Direct Air Carbon Capture & Storage: Technological Limits or another one Carbon Offset Game? (v2)

Disclaimer
This analysis was created solely for educational and analytical purposes. Its objective is not to discredit, harm, or undermine any organization, entity, or individual. Rather, it aims to critically examine and transparently present the current technical, physical, and systemic constraints associated with Direct Air Carbon Capture & Storage (DACCS) technologies, particularly in the context of large-scale atmospheric CO_2 removal scenarios. All data used in this report are based on publicly available information, scientific sources, and documented statements. The interpretation, calculations, and modelling are the independent work of the authors and do not claim to reflect internal figures, engineering blueprints, or undisclosed parameters of any company, including Climeworks. W This assessment aims to contribute to the broader public discussion by highlighting the real-world challenges and assumptions that must be considered when evaluating DACCS as a climate solution.

1. Introduction and Technological Framework

The DACCS (Direct Air Carbon Capture & Storage) technology, as represented by Climeworks, has been presented from the outset as a breakthrough solution in the fight against climate change. The company utilizes equipment that draws in air and chemically binds CO_2 to filters, which is subsequently stored underground. This concept has raised high expectations among those who tend to "like" ideas without understanding them, while generating skepticism among the engineering and climate science communities.

As illustrated in the 2025 article by *Heimildin*[(1)], which includes commentary and insights from Climeworks leadership, the physical, energetic, emissions-related, and economic limitations of DACCS technology remain both fundamental and widely underestimated in public discourse.

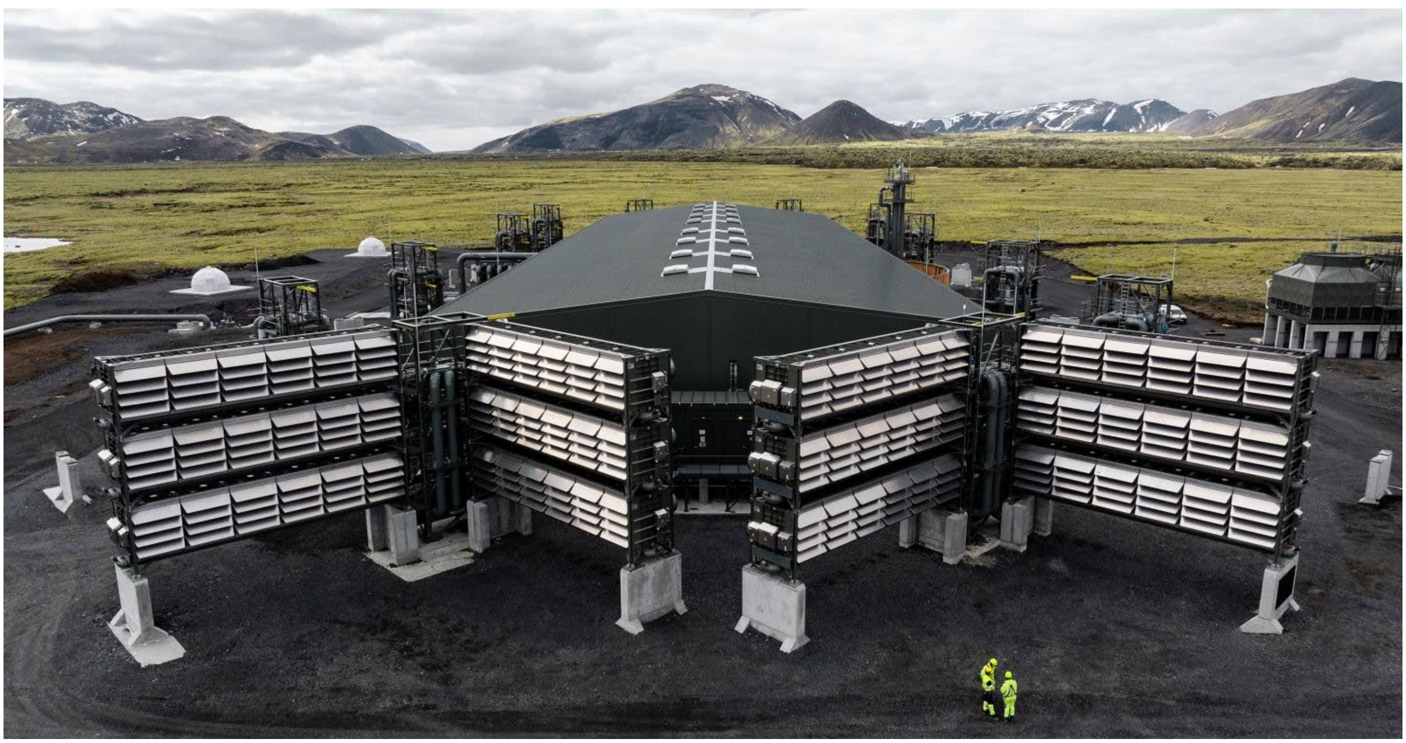


Image 1- Climeworks' Mammoth DACCS plant in Hellisheiði, Iceland

Climeworks' Mammoth DACCS plant in Hellisheiði (Iceland), the world's largest facility built to extract CO_2 from the atmosphere, functioning like a giant vacuum – officially began operations in 2023. It is the company's second commercial direct air capture plant in Iceland, following Orca, which became operational in 2021. Mammoth DACCS has a capacity eight times greater than its predecessor and is designed to reach a nameplate capacity of up to 36,000 tons of CO_2 per year.

Image 2 - Climeworks' Orca DACCS plant in Hellisheiði, Iceland

While we reference this article for specific quotations and factual framing, it served primarily as an analytical trigger, not as a source of our conclusions. **All calculations, quantitative assessments, and systemic interpretations presented in this report are original unless explicitly cited.** The analysis applies engineering reasoning, thermodynamic evaluation, and critical systems thinking to reconstruct the performance profile of DACCS technology using publicly disclosed and inferred parameters.

2. Energy Intensity and Physical Efficiency

DACCS technology is extremely energy-intensive. As admitted by Climeworks' co-CEO Jan Wurzbacher himself: *"for every ton that the Mammoth capture plant captured, up to 5,000 to 6,000 kilowatt-hours of energy would be required."* [(1)]. For comparison, 5,500 kWh of energy to capture one ton of CO_2 is an order of magnitude higher than the cost of capturing industrial point-source emissions per ton of CO_2.

However, unless this service is 100% emission-free (you'll soon find out that it's not), the carbon footprint of the capture process itself dramatically increases depending on the energy mix supplying the DACCS system. Given the various emission factors of electricity sources, it becomes clear that capturing one ton of CO_2 can be counterproductive from a climate perspective.

For instance:

- With a national electricity emissions factor of 70 g CO_2e/kWh, the capture of one ton of CO_2 results in 385 kg CO_2e of emissions, meaning only 615 kg are effectively captured.
- With an emissions factor of 170 g CO_2e/kWh, the net effect is just 6,5% capture.
- From 190 g CO_2e/kWh and above, the net climate impact becomes negative, the process of capture generates more emissions than it removes.

This is further explained in the following chapter.

