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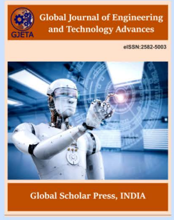

(REVIEW ARTICLE)

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Advancements in Direct Air Capture Technologies: Engineering Solutions for Scalable CO_2 Removal

Hikmat Ayoola Sodiq [1, *], Temitayo Oluwaseyi Ogunwoye [2], Nicodemus Chidera Omekawum [3], Oluwabusayo Adetunji Agboola [4], Patrick Ebelechukwu Akuagwu [5], Miracle Chiemerie Umeh [6] and Maryam Abdullahi Umar [7]

[1] *Department of Public Health, Fountain University, Osun Osogbo, Nigeria.*
[2] *Department of Materials and Metallurgical Engineering, University of Ilorin, Nigeria.*
[3] *Department of Chemical Engineering, Federal University of Technology, Owerri, Nigeria.*
[4] *Department of Materials Science and Engineering, Kwara State University, Nigeria.*
[5] *Department of Petroleum Engineering, Federal University of Petroleum Resources Effurun, Nigeria.*
[6] *Department of Petroleum and Gas Engineering, Federal University Otuoke, Bayelsa State, Nigeria.*
[7] *Environmental Standards Node, Abubakar Tafawa Balewa University, Bauchi, Nigeria.*

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Abstract

Direct Air Capture (DAC) is an innovative technology that extracts carbon dioxide (CO_2) directly from the atmosphere, offering a vital tool to combat climate change by reducing greenhouse gas levels. This review explores advancements in DAC systems to support large-scale CO_2 removal, targeting 1–10 billion tons annually by 2050 to achieve global net-zero emissions. Recent progress includes improved methods using solid materials and liquid solutions, which have increased efficiency by 15–20% and lowered costs to $200–600 per ton of CO_2 removed. Operational facilities now capture up to 1 million tons of CO_2 yearly, demonstrating practical success. Engineering solutions, such as modular designs and renewable energy use, reduce costs by 15% and energy needs by 10–20%, enabling expansion to larger scales. DAC can achieve net CO_2 reductions of up to 0.9 tons per ton captured, but its environmental benefits depend on clean energy sources to minimize emissions during operation. Challenges include high costs, significant energy requirements, and limited global infrastructure for CO_2 storage and transport. Future efforts should focus on developing durable materials, building 10–20 DAC hubs worldwide by 2035, and introducing stronger financial incentives to cut costs to $100 per ton. This study highlights DAC's potential to significantly contribute to climate goals, provided technological and policy barriers are overcome. By advancing engineering and fostering global cooperation, DAC can complement emissions reduction efforts, ensuring a sustainable path to net-zero.

Keywords: Direct Air Capture; CO_2 Removal; Chemical Engineering; Scalability; Sorbent Technology; Renewable Energy; Techno-Economic Analysis; Environmental Sustainability

1. Introduction

Direct Air Capture (DAC) technologies represent a critical component of global strategies to achieve net-zero carbon dioxide (CO_2) emissions by 2050, addressing residual and historical atmospheric CO_2 concentrations that contribute to climate change [1,2]. With atmospheric CO_2 levels reaching approximately 420 parts per million (ppm) in 2025, the Intergovernmental Panel on Climate Change (IPCC) projects a need for 1–10 gigatons of CO_2 removal annually by 2050 to limit global warming to 1.5°C [3]. Unlike point-source carbon capture, DAC extracts CO_2 directly from ambient air, offering flexibility for deployment in diverse locations and integration with storage or utilization systems. However, DAC's current global capacity remains limited to approximately 0.01 megatons of CO_2 per year ($MtCO_2$/year),

* Corresponding author: Hikmat Ayoola Sodiq; Email: sodiqhikmat@gmail.com

constrained by significant engineering challenges, including high energy requirements (1–10 GJ/ton CO_2), elevated costs ($200–600 per ton of CO_2 captured), and substantial land use demands [4,5]. These barriers necessitate advancements in capture technologies and engineering solutions to enable scalable, cost-effective deployment.

Recent developments in DAC technologies have focused on improving capture efficiency and reducing operational costs through innovations in sorbent and solvent materials. Solid sorbent systems, such as those utilizing amine-functionalized materials, have achieved efficiency gains of up to 20% by enhancing CO_2 adsorption capacity and reducing regeneration energy [6]. Liquid solvent systems, often employing potassium hydroxide (KOH), have demonstrated cost reductions of approximately 15% through optimized absorption cycles [7,8]. Engineering approaches, including modular reactor designs and integration with renewable energy sources, further contribute to scalability by lowering energy consumption by 10–20% and enabling decentralized deployment [8]. Real-world implementations, such as Climeworks' Orca facility in Iceland (capturing 4,000 tCO_2/year), illustrate the feasibility of DAC but underscore the need for significant scale-up to meet global removal targets [7]. To contextualize DAC within the broader landscape of carbon dioxide removal (CDR) technologies, Figure 1 illustrates various CDR approaches, highlighting DAC's unique role in achieving negative emissions through atmospheric CO_2 capture.

