Carbon Dioxide Removal Technologies: Contributions, Challenges, and Opportunities

Introduction

Carbon dioxide removal (CDR) represents a fundamentally different approach to climate mitigation than emissions reduction. While traditional climate strategies focus on cutting greenhouse gas emissions from energy, transport, industry, and agriculture, CDR technologies actively extract CO2 that already exists in the atmosphere and store it durably to prevent its contribution to climate change (Fuss *et al.*, 2016). The distinction is critical: emissions reductions prevent future warming by avoiding new emissions, whereas CDR addresses legacy emissions and the inevitable "hard-to-abate" residual emissions that remain even after aggressive decarbonization efforts (Chiquier *et al.*, 2025)

The scientific consensus increasingly recognizes that emissions reductions alone cannot achieve the Paris Agreement's ambitious 1.5°C warming target. Current mitigation pathways show that even with aggressive near-term action, achieving net-zero emissions will require some form of CDR deployment at gigaton scale by mid-century (Fuss *et al.*, 2016). Most climate models limiting warming to well below 2°C include CDR components, while 1.5°C scenarios are barely conceivable without substantial CDR deployment (Fuss *et al.*, 2016). This highlights the role of CDR as a cornerstone of climate strategy, but it also reflects a sobering reality: the window for preventing all climate impacts through emissions cuts alone has narrowed considerably, necessitating the rapid development and deployment of removal technologies. In this paper, we draw on empirical insights from the design, construction, and early deployment of a Direct Air Capture (DAC) pilot plant in Teesside, Middlesbrough to examine how technological, logistical, and socio-political factors shape the real-world feasibility of carbon dioxide removal (CDR) technologies. We begin by reviewing the existing literature on CDR, outlining the opportunities and constraints associated with different removal pathways and situating DAC within this broader technological landscape. We then present a case study of a DAC facility currently under construction, using it to explore the practical challenges associated with scaling engineered carbon removal solutions, including infrastructure requirements, regulatory considerations, community engagement, and supply-chain dependencies. Through this analysis, we highlight how experiential learning from early projects can inform more effective, equitable, and responsible expansion of CDR capacity globally.

Current State of CDR Technologies and Deployment

CDR operates across a diverse portfolio of technological approaches, each with distinct mechanisms, maturity levels, environmental trade-offs, and deployment potential. These approaches span from highly engineered industrial processes that directly capture CO_2 from ambient air and compress it for underground storage, to nature-based solutions leveraging biological and geological processes to sequester carbon in living systems and soils, to emerging marine-based techniques that enhance the ocean's natural carbon uptake capacity. Understanding this diversity is essential because no single CDR pathway possesses the technical maturity, cost-effectiveness, scalability, and environmental acceptability to serve as a complete climate solution. Instead, successful decarbonization pathways rely on strategically diversified CDR portfolios where complementary technologies address different regional contexts, resource availability patterns, and economic constraints (Chiquier *et al.*, 2025).

Research on carbon dioxide removal has expanded rapidly over the past decade, with increasing scientific attention to the potential, costs, and environmental implications of different removal pathways (Presty *et al.*, 2024). However, despite this momentum, real-world deployment remains extremely limited. Most mitigation scenarios indicate that meeting the Paris Agreement goals will require between 1 and 10 Gt CO_2 per year of removal by mid-century, depending on the pace of near-term emissions reductions. Current deployment is orders of magnitude below this level, with only a small number of commercial CDR plants operating worldwide (Javadi *et al.*, 2024). This gap between projected need and present capacity underscores both the urgency of accelerating deployment and the uncertainty surrounding whether any CDR pathway can scale to gigaton levels within the required timeframe.

The move from theoretical discussions of CDR to real deployment brings questions of governance, equity, permanence, and co-benefits into sharp focus. Depending on how it is designed and implemented, CDR can support climate resilience and sustainable development through biodiversity restoration, improved agricultural productivity, and low-carbon energy generation. It can also reproduce existing inequalities if decisions are made without attention to distributional fairness, inclusive participation, and the recognition of diverse knowledge systems. These governance considerations are as important as the technical performance of CDR systems in determining whether they deliver durable and socially legitimate climate benefits

Barriers and constraints associated with different types of CDR technology

Bioenergy with carbon capture and storage (BECCS) offers dual benefits of energy production and carbon removal, but its large-scale potential is constrained by land competition, biomass accounting uncertainties, and sustainability risks across global supply chains (Chiquier *et al.*, 2025). Technical challenges include costly retrofits, variable feedstock quality, and corrosion issues associated with CO_2 compression and dehydration (Bach *et al.*, 2024).