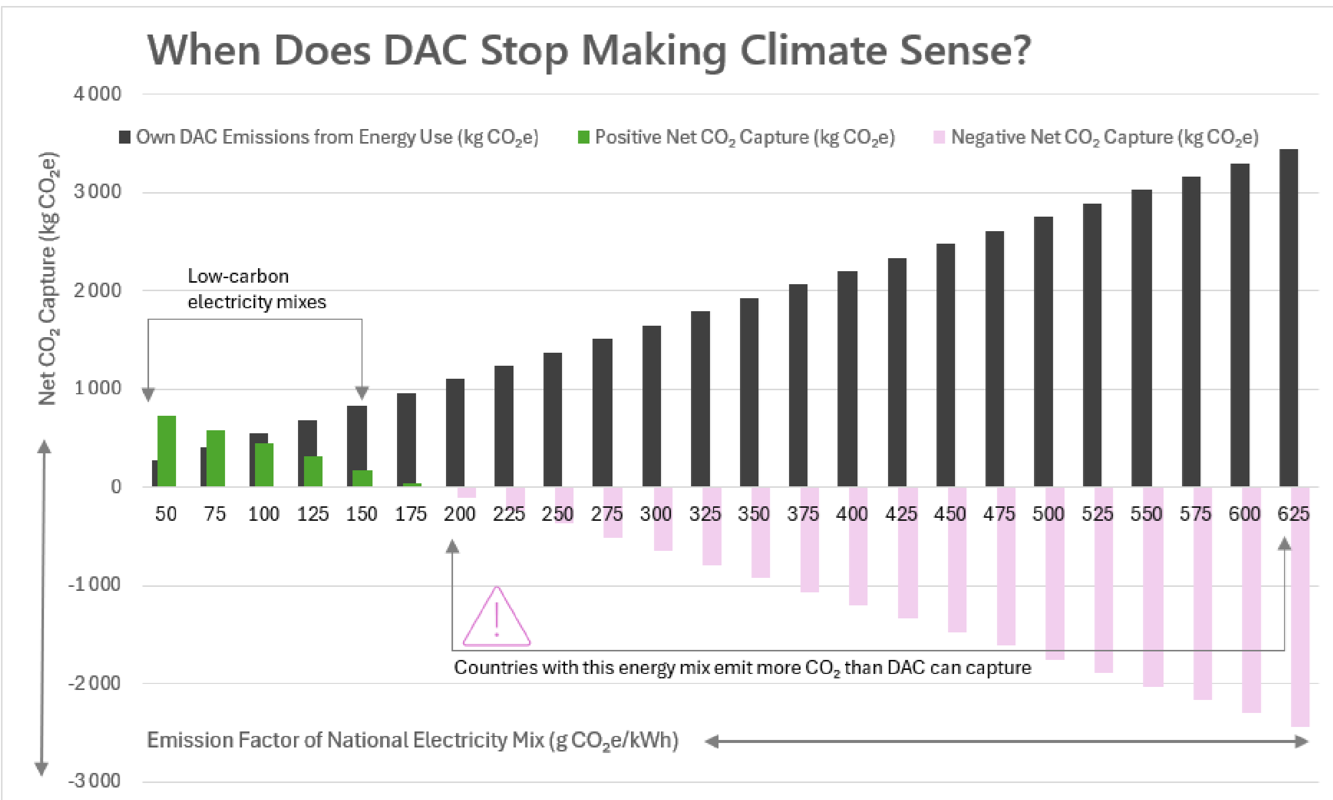


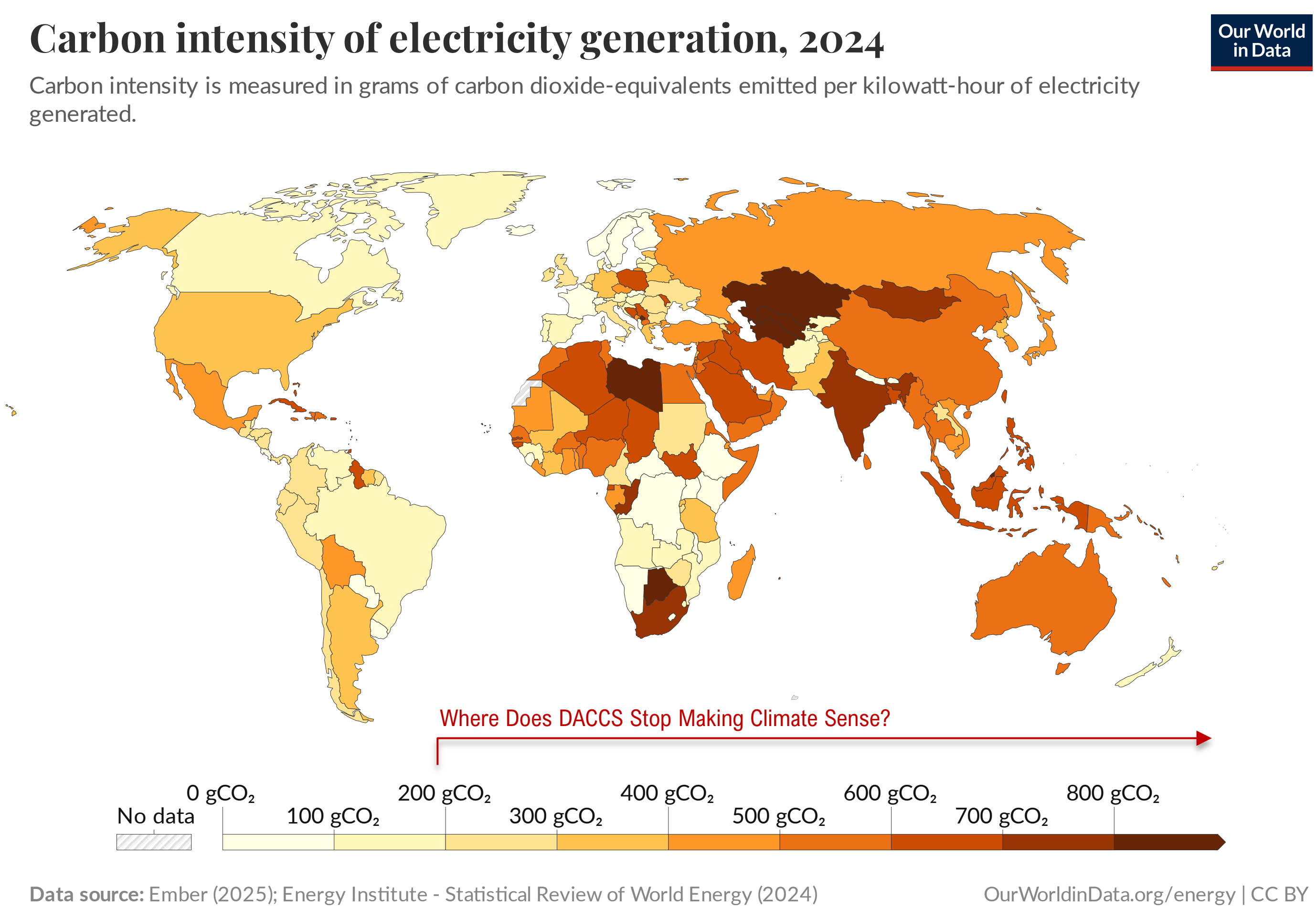
Chart No. 1: When Does DACCS Stop Making Climate Sense?

Interpretation of the Chart No.1: When Does DACCS Stop Making Climate Sense?

The chart above illustrates the net CO_2 capture balance of DACCS technology depending on the emissions factor of electricity in a given country. The horizontal axis represents the Carbon intensity of electricity generation by Carbon Emissions Factor (CEF) in grams of CO_2e per kilowatt-hour (g CO_2e/kWh), reflecting the carbon intensity of the national electricity mix. The vertical axis shows the net CO_2 capture after subtracting emissions from the energy consumed to capture one ton of CO_2 (5,500 kWh per 1 ton CO_2, based on Climeworks data).

Green bars indicate countries where DACCS yields a positive climate effect – that is, the total emissions from operation are lower than the volume of CO_2 captured. However, this benefit is highly dependent on a low to very low CEF, typically below 170 g CO_2e/kWh. This generally includes countries with high shares of hydropower, geothermal, or nuclear energy (e.g. Iceland, Norway, France, Sweden, Slovakia, Finland).

Conversely, pink bars represent cases where DACCS technology produces more emissions than it removes. When emissions factors exceed ≈190 g CO_2e/kWh, the net climate effect becomes negative, each ton of captured CO_2 is accompanied by an even higher amount of emissions generated solely by the capture process. These levels are common in countries reliant on fossil fuels for electricity production (e.g. China, India, Russia, USA, Poland, Germany, Australia...).



Therefore, if DACCS uses electricity with a high carbon intensity, the result is not climate mitigation, but climate exacerbation.

The chart also highlights the physical and systemic limitations of this technology. It is not a universal tool applicable on a global scale, its use makes sense only within strictly defined geographic and energy conditions. Outside these parameters, DACCS becomes merely an expensive way to convert electricity into new emissions.

3. The Illusion of Clean Capture

One of the most common responses to criticisms of DACCS's climate effectiveness is the proposal that these systems should simply be powered by locally installed renewable energy sources, typically photovoltaic (solar) power plants or wind turbines. At first glance, this suggestion seems rational. In reality, it merely shifts the problem rather than addressing its physical foundation.

Renewable energy technologies are not emission-free. Every megawatt-hour generated from solar or wind power is the result of prior investments in materials, energy, and manufacturing processes, including metal extraction, panel and turbine production, battery energy storage systems (BESS), transport, and installation.

C Currently published values of so-called embodied emissions for photovoltaic systems typically range from 25 to 75 g CO_2e/kWh, depending on the calculation methodology. To illustrate this, we refer to the official Declaration of Carbon Footprint by REC Solar for their monocrystalline photovoltaic modules, reporting values between 519–553 g CO_2e/Wp. All modules were assessed in accordance with the ECS CRE4 methodology (France).

We can then mathematically derive the Carbon Emission Factor (CEF) for a photovoltaic panel as:

$$\boldsymbol{CEF} = \frac{CF_{W_p}}{Y_{annual} \times Lifespan_{years}}$$

where:

CEF ... Carbon Emissions Factor (g CO_2/kWh)
CF_{Wp} ... Photovoltaic Panel Carbon Footprint (g CO_2/kW_p)
Y_{annual} ... annual energy yield or annual electricity generation (kWh/Wp)
$Lifespan_{years}$ ... Photovoltaic panel lifespan (years)

The results of this CEF modelling are presented in Chart No. 2.

Note: ECS CRE4 is a cradle-to-gate LCA methodology; actual CEF values would be higher under a full life-cycle assessment (cradle-to-grave). This is intended as an illustrative example only. As REC notes in its certificate: „Furthermore, REC sources the silicon for its cells from Europe which allows the modules to have a much better carbon footprint thanks to the use of a low carbon energy mix in production."