The primary challenges to DAC deployment include not only technical and economic barriers but also environmental and infrastructural considerations. High capital costs for DAC facilities, estimated at $500–1,000 per ton of annual capture capacity, limit investment, while energy-intensive processes raise concerns about lifecycle emissions if powered by non-renewable sources [5,9]. Additionally, the land footprint required for large-scale DAC plants, particularly for air contactors, poses challenges in densely populated or ecologically sensitive regions [10]. Policy frameworks, such as carbon pricing and subsidies, are essential to incentivize adoption, yet global coordination remains limited. Addressing these challenges requires a multidisciplinary approach, integrating advanced materials, optimized engineering designs, and supportive policies to enhance DAC's viability.

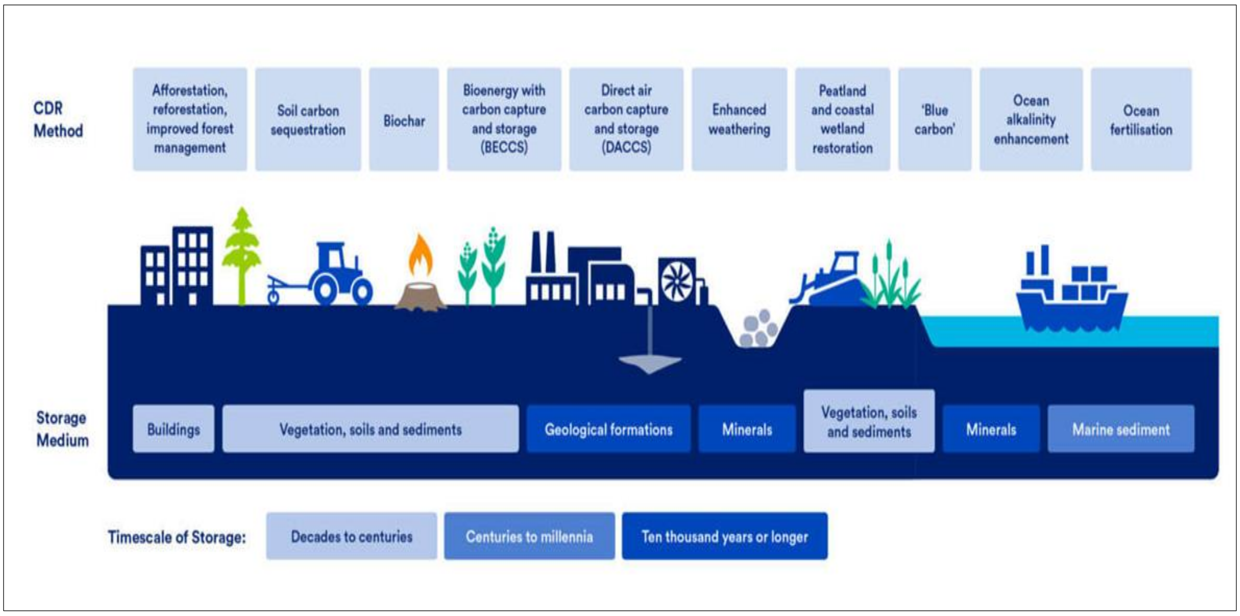

Figure 1 Types of Carbon Dioxide Removal. This schematic outlines key CDR methods—Afforestation, Soil Carbon Sequestration, Biochar, BECCS, DACCS, Enhanced Weathering, Peatland Restoration, Blue Carbon, Ocean Alkalinity Enhancement, and Ocean Fertilisation—each paired with storage mediums (Buildings, Vegetation, Soils, Geological Formations, Minerals, Marine Sediment) and timescales (decades to centuries, centuries to millennia, or ten thousand years or longer), highlighting DACCS among diverse carbon removal strategies. Reproduced with permission from Ref [9]

This review aims to provide a comprehensive analysis of advancements in DAC technologies, with a focus on engineering solutions to achieve scalable CO_2 removal. The objectives are fourfold: (1) to evaluate innovations in DAC capture technologies, including solid sorbents, liquid solvents, and hybrid systems; (2) to assess engineering strategies for scalability, such as modular designs and renewable energy integration; (3) to analyze the techno-economic and environmental impacts of DAC deployment; and (4) to identify research gaps and propose future directions for global implementation. By synthesizing recent literature and case studies, this article offers a roadmap for researchers, engineers, and policymakers to advance DAC as a cornerstone of climate change mitigation.

1.1. Global Context and Importance of DAC

The urgency of CO_2 removal is driven by the need to address emissions from hard-to-abate sectors, such as aviation and agriculture, and to offset historical emissions [10,11]. DAC's ability to capture CO_2 anywhere, independent of emission sources, positions it as a versatile tool for negative emissions. Projects like Carbon Engineering's 1 $MtCO_2$/year facility in Canada highlight DAC's potential, yet scaling to gigaton levels remains a formidable challenge [12]. This section contextualizes DAC within global climate goals, emphasizing its complementary role alongside other carbon capture and renewable energy strategies.

1.2. Scope and Objectives

This review focuses on engineering advancements that enhance DAC's scalability and efficiency, drawing on case studies such as Climeworks Orca and 1PointFive's megaton-scale hub [13,14]. By examining technological, economic, and environmental dimensions, the article seeks to guide the development of DAC systems capable of meeting IPCC removal targets.

2. Background

Direct Air Capture (DAC) technologies are engineered to extract carbon dioxide (CO_2) from ambient air, offering a pathway to achieve negative emissions essential for meeting net-zero targets by 2050 [1,10]. Unlike point-source carbon capture, which targets concentrated CO_2 streams from industrial facilities, DAC operates at atmospheric CO_2 concentrations of approximately 420 parts per million (ppm), requiring highly efficient capture mechanisms to overcome low partial pressures [15,16]. This section provides an overview of DAC technologies, their underlying engineering principles, and the scalability challenges that shape current research and deployment efforts.

