Carbon Capture

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Carbon Capture and Storage (CCS) encompasses a family of technologies that intercept $\mathrm{CO_2}$ either at the point of emission (*e.g.*, at a power plant or industrial facility) or directly from the atmosphere (Direct Air Capture, DAC). The captured carbon is then compressed and injected into geological formations for long-term storage, or utilized in industrial processes (Carbon Capture, Utilization and Storage, CCUS).

Bioenergy with Carbon Capture and Storage (BECCS) combines biomass combustion (which draws $\mathrm{CO_2}$ from the atmosphere through plant growth) with CCS, yielding net negative emissions — removing more $\mathrm{CO_2}$ from the atmosphere than is released.

Fundamental Assumptions

CCS assumes that injected $\mathrm{CO_2}$ will remain permanently sequestered in subsurface formations — primarily saline aquifers and depleted oil/gas reservoirs. The relevant timescale is centuries to millennia. The fraction of stored $\mathrm{CO_2}$ that must remain sequestered after 1000 years to count as permanent storage is typically set at $> 99\%$.

The storage efficiency η_s is defined as:

$$\eta_s = 1 - \frac{m_{\text{leaked}}}{m_{\text{injected}}}$$

Current monitoring data from operating sites (*Sleipner, Weyburn*) suggest $\eta_s \approx 1$ over decadal timescales, but extrapolation to millennial timescales remains speculative.

Land Requirements for BECCS

BECCS requires large areas of productive land for biomass cultivation. To achieve net negative emissions of 10 GtCO_2/year (a level assumed in many 1.5°C scenarios), BECCS would require an estimated 380–700 million hectares of land (*Smith et al.*, 2016), equivalent to roughly 25–45% of current global cropland. This directly conflicts with food security, biodiversity conservation, and indigenous land rights.

Economic Justification

The economic rationale for CCS is residual abatement: some industrial processes (cement production, steelmaking, aviation) are hard to abate through electrification alone. Cement production, for instance, releases $\mathrm{CO_2}$ through calcination (the chemical decomposition of limestone):

$$\mathrm{CaCO_3} \xrightarrow{\Delta} \mathrm{CaO} + \mathrm{CO_2}$$

This process-related emission cannot be eliminated by switching to renewable electricity — CCS is therefore a necessary component of deep decarbonization in these sectors according to most IAMs.

For Direct Air Capture, current costs are in the range $\$300\text{–}1000/\mathrm{tCO_2}$, well above any credible SCC estimate for near-term policy. The experience curve hypothesis predicts cost reductions, but DAC lacks the high-volume manufacturing drivers that propelled solar cost declines — it is primarily a chemical engineering challenge, not a manufacturing one.

Societal Fairness Critique

CCS has been criticized for constituting a moral hazard — the provision of a technological "escape route" that reduces the perceived urgency of emissions reductions. Critics argue that investment in CCS displaces investment in more certain mitigation measures and provides fossil fuel companies with a social license to continue operations under the expectation of future capture.

Additionally, the siting of carbon injection sites and biomass plantations raises environmental justice concerns. Communities near storage sites bear localized risks (seismicity, potential leakage) while benefits are globally distributed.

Empirical Evidence

- Operating CCS capacity (2023): Global CCS capacity is approximately 50 MtCO_2/year — less than 0.2% of annual global emissions (Global CCS Institute, 2023). The IPCC AR6 requires scaling to several GtCO_2/year by mid-century in most 1.5°C pathways.
- Cost evolution of DAC: Carbon Engineering's plant in Canada achieves costs around $\$300/\mathrm{tCO}_2$; Climeworks' Orca plant in Iceland operates at approximately $\$1000/\mathrm{tCO}_2$. No learning curve comparable to solar PV has yet materialised.
- BECCS deployment: Despite its prominence in IAM scenarios, BECCS remains at demonstration scale only. The Drax power station in the UK deploys a pilot BECCS facility, but full-scale deployment faces feedstock sustainability challenges.

Geoengineering

Geoengineering (also called climate intervention or climate engineering) refers to deliberate, large-scale technological interventions in Earth's climate system. Two broad approaches exist:

- Solar Radiation Management (SRM): Reducing the amount of solar energy absorbed by Earth, for example by injecting reflective aerosols (typically sulphate particles) into the stratosphere (Stratospheric Aerosol Injection, SAI), or by brightening marine clouds (Marine Cloud Brightening, MCB).
- Carbon Dioxide Removal (CDR): Removing CO_2 from the atmosphere (CCS and BECCS, discussed above, fall within CDR; other methods include enhanced weathering, ocean fertilization, and afforestation).

The following analysis focuses principally on SAI, which is the most analytically contested SRM proposal.

Fundamental Assumptions

SAI aims to offset the positive radiative forcing from greenhouse gases by increasing Earth's albedo α (reflectivity). The planetary energy balance at the top of atmosphere is:

$$\frac{S_0}{4}(1-\alpha) = \epsilon\sigma T_e^4$$

where $S_0 \approx 1361\ \mathrm{W\ m^{-2}}$ is the solar constant, ϵ is the longwave emissivity, σ is the Stefan-Boltzmann constant, and T_e is the effective emission temperature. Increasing α reduces the left-hand side, thus lowering equilibrium temperature. Volcanic analogues (*Pinatubo*, 1991, which injected ~20 Tg of SO_2 and cooled global mean temperatures by ~0.5°C) provide empirical support for the physical mechanism.