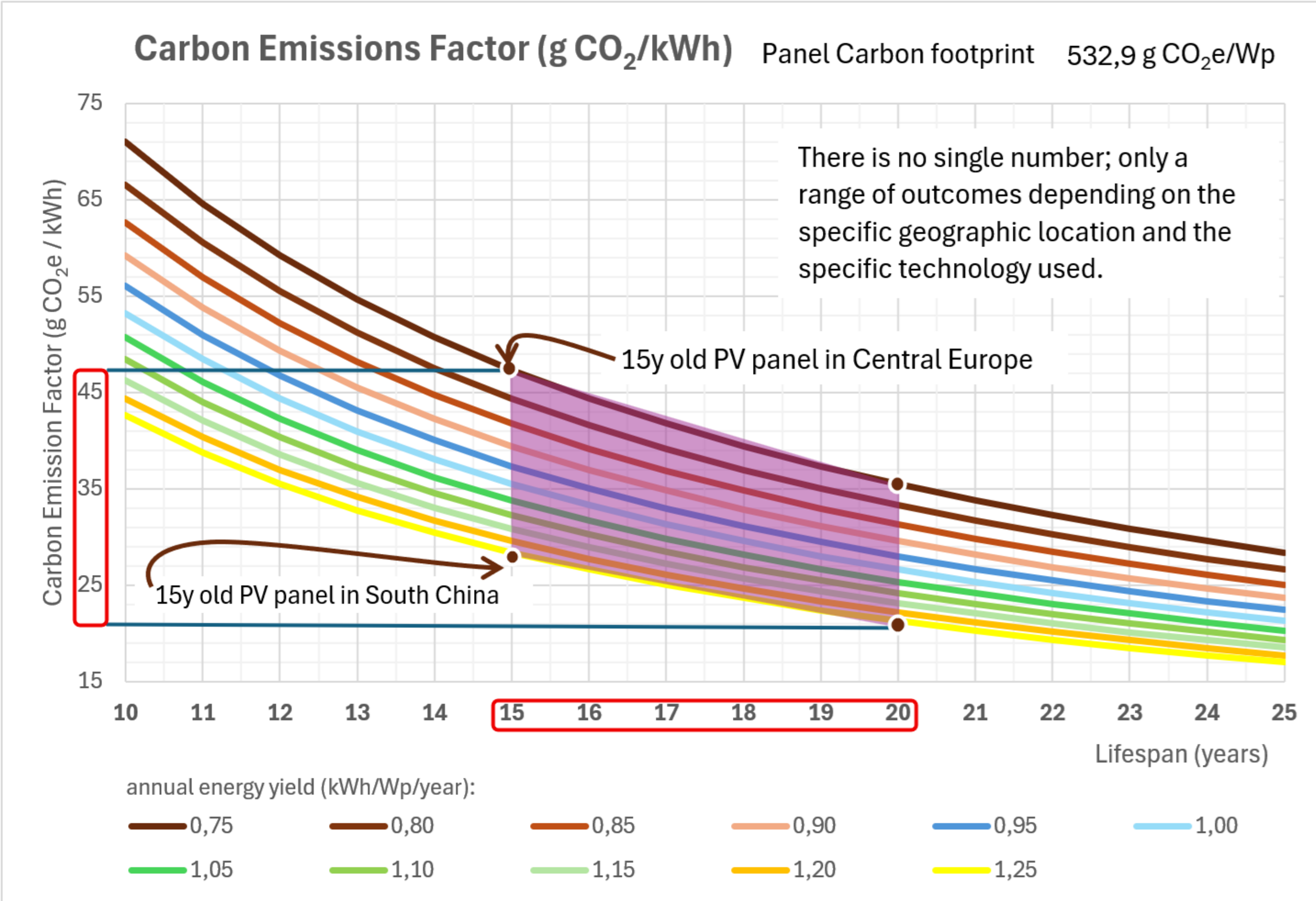


Chart No. 2: Photovoltaics Carbon Emission Factor (cradle-to-gate).

This chart illustrates how the CEF of the same photovoltaic panel does not depend on a single value, but on the interplay between panel lifespan and geographic yield. For a 15-year-old panel, outcomes range widely: from 28 g CO_2e/kWh in high-yield regions like South China, to 47 g CO_2e/kWh in less productive areas such as Central Europe. The highlighted band (lifespan 15–20 years) reveals how sensitive carbon performance is to both location and operating assumptions. Declaring PV systems “zero-emission” without disclosing these variables misrepresents their real climate impact.

We must also account for the CEF of industrial-scale BESS using a comparable approach. These systems typically have significantly higher embodied emissions per unit of usable capacity, especially when factoring in the number of full charge/discharge cycles and the roundtrip efficiency over their operational lifetime. To calculate this, we need to know, depending on the battery technology, its expected lifetime (expressed in full equivalent cycles), roundtrip efficiency, and the carbon footprint of its production. Under a conservative scenario, the resulting CEF ranges between 62 and 76 g CO_2/kWh.

If we use a cradle-to grave LCA Total CEF value (PVe panels + BESS) of 170 g CO_2e/kWh and apply it to the DACCS process, which consumes 5,500 kWh to capture one ton of CO_2, we get 935 kg CO_2e of emissions produced.

In other words, the carbon footprint of the energy consumed to capture one ton of CO_2 amounts to 935 kg CO_2e, while the "capture" itself is claimed to remove 1,000 kg from the atmosphere. The net effect is thus only 65 kg CO_2e, i.e. a net capture of 6.5%, which is a marginal climate benefit, and that's under ideal conditions. Even if we assume the creation of a highly optimized, low-emission off-grid PV system with industrial-scale BESS, achieving a total CEF of just 85 g CO_2e/kWh; capturing one tonne of CO_2 would still result in NEW 468 kg CO_2e emitted. And that assumes the system performs as efficiently as claimed by its developers. So far, evidence suggests otherwise. Later in this report, we explain why.

The argument "let's just power DACCS with wind or solar" therefore fails both climatically and systemically. In today's energy landscape, there is no unallocated, 100% clean and emission-free energy available. Every unit of electricity used for DACCS is a kilowatt-hour that is no longer available to reduce emissions elsewhere in the economy. This is why DACCS must be evaluated not just as an isolated technology, but within the broader context of the energy system. And within this context, the conclusion remains clear: DACCS is not yet a climate solution, it is an energy luxury.

4. Emissions Balance of DACCS

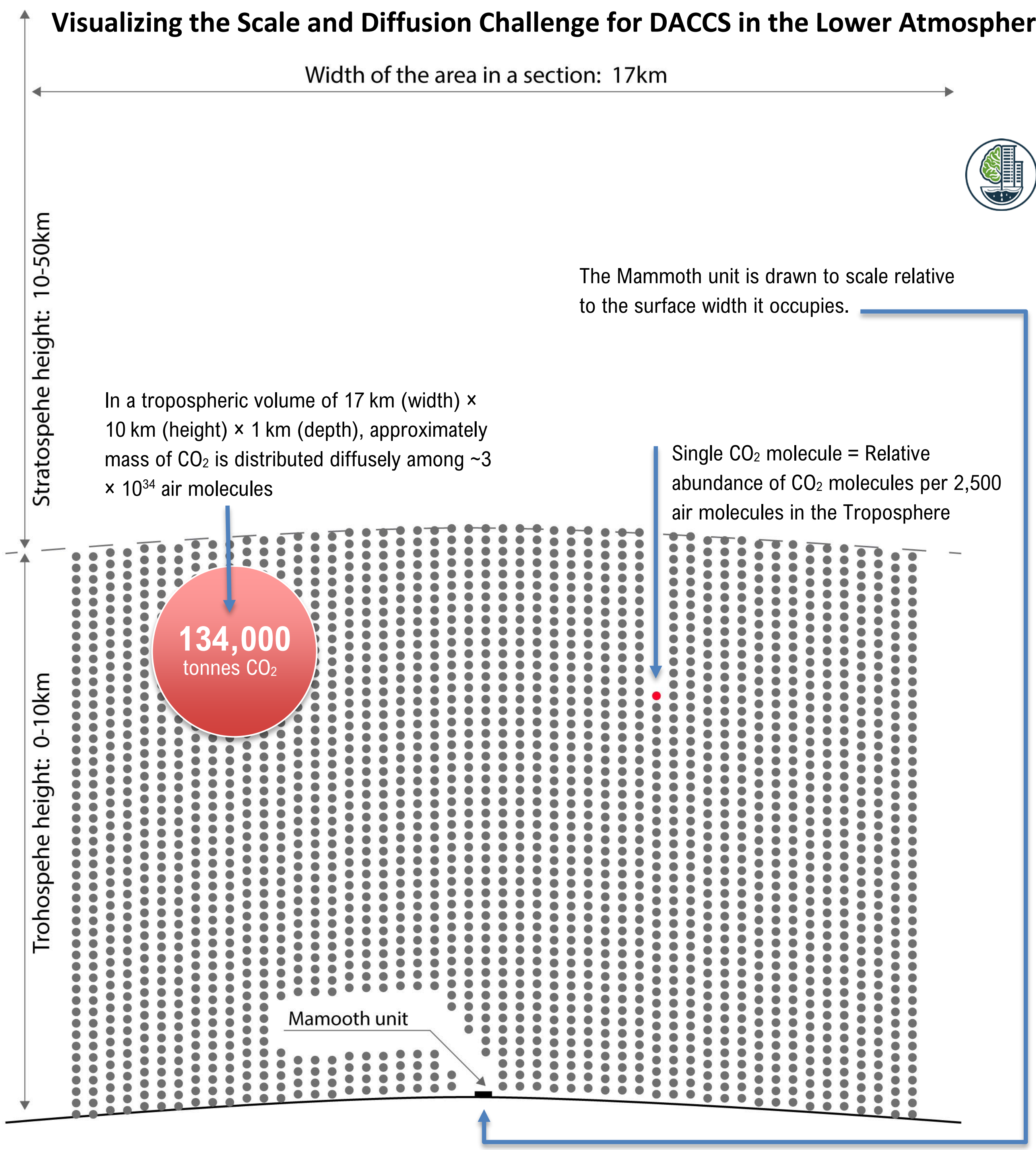
Since the beginning of its operations in 2021, Climeworks has captured a cumulative total of approximately 2,400 tons of CO_2 in Iceland. However, in the single year of 2023 alone, the company reported 1,700 tons of CO_2 equivalent emissions generated through its own operations. This figure includes direct and indirect emissions (Scopes 1, 2, and upstream Scope 3), primarily related to electricity use, transport, and materials. *"the emissions that occur due to Climeworks' activities are therefore more than it captures"* [(1)]. This ratio clearly points to a **net climate deficit**, a technological platform intended to remove greenhouse gases from the atmosphere is, in reality, unable to even compensate for its own operational emissions. Despite ongoing claims of climate neutrality in the future, these numbers illustrate the challenge of achieving a **true net-negative carbon balance** without overreliance on offsets or avoided emissions claims.