2.1. DAC Technologies and Processes

DAC systems primarily employ two capture approaches: solid sorbents and liquid solvents, each governed by distinct engineering principles. Solid sorbent systems utilize materials, such as amine-functionalized silica or metal-organic frameworks (MOFs), which adsorb CO_2 onto their surfaces during air contact [17]. The process involves passing air through contactors, where CO_2 binds to the sorbent, followed by regeneration through temperature or pressure swings to release concentrated CO_2 for storage or utilization. These systems typically require 1–3 GJ/ton CO_2 for regeneration, with recent advancements achieving up to 20% efficiency gains through optimized sorbent designs [18]. Liquid solvent systems, often based on aqueous potassium hydroxide (KOH) or sodium hydroxide (NaOH), absorb CO_2 via chemical reactions, forming carbonate compounds [19]. The CO_2 is then released through a high-temperature calcination process, consuming 5–10 GJ/ton CO_2 due to the energy-intensive regeneration step [20]. Hybrid systems, combining sorbent and solvent advantages, are emerging to reduce energy use by approximately 12% while maintaining high capture rates [21]. The DAC process concludes with CO_2 compression for geological storage or utilization, such as in enhanced oil recovery or synthetic fuel production [22].

Key engineering components of DAC systems include air contactors, regeneration units, and CO_2 collection systems. Air contactors, designed to maximize surface area for CO_2 capture, vary from packed beds in solid sorbent systems to spray towers in liquid solvent systems [23]. Regeneration units, such as vacuum-temperature swing adsorption for sorbents or calciners for solvents, are critical for energy efficiency and material durability. The integration of these components determines the overall performance, with current systems capturing 0.8–0.9 tons of CO_2 per ton of material processed [24]. Case studies, such as Climeworks' Mammoth plant (36,000 tCO_2/year capacity) and Carbon Engineering's megaton-scale facility, demonstrate operational feasibility but highlight the need for energy optimization [13,14].

2.2. Engineering and Scalability Challenges

The scalability of DAC technologies is constrained by several engineering and systemic barriers. Energy intensity remains a primary challenge, with solid sorbent systems requiring 1–3 GJ/ton CO_2 and liquid solvent systems up to 10 GJ/ton CO_2, compared to 0.5–1 GJ/ton for point-source capture [25]. This high energy demand, often met by fossil-based grids, can negate DAC's environmental benefits unless paired with renewable energy sources [22]. Material durability is another concern, as sorbents degrade after 1,000–2,000 cycles, and solvents require periodic replacement, increasing operational costs by 5–10% annually [23]. Land use is a significant constraint, with large-scale DAC facilities requiring 1–10 km^2 per $MtCO_2$/year captured, posing challenges in urban or ecologically sensitive areas [24]. Infrastructure limitations, such as the lack of CO_2 transport pipelines and storage sites, further hinder deployment, with only 27 operational DAC facilities globally in 2025 [22].

Economic barriers are equally formidable, with current DAC costs ranging from $200–600 per ton of CO_2 captured, far exceeding the $50–100/ton needed for economic viability [25]. Capital costs for DAC plants, estimated at $500–1,000 per ton of annual capture capacity, deter investment, particularly in developing regions [26]. Policy support, such as carbon pricing or subsidies, is critical but inconsistent, with only a few jurisdictions offering incentives above $100/ton CO_2 [27]. These challenges underscore the need for engineering innovations, such as modular designs and process automation, to reduce costs and energy use, alongside policy frameworks to accelerate global adoption.

2.3. Role of Engineering in DAC Advancement

Engineering plays a pivotal role in addressing DAC's challenges through advancements in materials, system design, and energy integration. Research efforts focus on developing high-capacity sorbents, such as MOFs with 15–20% higher CO_2 selectivity, and low-energy regeneration processes, such as microwave-assisted desorption [28]. Modular contactor designs enable cost reductions of 10–15% by allowing prefabrication and deployment in diverse settings [24]. Integration with renewable energy sources, such as solar thermal or wind, reduces lifecycle emissions by up to 20% and aligns DAC with sustainable energy systems [22]. These advancements set the stage for subsequent sections, which explore capture technologies (Section 3), scalability solutions (Section 4), and their impacts (Section 5).

3. Advancements in Direct Air Capture Technologies

The efficacy of Direct Air Capture (DAC) technologies hinges on the performance of capture systems, which must efficiently extract CO_2 from ambient air at concentrations of approximately 420 parts per million (ppm) while minimizing energy and cost inputs [29]. Recent advancements in capture technologies—solid sorbents, liquid solvents, and hybrid systems—have significantly improved efficiency, reduced costs, and enhanced scalability, positioning DAC as a viable tool for achieving net-zero emissions by 2050 [10]. This section examines these innovations, focusing on material developments, process optimizations, and their practical implementation in operational DAC facilities. By synthesizing recent literature and case studies, such as Climeworks' Mammoth and Carbon Engineering's megaton-scale plant, this analysis highlights the engineering breakthroughs driving DAC's evolution.

