/bed</li> </ul>		
		2D	Develop low pressure adsorber structure/bed     Develop low cost modular contactors		
	Membranes	3A	<ul> <li>Develop standard DAC membrane equipment including air handling and membrane structure (e.g., hollow fibers or rolled up membranes)</li> <li>Design and test optimal modules for membrane separations</li> </ul>		
		3B	- Prove feasibility of large-scale production and assembly of spiral-wound ion-exchange membrane units		
#11	Conducting	proce	ess intensification studies		
	Study synergistic effects between different unit operations/processes for an efficient performance and low energy consumptions and design process intensification strategies based on this				
#12	Conducting independent comparative studies for process designs and main equipment				
	<ul> <li>Compare the performance of different bed designs</li> <li>Compare different packing designs for DAC application</li> <li>Compare the performance of different regeneration methods</li> <li>Publish comparative studies on all the above, open access</li> <li>Assess the feasibility and suitability of passive air flow contactors</li> </ul>				
#13	Avoidance of proprietary DAC designs (build new supply ventures)				
	Incentivise ge packings, vac	eneric t cuum p	echnology developers to develop DAC-specific equipment (e.g., umps, other contacting equipment)		
#14	Support for development of specialized supply chains for generic DAC equipment				
	Define the co offering equip	ore elen	ents of each DACCS technology so that industrial parties can start designs for DAC companies.		
Systen	n Integration P	riority	Initiatives		
#15	Continue production of sound and independent TEAs and LCAs for existing and new DACCS systems				
	Continue the production of independent TEA and LCA studies for emerging and already existing DAC technologies while ensuring measured performance data (e.g., from pilot and demonstration plants) becomes publicly available, to underpin TEA and LCA studies.				
#16	Conduct local/regional/global climate sensitivity/environmental impact studies				
	Conduct local/regional climate sensitivity and environmental impact studies for technologies where these are missing (all but 1A and 2C).				
#17	Conduct up	scalin	g studies		
	Upscaling of DAC units is expected in the near future. Modular units may be easier for scaling up, however, learnings from upscaling testing and reporting, such as identifying optimal spacing between the air contactors, are crucial for identifying optimal settings for large-scale DACCS.				
#18	Conduct st	udies o	on regional environmental and socio-economic impacts		
	Create mode scenarios) for globalones) o	ls (e.g. r assess n regio	, integrated assessment models used for shared socio-economic pathway ning regional environmental and socio-economic impacts (in contrast to onal energy systems from large-scale DACCS deployment		
#19	Conduct st	udies o	on DAC integration into existing industrial and energy systems		

	Conduct studies on how to integrate DACCS into existing industrial and energy systems, with a focus on resource sharing/re-use, optimal siting, energy requirements and types. Also continue efforts examining the integration of DAC into existing airflow systems and equipment such as cooling towers, wind turbines, moving vehicles or HVAC systems.						
Infras	tructure Priority Initiatives						
#20	Building out global low-carbon energy supply						
	Building out the global clean energy grid is crucial for making DAC viable at scale. Independent of local siting decisions, global clean energy supply must be increased to prevent DAC from competing with other industries for available clean energy. On a national level, access to waste energy should be streamlined across different industries (e.g., nuclear, cement, steel, waste disposal etc.).						
#21	Managing limited water supply by smart siting and technology choice						
	Limited water supply is a common challenge across CDR approaches that can only be partially addressed through strategic siting decision and appropriate DAC technology choice. Better siting decisions can be enabled by building out geographical inventories and water risk assessments.						
#22	Managing limited land availability						
	Land availability-related obstacles can be partially addressed through DAC siting decisions, however, they cannot be completely resolved. This is a common challenge across CDR approaches.						
#23	Development of $\rm{CO}_2$ transport infrastructure						
	<ul> <li>Parallel to storage reservoirs, high volume pipeline networks need to be developed to make it possible to feed captured CO<sub>2</sub> into storage reservoirs.</li> <li>Explore synergies with other carbon removal and CCS technologies to build out pipeline networks faster and more cost-efficiently.</li> </ul>						
#24	Development of $CO_2$ storage reservoir						
	Given long permitting timelines, storage reservoirs must be developed today to make sure they are available once DAC technologies are ready to be deployed at scale. - Develop storage reservoirs around globe supporting integration with different DAC technologies - Set up storage reservoirs as pay-to-use wells within hub networks, where various DAC companies can store their CO <sub>2</sub> and related liability is covered by third-parties - Create streamlined permitting regimes and provide public access (government) to site-specific geologic data and assessments to help de-risk storage projects for storage developers and reduce storage development timelines.						

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