

Environment

Balancing the Carbon Equation

Why Direct Air Capture and Ocean Alkalinity Enhancement Must Work Together for Climate Stability?

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Direct Air Capture (DAC) and Ocean Alkalinity Enhancement (OAE) are two of the most discussed ways to remove carbon dioxide from the atmosphere, each with distinctive mechanisms, strengths, and drawbacks. DAC captures CO₂ directly from ambient air via chemical or physical sorbents followed by storage or utilization, while OAE works by bolstering the ocean's natural capacity to absorb CO₂ through increasing dissolved alkalinity, shifting inorganic carbon equilibria, and buffering pH changes. In this opinion piece I argue that neither method is sufficient alone but that together they could form a more resilient, scalable negative emissions portfolio. DAC offers precision and controllability; OAE leverages vast ocean sinks and offers co-benefits for ocean acidification, but faces challenges around environmental risks, monitoring, permanence, and scale. I call for an integrated strategy: rigorous foundational science, transparent accounting, regulatory guardrails, and public engagement. Such an approach must prioritize emissions reduction first, then deploy DAC and OAE where they are most effective, ethical, and socially acceptable.

Keywords: Direct Air Capture; Ocean Alkalinity Enhancement; Carbon Dioxide Removal; Climate Change Mitigation; Negative Emissions Technologies

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HUMANITY has begun to treat carbon dioxide not just as an end product of energy systems but as something that must be actively removed from the atmosphere. Among the many contenders for negative emissions technolo-

gies, Direct Air Capture (DAC) and Ocean Alkalinity Enhancement (OAE) have captured major attention. Each offers promise, yet each carries strong caveats. What seems increasingly clear is that these are not alternatives but complements—and that the

path forward must be one of integration, anchored in science, ethics, and social license.

DAC bristles with appeal: it is precise, controllable, decoupled from geography (in the sense that you can build a DAC plant almost anywhere with the right energy input), and its engineering challenges, while formidable, are well understood (Erans et al., 2022). Yet the cost per ton of CO₂ removed remains high; energy consumption and materials use are substantial (Bouaboula et al., 2024). There are also questions about where you store the CO₂, for how long, and what unintended environmental risks may follow. In short: DAC is powerful but expensive, energy-intensive, and not without trade-offs.

OAE, by contrast, leverages the massive scale of Earth's oceans and the natural buffering chemistry of seawater (Hinrichs et al., 2023). By increasing alkalinity—via mined minerals (e.g., crushed silicates), hydroxides, or electrochemical production of alkaline substances—the ocean's capacity to absorb CO₂ can be enlarged, acidification can be ameliorated, and carbon stored in more stable dissolved forms. Recent modeling shows that in regions like the Bering Sea, addition of alkalinity can yield carbon uptake efficiencies above 90 percent (Oschlies et al., 2023). In other work modeling the North Sea, adding alkalinity along shallow coasts delivers higher efficiency (~0.79 mol CO₂ per mol alkalinity added) than in deeper offshore areas (Dale et al., 2024). Yet OAE is far from risk-free or turnkey.

There are concerns about environmental side effects. Altering ocean chemistry may affect ecosystems in unpredictable ways (Guo et al., 2025). If alkalinity is added too quickly or unevenly, local pH changes could stress marine life, especially calcifying organisms. Some minerals used for enhancement may carry heavy metals (Suitner et al., 2024). The geographic and temporal variability of ocean circulation, mixing, and biological uptake also mean that added alkalinity might not immediately translate into atmospheric CO₂ drawdown (Xin et al., 2024). Measurement, reporting, and verification (MRV) are difficult: how can one accurately track how much CO₂ was removed, how long it stays out of the atmosphere, and where? Some studies warn that coarse models understate near-shore chemical perturbations by large factors (Honegger et al., 2020).

Permanence is ambiguous. Dissolved inorganic carbon in bicarbonate and carbonate forms is more stable than gaseous CO₂, but ocean dynamics may move carbon into parts of the ocean where it returns more slowly to the atmosphere—but perhaps not indefinitely (Bialik et al., 2022). Alkalinity additions in shallow regions may offer faster uptake but also more rapid mixing into cycles that may eventually re-release CO₂ (Chikamoto et al., 2023). The delay between addition and full atmospheric equilibration is not trivial. Third, costs and logistics: obtaining, grinding, transporting, and dispersing minerals at the gigaton scale is heavy work; hydroxides or other chemicals may require large inputs of energy and infrastructure; the supply chains, environmental permitting, and social acceptance could slow deployment (Babakhani et al., 2022).

Comparing DAC and OAE side by side suggests that each handles some problems better than the other. DAC can be placed near suitable energy sources; it is modular, monitorable, and more predictable, but often at high cost and energy intensity

(Barahimi et al., 2023). OAE scales with nature, offers potential co-benefits (mitigating acidification, preserving marine ecosystems), but suffers from greater uncertainties and potentially higher ecological risks (Cox et al., 2024).

What if instead of picking one over the other, I think of DAC + OAE as a portfolio? In many places, DAC might be used to achieve “hard-to-abate” removal: point-source emissions that are already difficult to capture at origin, or legacy emissions where concentration of CO₂ in air is low (McQueen & Drennan, 2024). OAE could work best near coastal or cold, well-mixed ocean zones, where alkalinity additions would be most effective, and where monitoring can be done with sufficient precision (Oschlies et al., 2023). In such settings, OAE and DAC could play off each other: DAC handles the precision and permanence, OAE the scale and cost amortization over large marine volumes.

This integrated approach implies several priorities. Rigorous foundational science must continue: lab experiments, pilot field trials, fine-scale modeling of local ocean chemistry and ecosystem impacts. Regulatory frameworks must be crafted to ensure environmental safeguards, fair distribution of risk, and transparency; governance over marine interventions is complex and often underdeveloped. Accounting systems (carbon credits, offsets) need to treat DAC and OAE removals with parity only insofar as permanence, leakage, ecological cost, and MRV are handled credibly (Lawrence et al., 2018). Public and stakeholder engagement is essential: coastal communities, Indigenous peoples, fishers and biodiversity interests must have voice and agency.

An ethical bedrock must carry emissions reductions first. Neither DAC nor OAE should be deployed as an excuse to continue fossil fuel extraction. Negative emissions must be a backstop, not a substitute. The faster we cut emissions at source, the less reliance on removal technologies we will need. Because deploying DAC and OAE at scale will entail land, mineral, water, energy, and ecosystems trade-offs, those trade-offs become smaller if we've already reduced emissions strongly (Motlaghzadeh et al., 2023).

Finally, funding and policy frameworks must keep up. Carbon pricing, incentives, research grants, international cooperation, standards—all of them matter. Without large-scale coordination, many projects could proliferate in an ad hoc manner, producing patchy environmental and social outcomes.

In conclusion, DAC and OAE each have serious positives and serious negatives. DAC is expensive and energy-intensive but controllable; OAE offers scale, potential co-benefits, but more risk and uncertainty. The stakes are high: climate change is accelerating, and the emissions math is unforgiving. It is not enough to hope for silver-bullet solutions. What we need is a well-balanced negative emissions strategy: emissions cuts first, deployment of removal technologies second, with DAC and OAE working together where they make sense, governed by science, ethics, and the public interest. If done wrong, negative emissions could become another vector for greenwashing, ecological damage, or unjust distribution of burdens. If done right, this portfolio could help us tilt the scale toward a more stable, viable climate future. ■

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