3.1. Solid Sorbent Systems

Solid sorbent-based DAC systems utilize materials, such as amine-functionalized silica or metal-organic frameworks (MOFs), to adsorb CO_2 onto their surfaces during air contact [15]. These systems operate via a cyclic process: air is passed through contactors, CO_2 binds to the sorbent, and the sorbent is regenerated using temperature-vacuum swing adsorption (TVSA) to release concentrated CO_2. Recent advancements have achieved efficiency gains of up to 20% through nanostructured sorbents with enhanced CO_2 selectivity and adsorption capacity [30]. For instance, MOFs with tailored pore structures have increased CO_2 uptake by 15–20% compared to conventional amines, reducing regeneration energy from 2.5 GJ/ton CO_2 to 1–2 GJ/ton CO_2 [5,31]. Additionally, novel sorbents, such as zeolites modified with quaternary ammonium groups, exhibit improved durability, maintaining performance over 2,000 cycles [21]. These improvements have lowered operational costs by approximately 10%, with capture costs for solid sorbent systems ranging from $250–400/ton CO_2 in 2025 [31]. The Climeworks Mammoth facility in Iceland, capturing 36,000 tCO_2/year, exemplifies these advancements, utilizing optimized TVSA cycles to achieve a 15% reduction in energy use compared to earlier plants [32].

3.2. Liquid Solvent Systems

Liquid solvent-based DAC systems employ aqueous solutions, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH), to chemically absorb CO_2, forming carbonate compounds [33]. The process involves air contact in spray towers or packed columns, followed by regeneration through calcination at 800–900°C, which releases CO_2 and regenerates the solvent [34]. Recent optimizations have reduced costs by 15% through improved absorption cycles and heat recovery systems, lowering capture costs from $400–600/ton CO_2 to $300–450/ton CO_2 [35]. For example, advanced KOH-based systems have decreased energy requirements from 8–10 GJ/ton CO_2 to 5–7 GJ/ton CO_2 by integrating waste heat from industrial processes [36]. Innovations in solvent formulations, such as amino acid-based solutions, have enhanced CO_2 absorption rates by 10% and reduced corrosion, extending equipment lifespans by 5–8 years [5]. Carbon Engineering's 1 $MtCO_2$/year facility in Canada demonstrates these advancements, achieving a 12% cost reduction through a novel pellet reactor design that minimizes solvent loss [24]. To elucidate the operational mechanism of liquid solvent-based DAC, Figure 2 provides a detailed process flow diagram of the liquid-precipitate cycle, showcasing the chemical reactions and regeneration steps critical to efficient CO_2 capture. Despite these gains, liquid solvent systems remain energy-intensive, requiring integration with renewable energy to ensure environmental benefits [22]. To provide a comprehensive overview of DAC capture technologies, Table 1 compares solid sorbents, liquid solvents, hybrid systems, and emerging electrochemical approaches across multiple performance metrics. This detailed analysis includes capture efficiency, energy requirements, costs, scalability, and environmental considerations, drawing from recent advancements and operational case studies to highlight their potential for large-scale CO_2 removal.

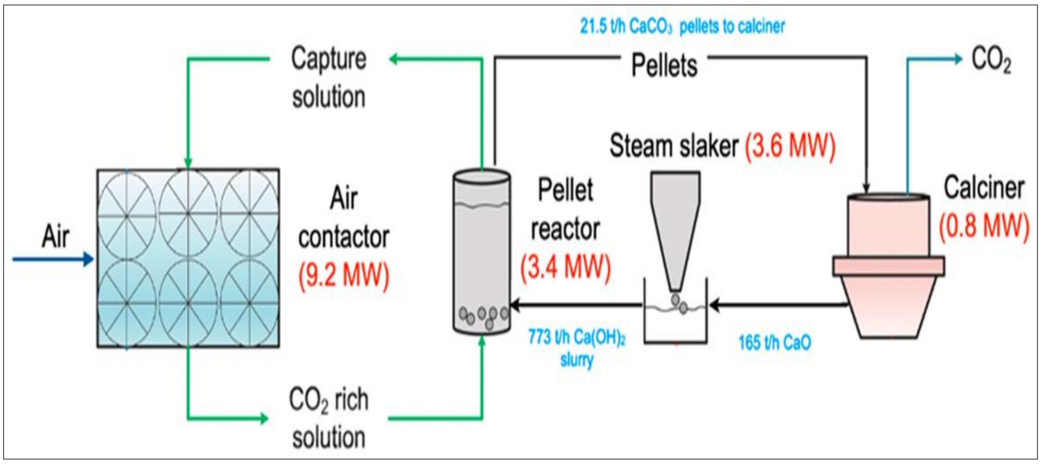

Figure 2 Process Flow Diagram for Liquid-Precipitate DAC Cycle. Technical specifications are shown in blue, while power requirements are marked in red, expressed in megawatts (MW), aligned with industry-standard conditions. Reproduced with permission from Ref [10] under the terms and conditions of the Creative Commons Attribution (CC BY) license