5. Physical Limits of the Atmosphere: Why It's Not Enough to Just Install DACCS at Ground Level

The notion that it's enough to install a sufficient number of DACCS units on the Earth's surface to gradually extract the excess CO_2 from the atmosphere is physically tempting, but climatically misleading. It ignores the three-dimensional nature of the atmosphere, the low concentration of CO_2, and the dynamics of its vertical and horizontal distribution.

CO_2 makes up only about 0.0427% of the atmosphere by volume (427 ppm), which means that out of one million air particles, only 427 are CO_2 molecules. These molecules are dispersed through diffusion and turbulent flows across the entire height of the troposphere (approximately 12–17 km), parts of the lower stratosphere, and unevenly across regions depending on sources, geography, wind, and topography.

Although diffusion ensures long-term concentration equalization, it is a slow process, and CO_2 levels are rising throughout the full volume of the atmosphere, not just near the surface. DACCS units, however, operate exclusively in a thin layer close to the ground, where molecule movement is governed by local conditions: temperature inversions, laminar flows, urban canyons, turbulence, or heat islands.



This illustration shows the disproportion between the physical scale of a DACCS Mammoth unit and the diffuse distribution of CO_2 in a 17 × 10 × 1 km volume of the troposphere. While the unit is drawn to scale, the surrounding atmosphere contains over 134,000 tonnes of CO_2, dispersed at a concentration of roughly 1 molecule per 2,500 air molecules. The image highlights the physical and energetic limitations of DACCS systems in extracting CO_2 from such dilute, stratified air masses.

This means that:

- DACCS units cannot actively draw CO_2 from higher altitudes, their reach is limited to the immediate surrounding air,
- CO_2 capture is constrained by air exchange with upper atmospheric layers, which is dependent on meteorological conditions,
- Effective CO_2 removal from upper atmospheric layers would require these "atmospheric vacuums" to be distributed vertically throughout the atmosphere, which is technologically and energetically inconceivable.

The physical consequence is that even a massive deployment of DACCS units at ground level cannot “drain” CO_2 from the entire atmospheric column. It is an extremely local and linear process, DACCS only cleans the portion of air that passes directly through the filter, which represents a tiny fraction of the global atmospheric volume.

Even if humanity were to develop a DACCS “vacuum” system large and powerful enough to continuously intake air volumes from the full vertical extent of the Troposphere, it would inevitably encounter critical atmospheric consequences.

Such an intervention would no longer be passive carbon removal but an active disruption of large-scale atmospheric circulation. Inducing sustained vertical airflow at the scale required to access diffuse CO_2 at higher altitudes would alter local pressure gradients, destabilize boundary-layer processes, and potentially interfere with regional weather systems. Beyond meteorological impacts, the energetic cost and turbulence induced by such forced convection would make the system environmentally and economically unsustainable. The atmosphere is not a static storage medium, it is a dynamic fluid governed by thermodynamics, not engineering ambition.

And this entire argument still concerns only the troposphere.
We haven’t even begun to address the challenge of extracting CO_2 from the stratosphere, where a non-negligible fraction of atmospheric CO_2 also resides, but where vertical mixing is even more limited and air density drops significantly.

It is, of course, entirely plausible that spreadsheets continue to deliver optimistic projections.

6. Some Mathematical Exercises Behind the Assumptions

To illustrate: the Earth's atmosphere has a total volume of approximately 4.2 billion km³. To capture just one ton of CO_2, about 1.258 billion m³ of air would need to be processed (at 427 ppm concentration):

$$\boldsymbol{n_{air}} = \frac{\rho_{air}}{M_{air,mol}} = \frac{1.225}{0.02897} = 42.28\, mol$$

$$Molar\ quantity\ of\ CO_2\text{:}\ \boldsymbol{n_{CO_2}} = C_{CO_2}\ x\ \ n_{air} = 0.000427\ x\ 42.28 = 0.018\, mol$$

Then Mass of CO_2 in air:

$$\boldsymbol{M_{CO_2,air}} = n_{CO_2}\ x\ M_{CO_2,mol} = 0.018 \times 44.01 = 0.792\ g/m^3$$

where:

n_{air} … molar quantity of dry air at sea level and 15 °C,

ρ_{air} ≈1.225 kg/m³ … is the density of air at sea level and 15 °C,

$M_{air,mol}$ = 28.97 g/mol … is the average molar mass of dry air,

C_{CO_2} =0.000427 … is the volumetric concentration of CO_2 for the 427 ppm,

$M_{CO_2,mol}$ =44.01 g/mol … is the molar mass of carbon dioxide,

Then **Processed Air Volume required per DACCS unit to capture one tonne of CO_2** is estimated at:

$$V_{air,DAC\ unit} = \frac{1t\ CO_2}{m_{CO_2}} = \frac{1000000}{0.795} = \mathbf{1.258 \times 10^6\ m^3}$$

The total CO_2 mass ($M_{total\ CO_2}$) in the Earth's atmosphere at this concentration is estimated at 3.34 trillion tons (3.34×10^{15} tons) or 3,340 gigatons (Gt):

V_{atm} … estimated Earth's atmosphere mass 4.2 x 10^{18} *m³* [(2)],

$$M_{total\ CO_2} = M_{CO_2,mol} \times V_{atm} = 0{,}000795\ x\ 4.2\ 10^{18} = \mathbf{3.337 \times 10^{12}}\ \text{tons}$$

5. Deep dive: Projected Scale and Energy Demand of Climeworks' DACCS Mammoth Units over a 20-Year Atmospheric CO_2 Removal Scenario

This chapter quantifies the infrastructure and energy demands of Climeworks' DACCS Mammoth system when scaled to achieve selected atmospheric CO_2 removal targets ranging from 1% to 20% of total atmospheric carbon mass. The scenario assumes a 20-year period to achieve of the removal target.

Overview of Core Assumptions

The following technical parameters form the basis of the scenario modelling:

- **Time Horizon**: 20 years of continuous DACCS operation.
- **Total Atmospheric CO_2 ($M_{total\ CO_2}$)**: ~3.34 trillion tons.
- **Targeted CO_2 Removal from Atmosphere (% of total) over 20y**: From 1% to 20% of total atmospheric CO_2.
- **Specific Energy Consumption (SEC)**: 5 500 kWh per ton of CO_2 captured, based on mid-range Climeworks' estimates.
- **DACCS unit analyzed**: Climeworks Mammoth plant (Climeworks' web specs.).
  - 72 **CO_2 Collector Modules** (CCs) per plant.
  - Total annual nameplate capacity per Mammoth: **36 000 tons CO_2**.

Air volume required per ton of CO_2 captured: $V_{air,DAC\ unit}$: $\mathbf{1.258\ \times 10^6\ m^3}$

Step-by-Step Methodology

Step 1: Target CO_2 Mass to Be Removed (tons over 20y)

We multiply the total atmospheric CO_2 (3.34×10^{12} tons) by each removal target (1%–20%) to get:

$$M_{CO_2,removed} = Target\ (\%)\ \times\ mM_{total\ CO_2}$$

Step 2: Volume of Air Required for Capture (m^3 over 20y)

We apply the known specific air processing volume to the CO_2 mass:

$$\boldsymbol{V_{air,capture}} = M_{CO_2,removed}\ \times\ V_{air,DAC\ unit}$$

Step 3: Derivation of Individual DACCS Collector Module Performance

Given Mammoth's setup:

- 72 CC modules per plant, 36 000 tons/year total plant capture, 365 days/year, 24 hours/day,

We compute the **airflow throughput per CC unit**:

$$\mathbf{V}_{cc,air} = \frac{(\text{Total annual nameplate capacity per Mammoth}) \times (V_{air,DAC\ unit})}{(\text{CCs per plant})x\ (365d\ x\ 24h\ x\ 60min\ x\ 60sec\ per\ year)}$$

$$\mathbf{V}_{cc,air} = \frac{36\ 000\ \text{t} \times 1.258 \times 10^6\ \text{m3/t}}{72 \times 31\ 536\ 000\ s/year} = 19.95\ m^3 s^{-1}$$

Assuming an average **intake area of 10 m²** per CC module we can calculate a **flow velocity**:

$$v_{CC} = \frac{\mathbf{V}_{cc,air}}{\text{average intake area}} = \frac{19.95\ m^3 s^{-1}}{10\ m^2} = 1{,}995\ ms^{-1}$$

Step 4: Total CO_2 Collector Units Required

We then compute how many units are needed to process the required air volume continuously over 20 years at the calculated flow rate:

$$\textbf{Total CC Units} = \frac{V_{air,capture}}{v_{CC} \times 20 years \times 31\ 536\ 000\ s/year}$$

Step 5: Equivalent Number of DACCS Plants (Mammoth-scale)