Nature based approaches such as afforestation, reforestation, soil carbon enhancement including soil carbon sequestration, biochar application, enhanced rock weathering, and marine methods such as ocean alkalinity enhancement are among the most widely researched carbon dioxide removal pathways and can deliver co benefits for biodiversity, soil health, and ecosystem resilience (Chiquier *et al., 2025*). However, their reliability and scalability are constrained by permanence risks from fire, pests, and land use change, sink saturation in soils, land tenure conflicts, and demanding monitoring requirements (Yang *et al., 2024*). Biochar can provide more durable carbon storage and agronomic benefits, although its effectiveness depends on feedstock characteristics, production conditions, and local soil context (Schmidt *et al., 2021*). Enhanced rock weathering and ocean alkalinity enhancement offer potential for longer term mineral storage, yet uncertainties in field performance, ecological impacts, and regulatory oversight continue to limit near term deployment (Bach *et al., 2024*).

These limitations across biological, geochemical, and marine pathways increase the importance of engineered approaches such as direct air capture, not as replacements but as complementary options that can operate alongside other CDR methods where their respective strengths and constraints align.

Figure 1 *Early-stage installation of the direct air capture pilot plant at the Net Zero Industry Innovation Centre, Teesside.*

Direct air capture and storage is the most technologically intensive carbon removal pathway, using engineered systems based on solid sorbents or liquid solvents to extract carbon dioxide directly from ambient air before permanent geological storage (Van Der Spek *et al.*, 2025). Expert assessments indicate that direct air capture could scale substantially, although current costs remain high, with estimates exceeding $500/ton and long-term learning potentially reducing costs to the $200 to $300/ton range by mid-century (Young *et al.*, 2023). The dominant constraint on scaling is energy intensity, which creates strong dependencies on the availability of low-carbon heat and electricity and links deployment to the pace of renewable energy infrastructure growth (Van Der Spek *et al.*, 2025).

Early-stage deployment of the pilot plant at the Net Zero Industry Innovation Centre illustrates several practical barriers that are not fully captured in high-level assessments. Supply-chain constraints significantly affect timelines, as sourcing bespoke components, specialist materials, and certified equipment can be slow and costly. Funding availability, whether from government programmes or private investors, shapes the pace of procurement and construction, particularly for start-ups operating with limited capital buffers. Siting considerations also play a critical role. Local planning requirements, permitting processes, and institutional support can accelerate or delay installation depending on how favourable the policy environment is.

Engineering design decisions made during early stages have major implications for cost, reliability, and rework requirements. Whether design is undertaken in-house, through an engineering, procurement, and construction contractor, or via hybrid arrangements, early choices determine the extent of later modifications. The geographical distance between the project site and the core engineering team further influences deployment efficiency. When the pilot plant is located abroad, travel demands increase operational costs and stretch team capacity, although some international locations offer stronger incentives for early-stage demonstration projects.

Beyond these project-level constraints, direct air capture faces systemic barriers. Carbon dioxide transport and storage infrastructure remains underdeveloped globally, with limited pipeline networks and few operational storage hubs. Cost-reduction trajectories remain uncertain, complicating investment planning and policy design. Studies from (Van Der Spek *et al.*, 2025) suggests that direct air capture will require long-term, targeted government support, just like the early decades of renewable energy deployment, to overcome high initial costs and infrastructure bottlenecks.

Evidence from comparative technology assessments suggests that diversified carbon removal portfolios are likely to be more cost effective and system resilient than reliance on any single carbon removal method (Chiquier *et al.*, 2025). Biodiversity-rich regions may prioritise nature-based approaches, while energy-abundant regions are better positioned for direct air capture. Governance challenges, including equity, environmental integrity, and alignment with emissions-reduction pathways, remain central to determining whether direct air capture contributes meaningfully to climate goals (Yang *et al.*, 2024). Carbon removal technologies carry a fundamental duality. They are potentially indispensable for climate stabilisation yet risk reproducing structural inequalities if deployed without robust governance (Mongkolpattana and Kengkanruea, 2025). Achieving climate targets therefore requires aggressive near-term emissions reductions alongside the strategic development of removal technologies, avoiding over-reliance on uncertain future removals (Galán-Martín *et al.*, 2021).

Conclusion

Carbon dioxide removal is increasingly recognised as a necessary complement to emissions reductions, yet each pathway faces constraints that limit its scalability and reliability. Nature-based and biomass-based approaches offer near-term potential but are challenged by permanence risks, land competition, and monitoring demands, while geochemical and marine methods remain scientifically and institutionally immature. Direct air capture provides a durable and verifiable removal option but is constrained by energy intensity, infrastructure gaps, and high capital costs.

Experience from the early deployment of the Teesside pilot plant shows that practical barriers such as supply-chain delays, funding limitations, siting requirements, engineering design choices, and team-location dynamics strongly influence real-world feasibility. These insights highlight the need to integrate technical, logistical, and governance considerations into future planning. Meeting climate targets will require a diversified portfolio of removal approaches, supported by robust governance and sustained policy commitment, alongside rapid emissions reductions. Early-stage demonstration projects provide essential learning that can guide the responsible and effective scaling of carbon removal technologies

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