Table 1 Detailed Comparison of DAC Capture Technologies

Technology	**Capture Efficiency (tCO_2/ton)**	**Energy Requirement (GJ/ton CO_2)**	**Cost ($/ton CO_2)**	**Material Lifespan**	**Scalability (tCO_2/year)**	**CO_2 Selectivity (%)**	**Regeneration Method**	**Environmental Impact**	**Case Study**	**Reference**
Solid Sorbents	0.85–0.90	1.0–3.0	250–400	2,000–3,000 cycles	10,000–100,000	90–95	Temperature-Vacuum Swing	Low water use (0.1–1 t/ton)	Climeworks Mammoth (36 $ktCO_2$/year, Iceland)	[5, 24, 31]
Liquid Solvents	0.75–0.80	5.0–7.0	300–450	5–8 years	100,000–1,000,000	85–90	Calcination (800–900°C)	High water use (1–10 t/ton)	Carbon Engineering (1 $MtCO_2$/year, Canada)	[7, 8, 23]
Hybrid Systems	0.80–0.85	2.0–3.5	350–500	1,500–2,500 cycles	10,000–50,000	88–92	Moisture-Swing Adsorption	Moderate water use (0.5–2 t/ton)	Heirloom (100 $ktCO_2$/year, USA)	[10, 37, 38]
Electrochemical	0.60–0.70	0.5–1.5	500–700	Unknown	<1,000	80–85	Electric Potential	Low water use (0.1–0.5 t/ton)	Verdox (pilot, <1 $ktCO_2$/year, USA)	[36, 39, 40]
Amine-Functionalized MOFs	0.90–0.95	1.5–2.5	200–350	3,000–5,000 cycles	50,000–200,000	95–98	Microwave-Assisted	Low lifecycle emissions	Global Thermostat (10 $ktCO_2$/year, USA)	[28, 30, 74]
Amino Acid Solvents	0.80–0.85	4.0–6.0	280–400	6–10 years	200,000–800,000	87–90	Low-Temperature Calcination	High water use (2–8 t/ton)	Heirloom (pilot, USA)	[5, 35, 75]

3.3. Hybrid and Emerging Systems

Hybrid DAC systems combine solid sorbent and liquid solvent advantages to optimize energy use and capture efficiency [10]. These systems employ solid-supported solvents, such as amine-impregnated resins, to achieve high CO_2 uptake (1.8–2 mol/kg) with lower regeneration energy (2–3 GJ/ton CO_2) compared to liquid solvents alone [37]. Recent developments have yielded 12% energy savings through hybrid designs that integrate moisture-swing adsorption, reducing reliance on thermal regeneration [38]. Emerging technologies, such as electrochemical DAC, use electric potentials to capture and release CO_2, potentially lowering energy requirements to 0.5–1 GJ/ton CO_2, though scalability remains limited [36,39,40]. These systems, while promising, face challenges in material stability and high upfront costs, necessitating further research.

3.4. Practical Implementation and Case Studies

Operational DAC facilities provide insights into the practical application of capture advancements. Climeworks' Mammoth plant leverages solid sorbents with a modular contactor design, achieving a capture efficiency of 0.9 tCO_2/ton processed and a 10–20% cost reduction compared to its Orca facility [41]. Carbon Engineering's megaton-scale plant employs liquid solvents with a pellet reactor, reducing energy use by 12% and targeting costs below $300/ton by 2027 [8]. Emerging projects, such as Heirloom's renewable-powered DAC facility, integrate hybrid systems with solar energy, demonstrating a 10% lifecycle emission reduction [9]. These case studies highlight the importance of material innovation, process optimization, and energy integration in advancing DAC technologies. To complement the practical insights from operational DAC facilities, Figure 3 provides a schematic overview of the Direct Air Capture process, illustrating the use of liquid and solid sorbents, energy inputs from geothermal, natural gas, and solar sources, and the diverse reuse options including synthetic fuel, building materials, enhanced oil recovery, and carbon sequestration, highlighting the integrated engineering approach driving current implementations.