We divide Total Carbon Collector Units (CCU) units by 72 (modules per Mammoth plant):

$$DAC\ Plants = \frac{\text{Total CCU}}{\text{Collector Modules (CCs) per plant}} = \frac{\text{Total CCU}}{72}$$

Step 6: Estimated Annual Energy Demand (PWh/year)

We calculate the amount of CO_2 to be captured annually and apply the specific energy consumption:

$$\boldsymbol{CO_2}\ \textbf{Annual}\ [\mathbf{t}] = \frac{M_{CO_2,removed}}{20\ years}$$

$$\boldsymbol{DAC\ Estimated\ Annual\ Energy\ Demand} = \frac{CO_2\ \text{Annual (t)} \times SEC\ (kWh/t)}{10^9}$$

Results Table Overview

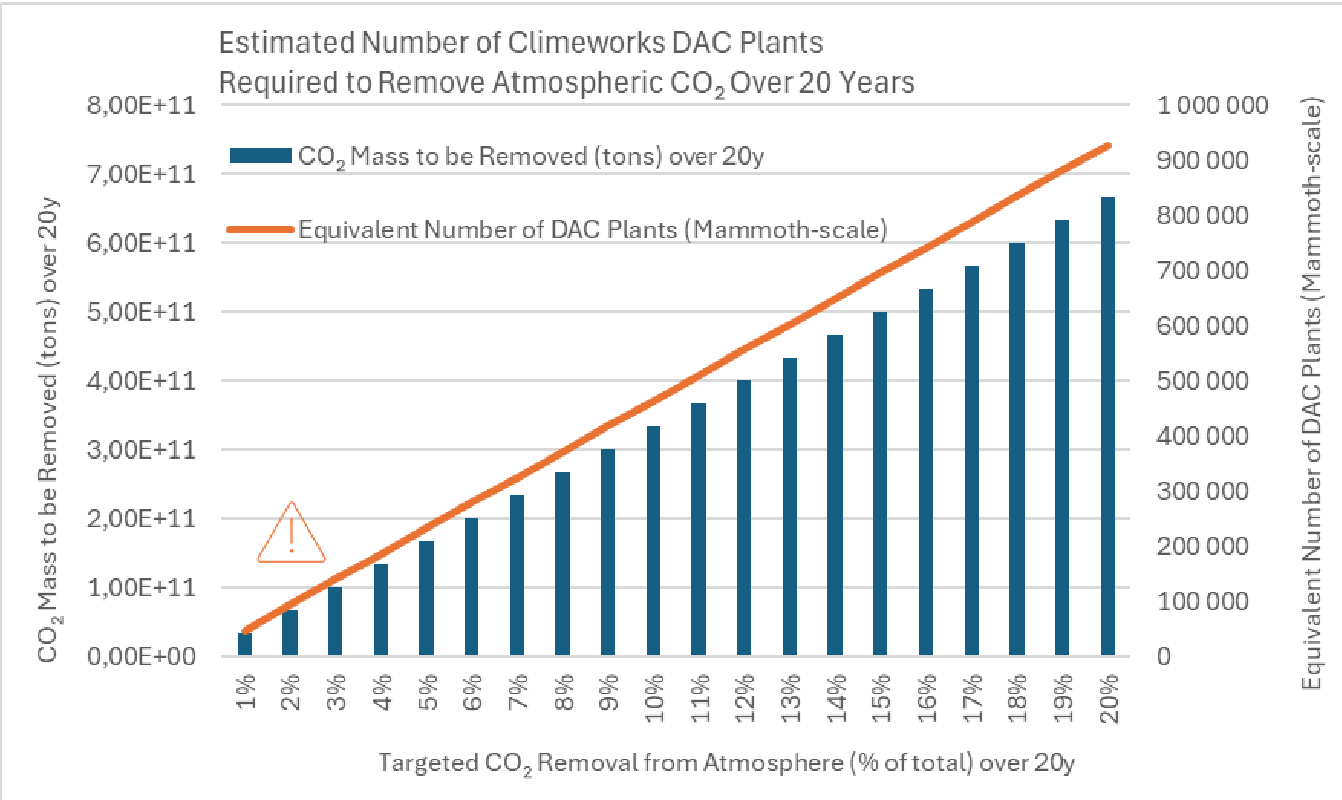
The full results are presented in the accompanying table (TAB.1):

Targeted CO_2 Removal from Atmosphere (% of total) over 20y	CO_2 Mass to be Removed (tons) over 20y	Volume of Air Required for Capture (m^3) over 20y	Total CO_2 Collector Units Required (based on Mammoth design)	Equivalent Number of DACCS Plants (Mammoth-scale)	DACCS Estimated Annual Energy Demand (PWh/year)
1%	3,34E+10	4,20E+16	3 337 460	46 354	9
2%	6,67E+10	8,40E+16	6 674 921	92 707	18
3%	1,00E+11	1,26E+17	10 012 381	139 061	28
4%	1,33E+11	1,68E+17	13 349 842	185 414	37
5%	1,67E+11	2,10E+17	16 687 302	231 768	46
6%	2,00E+11	2,52E+17	20 024 763	278 122	55
7%	2,34E+11	2,94E+17	23 362 223	324 475	64
8%	2,67E+11	3,36E+17	26 699 684	370 829	73
9%	3,00E+11	3,78E+17	30 037 144	417 183	83
10%	3,34E+11	4,20E+17	33 374 604	463 536	92
11%	3,67E+11	4,62E+17	36 712 065	509 890	101
12%	4,00E+11	5,04E+17	40 049 525	556 243	110
13%	4,34E+11	5,46E+17	43 386 986	602 597	119
14%	4,67E+11	5,88E+17	46 724 446	648 951	128
15%	5,01E+11	6,30E+17	50 061 907	695 304	138
16%	5,34E+11	6,72E+17	53 399 367	741 658	147
17%	5,67E+11	7,14E+17	56 736 828	788 011	156
18%	6,01E+11	7,56E+17	60 074 288	834 365	165
19%	6,34E+11	7,98E+17	63 411 748	880 719	174
20%	6,67E+11	8,40E+17	66 749 209	927 072	184

The table summarizes key technical estimates for a 20-year CO_2 removal scenario using Climeworks' Mammoth DACCS units. It linearly projects the required air processing volumes, number of collector units, number of Mammoth-scale DACCS plants, and associated annual energy demands for targeted CO_2 removal ranging from 1% to 20% of the current atmospheric stock. Each step reflects the scaling impact of the removal ambition. While the table provides a detailed numerical overview, the exponential growth in system requirements becomes more intuitively visible in the graphical interpretations that follow. These visualizations better illustrate the technological and energetic infeasibility of DACCS scale-up under current system designs.

Graphical Interpretation

Chart 2: Estimated Number of Climeworks DACCS Plants Required to Remove Atmospheric CO_2 Over 20 Years

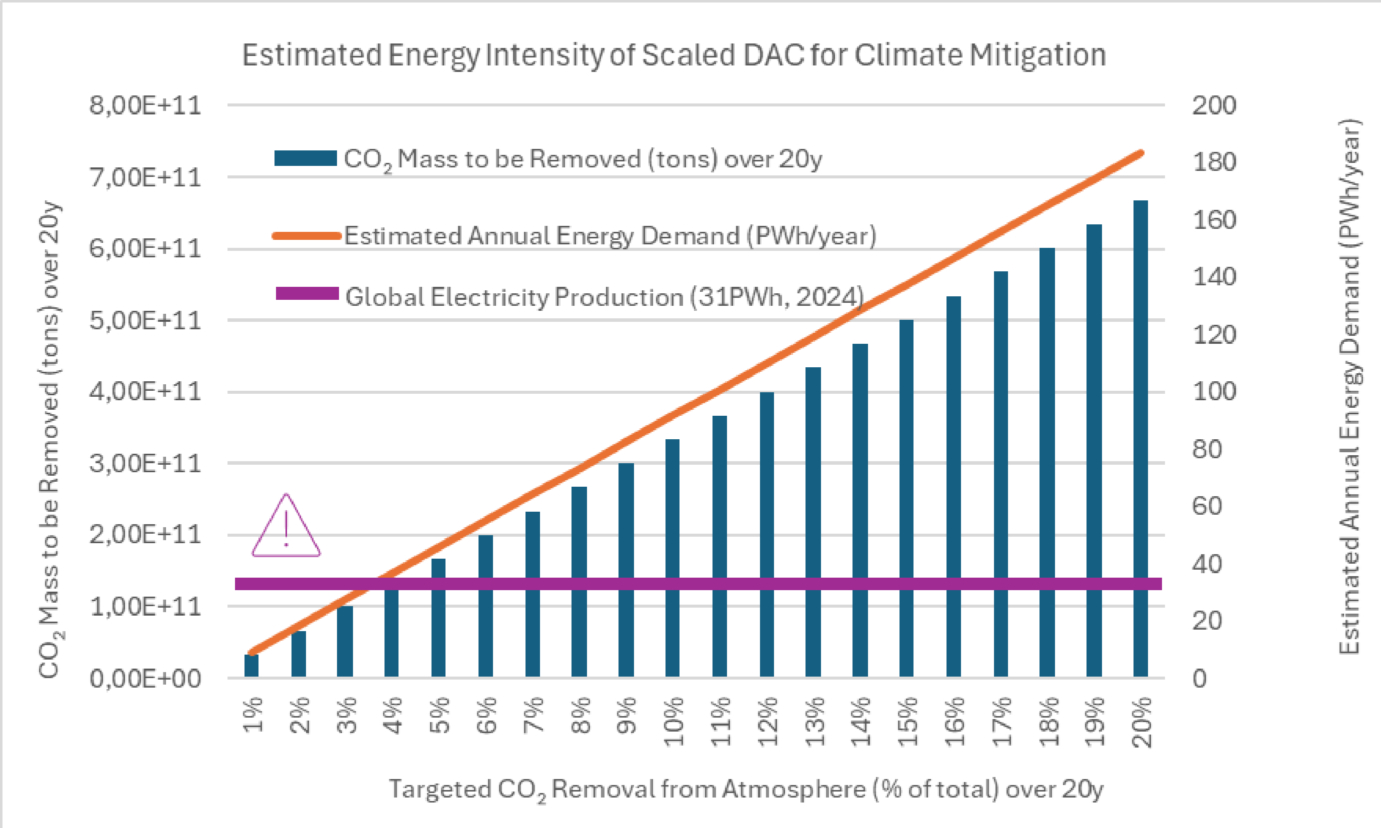


- X-axis: % of atmospheric CO_2 to be removed
- Left Y-axis: Total CO_2 mass to be removed [tons]
- Right Y-axis: Number of Mammoth DACCS plants required

A 10% removal target would require over **463 000 DACCS plants**, each with 72 units a **planetary-scale deployment**.