Termination Shock
SRM does not address the underlying cause of warming — elevated $[\mathrm{CO_2}]$ — but only masks its thermal effects. If SAI were abruptly terminated (*e.g.*, due to geopolitical breakdown or loss of funding), global temperatures would rapidly rebound toward the level expected under atmospheric $\mathrm{CO_2}$ concentrations. The termination shock rate of warming could be:

$$\left.\frac{dT}{dt}\right|_{\text{termination}} \approx \frac{\Delta T_{\text{masked}}}{\tau} = \frac{2-3^{\circ}\mathrm{C}}{1-5 \text{ years}}$$

Such a rate of warming — an order of magnitude faster than present-day trends — would be catastrophic for ecological and agricultural systems adapted to gradual change.

Economic Justification
SAI is extraordinarily cheap relative to its physical impact. *Barrett* (2008) estimates annual SAI costs at $\$1–8$ billion — feasible for a single mid-sized nation-state — to offset global warming. This creates a profound governance paradox: the technology is cheap enough that any determined actor can deploy it unilaterally, but its effects are global and non-consensual.

This characteristic has led some economists (*Weitzman*, 2015) to argue that SAI is best understood through the lens of catastrophic risk management rather than standard cost-benefit analysis:

$$\max_{x} E[U(C - D(T(x)))] - C(x)$$

The argument is that, if climate damages are characterized by fat-tailed distributions (small probabilities of catastrophic outcomes), risk-averse societies may rationally prefer SAI as an option despite deep uncertainty about its side-effects.

Societal Fairness
Geoengineering, and SAI in particular, raises the most severe equity concerns of any climate proposal:

- Distributional effects on precipitation: SAI would alter global precipitation patterns, potentially reducing monsoon rainfall in South and Southeast Asia and sub-Saharan Africa — regions that contribute least to the problem but are most dependent on reliable seasonal rainfall for food production (*Robock et al.*, 2009).
- Unilateral deployment: The low cost of SAI means that a small number of wealthy nations or even private actors could impose the technology on the world without consent — a profound violation of international sovereignty norms.
- Democratic deficit: There exists no legitimate international governance framework for authorizing or prohibiting SAI deployment. The UN Environment Assembly has failed to reach consensus on even a research governance framework.

Empirical Evidence
- Volcanic analogues: The 1991 Mt. Pinatubo eruption provides the closest natural analogue. Global mean temperature dropped by approximately 0.5°C in 1992–1993, and stratospheric ozone depletion was observed.
- Modeling studies: Earth system model ensembles (e.g., the Geoengineering Model Intercomparison Project, GeoMIP) consistently show global mean temperature reduction under

SAI but significant regional heterogeneity — with some regions experiencing warming and drying even under global cooling.

- Field experiments: The Harvard SCoPEx experiment (suspended due to governance concerns) and UK SPICE project have yet to advance to atmospheric injection at scale.

Comparative Assessment

The four categories of intervention differ fundamentally across key evaluative dimensions. The following synthesizes their profiles:

Dimension	Carbon Pricing	Renewable	CCS/DAC	Geoengineering
Readiness	Deployed	Scaling	Limited	Research stage
Cost ($/t$CO_2$)	$30–200	$0–50 (new builds)	$50–1000	$1–5 (offset)
Reversibility	High	High	Medium	Low (lock-in risk)
Equity profile	Regressive	Mixed	Morally hazardous	Highly inequitable
Governance	International	Primarily national	National	Global
Scientific certainty	High	High	Medium	Low-Medium

Concluding Remarks

No single proposal is sufficient. The quantitative demands of the carbon budget — eliminating approximately 37 GtCO$_2$/year of emissions while drawing down a cumulative overshoot of potentially 300–500 GtCO_2 — require a portfolio approach in which:

1. Carbon pricing corrects the market failure and mobilizes economy-wide incentive alignment, provided revenue is recycled progressively;
2. Renewable energy deployment delivers the bulk of near-term emission reductions in the power sector, where cost curves are now decisively favourable;
3. CCS plays a targeted role in hard-to-abate industrial sectors, provided scale-up challenges are met with public investment;
4. Geoengineering remains a last resort requiring international governance development before any deployment, given its severe equity implications and termination risks.

The deep tension throughout all four proposals is between efficiency and justice. Optimal economic solutions tend to assign abatement to the cheapest marginal opportunities, which are often located in the Global South — yet the historical moral responsibility for accumulated atmospheric CO_2 lies overwhelmingly with the industrialized North. Bridging this gap requires not only technical ingenuity but institutional arrangements — including climate finance, technology transfer, and loss and damage mechanisms — that current international negotiations have proven structurally inadequate to deliver.

The empirical record is ultimately sobering: despite four decades of negotiation and a rich literature of proposals, global annual emissions in 2023 were at an all-time high. The proposals reviewed herein are not lacking in technical merit. What they await is the political economy that would allow their coordinated implementation at the scale and speed that physics demands.