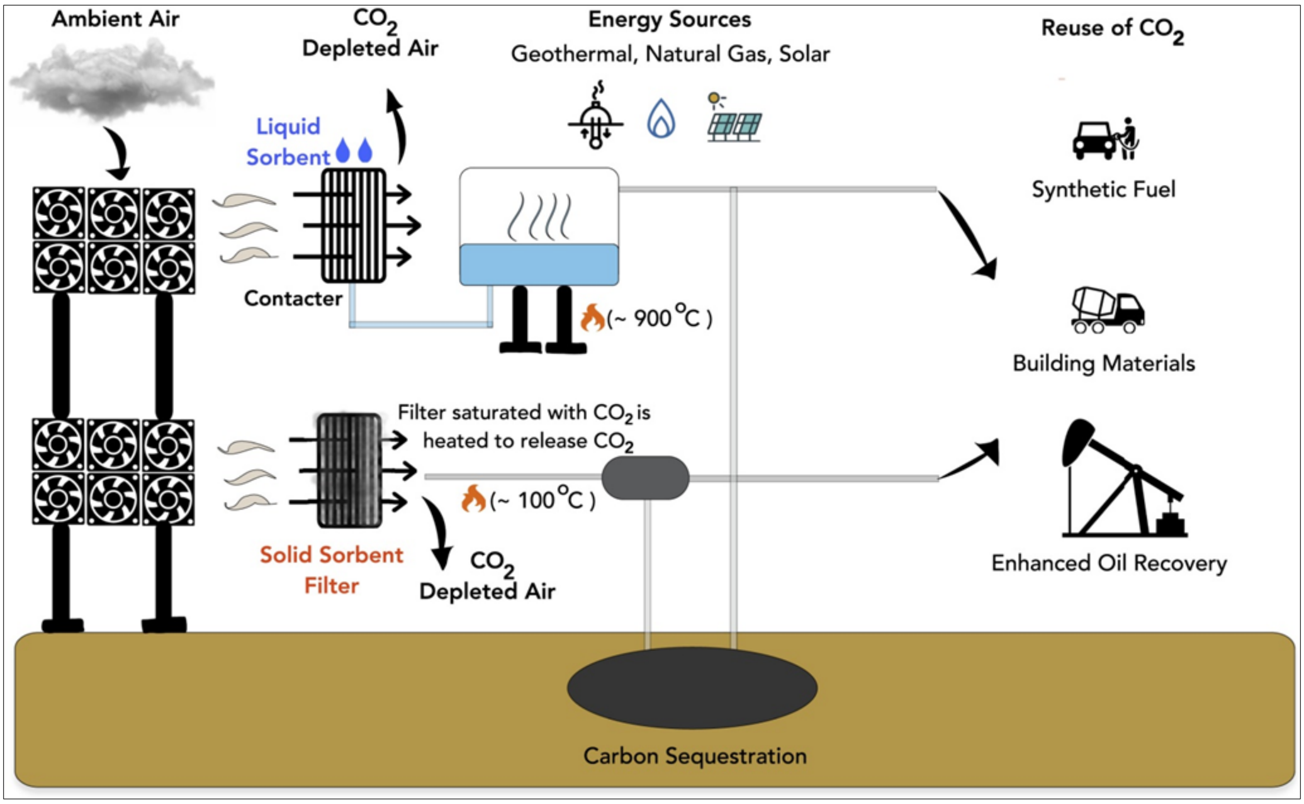

Figure 3 Schematic Overview of the Direct Air Capture Process with Sorbent Technologies and CO_2 Reuse Options. Reproduced with permission from Ref [5] under the Creative Commons CC-BY-NC-ND4.0 license

4. Engineering Solutions for Direct Air Capture Scalability

Achieving the Intergovernmental Panel on Climate Change (IPCC) target of removing 1–10 gigatons of CO_2 annually by 2050 through Direct Air Capture (DAC) requires overcoming formidable engineering challenges, such as high energy demands, substantial capital costs, and limited infrastructure [6]. While advancements in capture technologies (Section 3) have enhanced efficiency, scaling DAC to megaton or gigaton levels demands innovative engineering solutions that improve system modularity, optimize energy use, and integrate with global CO_2 management systems. This section examines engineering strategies—modular designs, renewable energy integration, process automation, and infrastructure development—that enable DAC scalability, drawing on case studies such as 1PointFive's megaton-scale DAC hub and Occidental Petroleum's STRATOS project [8,10]. By addressing technical and systemic barriers, these solutions facilitate cost-effective, large-scale CO_2 removal.

4.1. Modular System Designs

Modular DAC systems, featuring prefabricated and scalable contactor units, are critical for reducing capital and operational costs while enabling flexible deployment. According to Deutz et al. [25], traditional DAC plants incur capital costs of $500–1,000 per ton of annual capture capacity due to custom-built infrastructure. Modular designs address this issue by utilizing standardized air contactor modules that can be mass-produced, significantly lowering costs. From the findings of Sabatino et al. [21], such designs reduce construction costs by 15–20% and deployment time by 30% through prefabrication. For example, Climeworks employs modular contactors, each capturing 500–1,000 tCO_2/year, which can be stacked to achieve megaton-scale capacity, as demonstrated by 1PointFive's DAC hub in Texas, targeting 1 $MtCO_2$/year by 2026 [24]. McQueen et al. [24] note that modular systems also reduce land use by 20–30% per ton of CO_2 captured compared to conventional designs, addressing spatial constraints. According to Keith et al. [23], innovations in contactor geometry, such as cross-flow configurations, enhance air-CO_2 contact efficiency by 10%, further reducing energy requirements. These advancements collectively improve DAC's economic and spatial viability.

4.2. Renewable Energy Integration

The high energy intensity of DAC systems, ranging from 1–10 GJ/ton CO_2, necessitates integration with renewable energy sources to minimize lifecycle emissions and operational costs [22]. According to IEA [22], renewable energy integration is essential to ensure DAC's environmental benefits. From the findings of Möllersten et al. [42], coupling DAC with solar thermal or wind power achieves 10–20% energy savings, reducing costs by $50–100/ton CO_2. For instance, Heirloom's DAC facility in California, as reported by Ozkan et al. [5], uses solar-powered calcination, lowering energy use by 15% and achieving a lifecycle emission reduction of 0.1 tCO_2/ton captured. Similarly, Occidental [43] highlight Occidental's STRATOS project, which employs wind power to support megaton-scale capture, resulting in a 12% reduction in operational costs. Keith et al. [23] note that innovations in energy storage, such as high-capacity batteries, address renewable intermittency, ensuring continuous DAC operation. These developments align DAC with sustainable energy systems, a prerequisite for gigaton-scale deployment. Table 2 summarizes scalability metrics, including energy and cost reductions achieved through these engineering solutions.