It is important to note that this projection refers to the cumulative removal of x% of atmospheric CO_2 over a 20-year period not annually.

Chart 3: Estimated Energy Intensity of Scaled DACCS for Climate Mitigation



- X-axis: % of atmospheric CO_2 to be removed
- Left Y-axis: Total CO_2 mass to be removed [tons]
- Right Y-axis: Annual energy demand [PWh/year]

Capturing 10% of CO_2 would consume over **92 PWh/year**, compared to the current global electricity production of ~31 PWh/year (2024), shown by the magenta benchmark line.

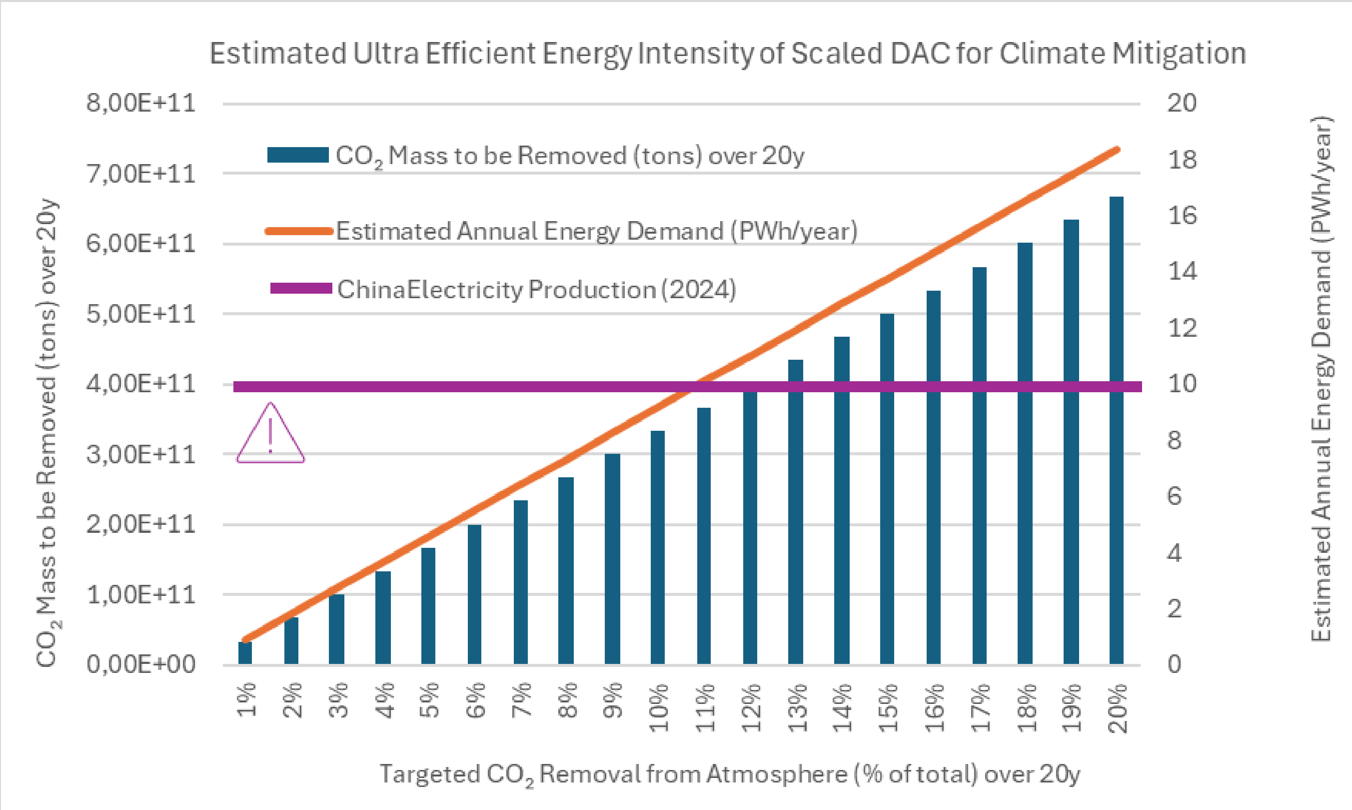
It is important to note that this projection refers to the cumulative removal of x% of atmospheric CO_2 over a 20-year period not annually.
The illustrated energy demand reflects the sustained effort required each year to reach that total by the end of the period. Misinterpreting this as annual removal would vastly understate the scale of the challenge.

Sensitivity Analysis: Ultra-Efficient DACCS Energy Scenario (–90% SEC Improvement)

To evaluate the theoretical feasibility of large-scale DACCS deployment under best-case energy conditions, we performed a sensitivity analysis in which the **specific energy consumption (SEC)** for CO_2 capture was reduced by 90% from **5 500 kWh/tCO_2 to 550 kWh/tCO_2**. This represents a **highly optimistic future scenario**, assuming breakthrough advancements in sorbent efficiency, heat recovery, and systems integration.

The results are presented in the figure below.

Chart 4: Estimated Ultra-Efficient Energy Intensity of Scaled DACCS for Climate Mitigation



- **Blue columns** represent total CO_2 mass to be removed over 20 years (as before).
- **Orange line** shows the revised **Estimated Annual Energy Demand (PWh/year)** assuming only 550 kWh per ton of CO_2 captured (as before).
- **Magenta line** represents **China's total electricity production in 2024**, which reached **10 PWh/year** (source: EMBER Global Electricity Review).

An interpretation:

Even under ultra-efficient conditions, the required annual energy to remove just 10% of atmospheric CO_2 remains close to 9.2 PWh/year, which is comparable to the entire electricity production of the world's largest power generator: China.

Scaling DACCS to climate-relevant levels still collides with hard physical limits, particularly in the availability of low-carbon energy, infrastructure buildout, and sustained operation over decades.

Conclusion of the chapter

This analysis demonstrates that even under technically optimistic and linearly scaled assumptions, DACCS technologies such as Climeworks' Mammoth units face **extreme physical, energetic, and spatial limitations** when applied to meaningful levels of climate mitigation.

Even assuming:

- maximum efficiency in air processing and chemical capture,
- unrestricted global deployment of DACCS units,
- and an idealized energy infrastructure,

…the required scale of operation remains **astronomical and unfeasible**, both from an energy and infrastructure perspective. The number of units, the surface area required, and the cumulative electricity demand (surpassing even the output of the world's largest electricity producers) show that DACCS is not merely an expensive tool; it is an **impractical one** at planetary scale.

Yet, the most fundamental limitation lies not in cost or logistics, but in physics itself:

DACCS systems cannot access the full volume of atmospheric CO_2.
These systems operate at surface level and depend on passive air intake or fans with limited reach. The global atmosphere is a 17-kilometer-deep, layered, dynamic system, and DACCS units can only interact with the thin boundary layer directly above ground.
Therefore, the concept of "cleaning the atmosphere" via DACCS is based on a flawed geometric assumption: we cannot scrub the sky from the ground.

This single fact renders the vision of large-scale atmospheric cleaning not only inefficient but **physically constrained to the point of absurdity**. Even if we solve engineering, energy, and economic hurdles, **we cannot scale these machines to address the entirety of Earth's air mass**.

And so, arises the most important question:

Is DACCS really about removing CO_2, or is it about selling permission to emit through offset/credits?

The data suggests the latter. Climeworks' business model centers around **offset generation and resale**, not internal decarbonization or system-level mitigation. In this light, DACCS begins to resemble not a climate solution, but a climate **accounting product**, optimized for market narratives rather than atmospheric stability.

6. Economic Sustainability and Technological Optimism

The climate paradox of Climeworks' current business model becomes even more pronounced upon examining the treatment of the captured CO_2. Rather than using the sequestered carbon to offset its own operational emissions, the company sells it to third-party customers as part of contractual carbon removal services:

"The company does not use the units it captures in its own operations but has sold them to the company's customers." [(1)]

This creates a structural inconsistency: a company that markets itself as a climate solution outsources both the responsibility for its operational emissions and the benefit of captured CO_2. While its technological apparatus emits more CO_2 than it removes, the company claims net-negative outcomes based on third-party purchases, not on internal climate performance.