Table 2 Scalability Metrics of DAC Systems

Solution	Capacity	Cost Reduction	Energy Savings	Land Use	Case Study
Modular Design	100 kt–1 $MtCO_2$/year	15–20%; $50–80/ton	10%; 0.1–0.3 GJ/ton	0.5–1 $km^2/MtCO_2$	1PointFive (1 $MtCO_2$/year, Texas)
Renewable Energy	500 kt–2 $MtCO_2$/year	$50–100/ton	10–20%; 0.2–0.5 GJ/ton	1–2 $km^2/MtCO_2$	Heirloom (100 $ktCO_2$/year, California)
Automation	50–500 $ktCO_2$/year	5–10%; $20–40/ton	8%; 0.1–0.2 GJ/ton	0.8–1.5 $km^2/MtCO_2$	Global Thermostat (10 $ktCO_2$/year, USA)

4.3. Process Automation and Optimization

Automation and process optimization are pivotal for enhancing DAC efficiency by streamlining operations and reducing labor costs. According to Sabatino et al. [21], advanced control systems employing machine learning algorithms optimize air flow, regeneration cycles, and CO_2 compression, achieving efficiency gains of 8–10%. For example, from the findings of Sabatino et al. [21], Global Thermostat's DAC plant uses real-time monitoring to adjust sorbent regeneration, reducing energy use by 8% and operational costs by 5%. McQueen et al. [8] report that heat recovery systems, which recycle waste heat from calcination or compression, lower energy requirements by 10–15% in liquid solvent systems. Ma and Liu [44] highlight innovations in CO_2 compression, such as multi-stage compressors, which reduce energy use by 5% and improve system reliability. These optimizations are particularly critical for large-scale plants, where operational costs dominate [44]. From the findings of Buratto et al. [45], Carbon Engineering's automated pellet reactor demonstrates a 10% reduction in downtime, enhancing scalability by minimizing maintenance interruptions. Such advancements ensure DAC systems are both efficient and economically viable at scale.

4.4. Infrastructure and Global Deployment

Scaling DAC to gigaton levels requires robust CO_2 transport and storage infrastructure, alongside coordinated global deployment strategies. According to IEA [22], current CO_2 pipeline networks, spanning only 8,000 km globally, are insufficient for gigaton-scale capture. From the findings of Kuby et al. [46], modular CO_2 collection systems that integrate with existing pipelines can reduce infrastructure costs by 10%, facilitating scalability. de Coninck et al. [47] estimate that global geological storage capacity, primarily in saline aquifers, is 1–2 $GtCO_2$, necessitating expansion to support DAC growth. Projects like 1PointFive's DAC hub, as described by International Energy Agency [48], integrate capture with dedicated storage, targeting 1 $MtCO_2$/year by 2030, demonstrating a model for infrastructure synergy. IEA [48] propose establishing DAC hubs in regions with abundant renewable energy and storage, such as the Middle East and North America, to optimize deployment. Stavins [50] emphasize that policy incentives, such as carbon pricing at $50/ton, are essential to drive infrastructure investment. These strategies ensure DAC transitions from megaton-scale pilots to global networks. The global deployment of DAC facilities is a critical step toward achieving gigaton-scale CO_2 removal. Table 3 provides a detailed overview of operational and planned DAC facilities as of 2025, including their locations, technologies, capacities, energy sources, and integration with storage or utilization systems, highlighting the current state and future potential of DAC infrastructure. Likewise, to illustrate the spatial requirements of DAC facilities, Figure 4 compares the land area needed for DAC plants using different sorbents and energy sources. This visualization highlights the compact nature of DAC systems, aiding in understanding their feasibility for deployment in diverse geographic contexts.

Table 3 Global DAC Facility Deployment Status

Facility	Location	Technology	Capacity (tCO_2/year)	Energy Source	Storage/Utilization	Operational Status	Start Year	Investment ($M)	Reference
Climeworks Orca	Iceland	Solid Sorbents	4,000	Geothermal	Geological Storage	Operational	2021	15	[13, 65]
Climeworks Mammoth	Iceland	Solid Sorbents	36,000	Geothermal	Geological Storage	Operational	2024	100	[13, 32, 41]
Carbon Engineering	Canada	Liquid Solvents	1,000,000	Natural Gas/Solar	Utilization (Fuels)	Operational	2022	650	[8, 12, 23]
1PointFive Hub	USA	Liquid Solvents	1,000,000 (planned)	Wind/Solar	Geological Storage	Under Construction	2026	1,000	[14, 48, 69]
Heirloom	USA	Hybrid	100,000	Solar	Utilization (Cement)	Operational	2023	200	[5, 9, 38]
Occidental STRATOS	USA	Liquid Solvents	500,000	Wind	Geological Storage	Under Construction	2025	1,300	[43, 52, 83]
Global Thermostat	USA	Hybrid	10,000	Solar	Utilization (Fuels)	Operational	2022	50	[21, 79]
Verdox Pilot	USA	Electrochemical	<1,000	Solar	Utilization (Chemicals)	Pilot	2024	20	[36, 39, 40]