This approach conflicts directly with the scientific understanding of GHG neutrality, as articulated in the **IPCC AR6 (SYR, Box 1, p. 60)**. The IPCC defines global net-zero GHG as a state where **all residual emissions are counterbalanced by durable, physical CO_2 removals**. Crucially, this balance must occur in real time and space, not via market abstractions or accounting transfers.

Yet Climeworks' model implicitly adopts a commodified offset logic, where:

- **Temporal asymmetry** arises (emissions now, removals possibly years later),
- **Geographic detachment** occurs (emission and removal may happen on different continents),
- **Methodological ambiguity** persists (reliability of carbon storage is often unverifiable),
- and **Moral outsourcing** prevails (emitters are "absolved" via purchase, without reduction).

This decoupling of emission responsibility from technological reality contributes to a new mode of greenwashing, not by denying climate change, but by monetizing its solution without delivering a physically net-positive effect. The result is a well-branded, technically functional, but systemically misleading construct. This mismatch between market narrative and physical impact renders the current model economically attractive, yet climatically ineffective, reinforcing a false optimism that delays necessary structural mitigation.

Even on its official website, Climeworks promotes its offering as an "all-in-one carbon removal service" that allows companies to "achieve net zero" by permanently removing CO_2 emissions that can't be reduced. However, such statements obscure the distinction between reduction and removal, and more importantly, between actual climate neutrality and market-based carbon accounting.

“Our offer makes it easy to reach your net zero and climate targets by permanently removing CO_2 emissions that can’t be reduced.”
(Climeworks, 2024 – Official website)

This framing suggests that companies can meet net zero targets without reducing their own emissions, simply by purchasing removals, whether delivered by Climeworks or its "trusted partners." Such a framework is not aligned with IPCC definitions of climate neutrality, which emphasize the need to first minimize emissions at the source and only use removals for residuals that cannot be technically avoided.

In practice, Climeworks offers a customizable portfolio of outsourced responsibility rather than a science-based path to system-wide decarbonization. This supports a compliance-by-purchase model that risks entrenching the very emissions it claims to erase.

7. Terminological Precision: GHG/Carbon Neutrality by the IPCC

Within the public discourse on climate neutrality, a persistent confusion exists between concepts such as *carbon neutrality*, *GHG neutrality*, and *climate neutrality*, terms often used interchangeably without scientific grounding. The **Intergovernmental Panel on Climate Change (IPCC)**, as the authoritative scientific body on climate assessment, makes a clear and deliberate distinction among these terms and avoids using vague constructs like “climate neutrality” altogether.

Net Zero CO_2 ≠ Net Zero GHG

According to the **IPCC AR6 Synthesis Report (2023)**:

“Reaching net zero CO_2 emissions is different from reaching net zero GHG emissions.”
(AR6 SYR, Box 1, p. 60)

This distinction is critical. *Net zero CO_2* pertains specifically to the balance between CO_2 emissions and CO_2 removals. In contrast, *net zero GHG* includes a weighted basket of greenhouse gases (e.g., CH_4, N_2O) expressed in CO_2-equivalents using metrics such as GWP100. The IPCC adds:

“The timing of net zero for a basket of GHGs depends on the emissions metric […] However, for a given emissions pathway, the physical climate response is independent of the metric chosen.”
(AR6 SYR, Box 1, p. 60)

In other words, **accounting choices may affect the numbers, but not the physics**.

Net Zero GHG Requires Physical CO_2 Removal

The IPCC further clarifies the conditions for reaching global GHG neutrality:

"Achieving global net zero GHG emissions requires all remaining CO_2 and metric-weighted non-CO_2 GHG emissions to be counterbalanced by durably stored CO_2 removals (high confidence)."
(AR6 SYR, Box 1, p. 60)

This requirement is not based on financial accounting or market proxies, but on measurable, verifiable, and permanent physical CO_2 removal, explicitly separating the concept from voluntary offset schemes.

And What About Offsets?

Nowhere in AR6 does the IPCC endorse *offsets*, whether in the form of market credits, certificates, or avoidance-based compensation schemes, as an acceptable pathway to neutrality. Offsets are:

- **not recommended** as mitigation tools,
- **not recognized** in the definition of net zero emissions,
- **not incorporated** into the scientific framing of climate-aligned emissions reductions.

Where physical CO_2 removals (CDR) are mentioned, they refer to actual geochemical or biological processes that permanently sequester carbon, not to financial transfers or assumptions of future non-emissions.

In Contrast: ISO 14068 and the Corporate Offset Narrative

Unlike the IPCC, the **ISO 14068-1:2023 standard**, designed for carbon-neutral certification of products and organizations, **embraces a corporate reporting logic**, allowing:

- Carbon neutrality claims without substantial in-house emissions reductions,
- Use of offsets as the primary mechanism, with **no quality or permanence thresholds**,
- The inclusion of *avoidance credits* based on hypothetical, non-occurred emissions.

This creates a dangerous disconnect between **scientific climate targets and reputational carbon accounting**. It elevates offsetting to a dominant mitigation tool without requiring physical climate benefit, undermining the integrity of net zero claims.

8. Scientific and Societal Critique

The case of Climeworks exemplifies a deeper structural flaw in contemporary climate strategies: replacing actual emission reductions with the illusion of "removal." This shift is not only scientifically fragile but also socially and economically counterproductive.

Professor **Mark Z. Jacobson** of Stanford University delivers one of the most comprehensive scientific critiques of carbon capture technologies to date. He argues unequivocally:

"Direct capture is a scam, carbon capture is a scam... These are all scam technologies that do nothing for the climate or air pollution."
(Jacobson, 2019)

Jacobson's peer-reviewed analysis evaluates both **point-source CCS** and **Direct Air Capture (DACCS)** under real-world energy system conditions. His findings validate and extend our own modelling in several key areas:

Matching Findings:

- **Extreme energy intensity**: Jacobson confirms that DACCS systems consume massive amounts of energy, and when powered by non-zero-carbon sources, they **can emit more CO_2 than they remove**.
- **Infrastructure inflation**: Both our analysis and his research show that scaling DACCS to a meaningful level would require **millions of units and thousands of plants**, each demanding vast quantities of materials, land, and logistics.
- **CO_2 transport emissions**: Like our consideration of systemic energy demands, Jacobson includes **pipeline construction and CO_2 pressurization** as non-trivial emission sources that undermine net-negative claims.
- **Temporal mismatch**: He echoes our point that **emissions happen today**, while **removal may take years**, if ever fully realized.

Additional Warnings:

- **Opportunity cost**: DACCS draws renewables away from electrification sectors like transport and heating, making it **actively harmful** to overall decarbonization timelines.
- **Thermal penalties**: Heating sorbents in DACCS processes typically requires temperatures of 80–120°C, making most systems reliant on natural gas or electricity from fossil-dominated grids.
- **Low system efficiency**: Jacobson estimates **net capture rates as low as -21%** in worst-case configurations, meaning more emissions are produced than avoided.
- **Moral hazard**: By promoting DACCS as a panacea, governments and companies delay hard decisions about fossil phase-out, while marketing "net zero" pathways that are physically unachievable.

This scientific assessment reinforces the systemic incoherence of using DACCS as a central pillar of climate strategy, especially when **market-based offsetting mechanisms** are layered on top.

Even **Al Gore**, during a public event in 2023 showing an image of the Orca facility, commented ironically:

"This is state of the art. Looks pretty impressive, doesn't it?"

His sarcasm reflects the growing disillusionment with high-tech solutions that appear more suited to **green branding** than climate stabilization. These quotations are used to illustrate the growing skepticism among parts of the scientific and policy communities. Full source references are provided for readers to evaluate the broader context themselves.

In sum, the deployment of DACCS under current paradigms, especially when **framed as a substitute for real decarbonization**, represents not a breakthrough, but a **structural delay mechanism**. As Jacobson concludes, these systems "divert attention and resources from real, scalable, and immediate solutions."

9. Conclusion

From a physical, energetic, and climate-accounting perspective, the case of Climeworks illustrates a profound mismatch between technological optimism and scientific reality. Despite presenting itself as a scalable solution for atmospheric CO_2 removal, Direct Air Capture (DACCS), in its current form, suffers from three fundamental failures: thermodynamic inefficiency, spatial limitation, and ethical inconsistency.

First, the energy input required to capture even a fraction of global CO_2 emissions is enormous. As shown in our modelling, even under idealized scenarios with 90% improved energy efficiency, capturing 10% of annual global emissions over 20 years would demand hundreds of thousands of Mammoth-scale units, consuming more electricity per year than any nation currently produces. This is not a climate solution, it is an energetic impossibility.

Second, DACCS systems are physically constrained to the thin surface layer of the atmosphere. The idea that ground-based machines can cleanse the entire planetary air mass ignores basic atmospheric structure and mass distribution. We cannot clean a 50-kilometer-deep, turbulent, global system by processing air passively at ground level. No matter how many machines we build, they will only ever touch a vanishingly small fraction of the atmosphere. This is a geometric limitation, not just an engineering one.

Third, the financial and ethical architecture of Climeworks' model undermines both scientific rigor and climate credibility. By monetizing captured CO_2 as offset credits for external actors, while continuing to emit operational emissions and transferring responsibility, the company bypasses the core principle of real-time, physical emission reduction, as defined in IPCC AR6. This commodification of climate responsibility is not mitigation, but climate theatre.

Moreover, the narrative surrounding DACCS appeals to corporate image management and personal absolution, offering indulgences in place of action. It suggests that climate responsibility can be outsourced, postponed, or paid off, rather than embedded in systemic transformation. This message is not just misleading, it is dangerous, because it distracts public attention from urgent, proven interventions: cutting fossil fuel use, preserving carbon sinks, and reforming energy systems at scale.

In the end, the greatest risk posed by DACCS is not its inefficiency, it is the illusion of progress.

As this analysis has shown, betting on atmospheric scrubbing as a central climate solution is scientifically indefensible and politically reckless. Stability will not come from speculative technologies that promise future neutrality. It will come from honest, immediate, and systemic emission reductions, grounded in physics, not fantasy.

Science, at its core, is a process of inquiry, grounded in hypotheses, verifiability, falsifiability, and replicability. It advances not by avoiding failure, but by embracing it as a necessary part of discovery. It is not only acceptable, but essential that some experimental paths lead to dead ends. This is how knowledge matures.

However, intellectual integrity demands that we call things by their proper names. When the evidence consistently points to structural, physical, and ethical flaws, it is not skepticism, but scientific responsibility, to say that a given approach has not met its promise. The case of Direct Air Capture is not a matter of premature judgment. It is a matter of recognizing patterns: too many caveats, too little substance, and an increasing gap between claims and capacity.

DACCS may still evolve. But today, it cannot be credibly presented as a proven climate solution, let alone as a mainstream tool for emission reduction or a reliable foundation for offset systems. To pretend otherwise is not scientific caution. It is narrative inflation.

This analysis is not an attack on innovation but a contribution to a transparent, data-driven discourse about the realistic potentials and limits of emerging climate technologies. Our findings are based on publicly available data, fundamental scientific principles, and published performance metrics. All technical assumptions are verifiable, and the tone of the analysis is a response to the magnitude of the claims made by promoters of the technology.

All projections in this report are based on linear extrapolations of publicly disclosed performance data of Climeworks' Mammoth unit and general physical laws governing gas capture. Where assumptions were necessary, we chose values that favor optimistic performance (e.g., energy efficiency, air throughput). Thus, the analysis should be interpreted as a best-case boundary model, not a worst-case criticism. While the technological performance is subject to engineering constraints, our critique of the offset model addresses a separate issue: the ethical and accounting implications of selling removals while emitting operationally. This duality must be assessed independently from the potential of DACCS as a technological concept.

We acknowledge the potential for technological progress in DACCS systems. However, even with significant efficiency improvements (e.g., 90% energy reduction modeled in Chapter 5), the scale and fundamental limitations remain unchanged. This suggests that DACCS may be a valuable niche tool but not a scalable substitute for emission prevention.

10. Recommendations

For Policymakers

Do not include DACCS as a primary tool in national or international climate strategies unless:

- its full life-cycle emissions are transparently disclosed,
- its energy source is verifiably carbon-free and does not compete with decarbonization priorities,
- its energy demand does not generate additional emissions exceeding the amount of CO_2 captured,
- and its role is clearly limited to compensating only hard-to-abate residual emissions, not to replace emission reductions at the source.

Climate policies must prioritize emission prevention, not deferred removal. DACCS is not a shortcut to climate neutrality, and treating it as such undermines credibility and climate integrity.

For Scientific Authorities and Advisory Bodies

It is time to adopt and publish unambiguous positions on speculative carbon removal technologies. Vague endorsements enable misuse in policy and marketing. Scientific neutrality does not mean silence, especially when techno-optimistic narratives are used to delay or displace effective mitigation.

We encourage expert panels (e.g., IPCC, national academies, research councils) to:

- clearly distinguish between *scientifically plausible* and *politically convenient* solutions,
- evaluate DACCS within strict thermodynamic, spatial, and temporal constraints,
- and caution against accounting illusions that confuse future removals with present reductions.

For CSR / ESG Managers and Consultants

Avoid integrating DACCS-based offset/credits into sustainability reports or carbon neutrality claims unless:

- the captured CO_2 has been demonstrably and durably stored,
- the offset does not mask ongoing emissions or reduce pressure for actual decarbonization,
- and the purchase is accompanied by disclosure of temporal, spatial, and methodological limitations.

Green branding must align with physical reality. Relying on DACCS credits without internal reduction efforts is not ESG leadership, it is a reputational liability.

For Environmentalists, Activists, and "Green" Enthusiasts

Support for DACCS should not become a symbolic substitute for systemic change. Climate activism loses impact when it endorses techno-fixes that serve corporate optics more than planetary stability.

Critically assess all solutions, even those marketed as "green." The climate challenge is not a branding issue, it is a physical one. Let's not trade structural change for gadgets.

For Media and Climate Communicators

Be vigilant in distinguishing science-based solutions from narratives driven by lobbying, marketing, or wishful thinking. Scrutinize claims about carbon removal with the same rigor as emissions scandals.

Communicating complex climate technologies requires skepticism, clarity, and courage. Your work helps shape public understanding, and public policy. Treat promises of DACCS with proportional scrutiny, not amplified hype.

11. Frequently Anticipated Objections and Clarifications

1. "The document is biased and dismisses innovation."

Clarification: This analysis does not intend to dismiss innovation, but rather to scrutinize it through a rigorous, data-based lens. The tone may reflect concern, but the methodology is rooted in physical laws, peer-reviewed data, and performance benchmarks published or claimed by Climeworks and other DACCS providers. Questioning feasibility is not anti-innovation; it is a precondition for scientific progress.

2. "You ignore the possibility of future technological improvements."

Clarification: The report explicitly includes a best-case scenario assuming a 90% reduction in energy demand. Even under such idealized assumptions, the logistical and atmospheric constraints render large-scale DACCS unrealistic as a mainstream mitigation strategy. Acknowledging progress is not the same as assuming it will overcome fundamental physical limits.

3. "The critique targets the business model more than the technology itself."

Clarification: Both are addressed , separately. Technological critique focuses on energy intensity, spatial scalability, and throughput. The critique of the offset model concerns ethical and accounting inconsistencies between physical removal and emission outsourcing. One does not invalidate the other; both are relevant to the real-world climate impact of DACCS.

4. "Quotations from critical scientists are out of context."

Clarification: The quotations used (e.g., from Prof. Mark Z. Jacobson or Al Gore) are referenced verbatim and are linked to full primary sources for independent verification. They represent a strand of expert opinion that has so far been underrepresented in mainstream discourse and therefore deserve visibility.

5. "This is an attack on Climeworks."

Clarification: Climeworks is used as a case study because it is currently the world's most prominent DACCS operator. The analysis does not question the motivations or integrity of the company or its employees. It questions the physical, environmental, and economic plausibility of their publicly presented model which, given the scale of climate risks, is a necessary part of responsible climate science.

6. “This ignores the potential role of DACCS in compensating hard-to-abate emissions.”
Clarification: The report acknowledges that DACCS could have niche utility for truly unavoidable emissions under strict conditions: verifiable zero-carbon energy inputs, full life-cycle accounting, and no interference with broader decarbonization pathways. What is contested is the inflation of DACCS’s role beyond those narrow applications.

Glossary of Terms

Term	Definition
DAC (Direct Air Capture)	A technological process that captures CO_2 directly from ambient air using chemical sorbents.
DACCS (Direct Air Carbon Capture and Storage)	An extended form of DAC where the captured CO_2 is stored permanently underground or in other stable forms.
CO_2e (Carbon Dioxide Equivalent)	A metric measure used to compare emissions from various greenhouse gases based on their global warming potential (GWP).
CEF (Carbon Emission Factor)	The amount of CO_2e emissions per unit of generated electricity (e.g., g CO_2e/kWh), used to evaluate the carbon footprint of energy systems.
CFWp (Carbon Footprint per Watt-peak)	The total embodied emissions in grams of CO_2e related to the manufacturing of a photovoltaic panel per kilowatt-peak of installed capacity.
Wp (Watt-peak)	The rated output of a photovoltaic panel under standard test conditions, representing its maximum power capacity.
kWh (Kilowatt-hour)	A unit of energy equal to one kilowatt (1,000 watts) of power used for one hour. Commonly used to express electricity consumption or production.
Annual Yield	The amount of energy produced by a photovoltaic system per installed watt of capacity over a year (kWh/Wp/year).
Capacity Factor (CF)	The ratio of actual energy output over a period to the maximum possible output if the system ran at full capacity continuously.
Roundtrip Efficiency	The efficiency of a battery storage system, calculated as the ratio of energy retrieved during discharge to the energy put in during charging.
BESS (Battery Energy	A system that stores electricity in batteries for later use, often paired with

Term	Definition
Storage System)	renewable energy sources for stability and load balancing.
Embodied Emissions	Total GHG emissions associated with the manufacturing, transport, installation, and end-of-life of a product or system.
LCA (Life Cycle Assessment)	A methodology to assess environmental impacts of a product across its entire life cycle, from raw material extraction to disposal.
Cradle-to-gate	A type of LCA boundary that includes emissions from raw material extraction to the factory gate (excludes use and disposal).
Cradle-to-grave	A full LCA boundary that includes all stages: production, use, and end-of-life.
Troposphere	The lowest layer of Earth's atmosphere, extending from the surface up to approximately 8–15 km, where weather occurs and most CO_2 is concentrated.
Stratosphere	The atmospheric layer above the troposphere, extending roughly from 10 km to 50 km above the Earth's surface.
Vertical Mixing	Atmospheric process where air and its constituents (including CO_2) are mixed between different altitudes, usually limited by thermal stratification.

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