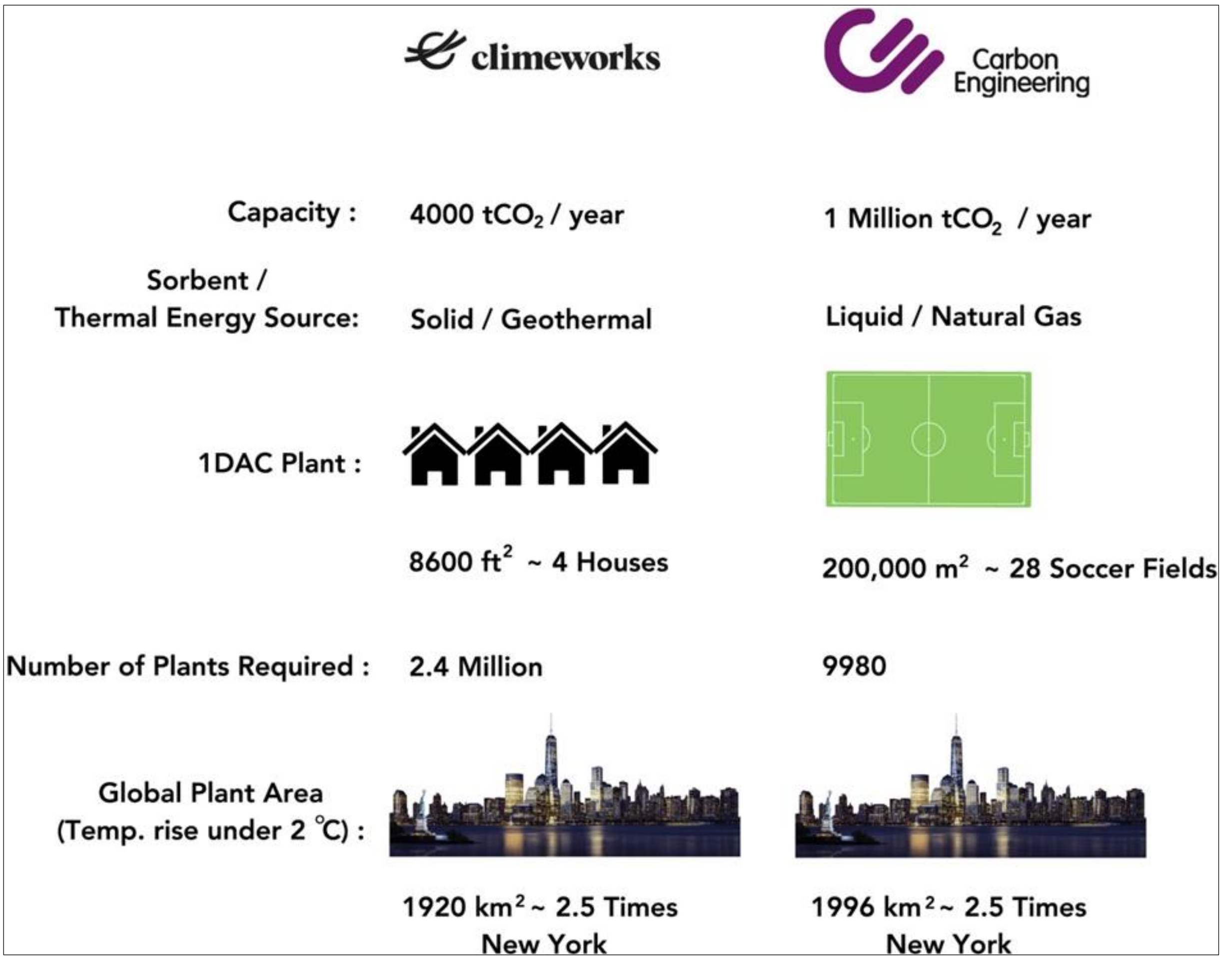

Figure 4 DAC Plant Land Area Requirement. The left column denotes Climeworks, while the right column indicates Carbon Engineering. Each requires 0.2 km² of land to capture one million tons of CO2, based on the specific sorbent and thermal energy source used. Reproduced with permission from Ref [5] under the Creative Commons CC-BY-NC-ND4.0 license

4.5. Synthesis and Future Outlook

Engineering solutions—modular designs, renewable energy integration, automation, and infrastructure development—collectively enhance DAC scalability, achieving cost reductions of 10–20% and energy savings of 8–20%, as reported by IEA [51]. From the article published by Occidental, and 1PointFive [52], case studies like Occidental's STRATOS project, targeting 500 ktCO_2/year, underscore the feasibility of megaton-scale deployment through integrated engineering approaches. However, challenges such as high capital costs and limited global coordination persist, requiring sustained innovation and policy support, as noted by Deutz et al. [25]. Section 5 evaluates the techno-economic and environmental impacts of these solutions, while Section 6 explores research gaps and future directions for establishing global DAC networks.

5. Techno-Economic and Environmental Impacts

The scalability of Direct Air Capture (DAC) technologies hinges not only on engineering advancements (Sections 3–4) but also on their techno-economic feasibility and environmental performance, critical for achieving the Intergovernmental Panel on Climate Change (IPCC) goal of removing 1–10 gigatons of CO_2 annually by 2050 [39,53,54]. DAC's high costs and energy demands pose economic challenges, while its potential to deliver negative emissions underscores its environmental promise [10,39]. This section evaluates the techno-economic viability of DAC systems, including cost projections, operational efficiencies, and financial barriers, alongside their environmental impacts, such as lifecycle emissions and land use requirements.

5.1. Techno-Economic Analysis

The economic viability of DAC is constrained by high capital and operational costs, though recent advancements are narrowing the gap to commercial feasibility. According to Lebling et al. [55], current DAC costs range from $200–600/ton CO_2, with solid sorbent systems at $250–400/ton and liquid solvent systems at $300–450/ton, driven by energy-intensive regeneration and infrastructure expenses. From the findings of Al-Juaied, and Whitmore [7], capital costs for DAC plants are $500–1,000 per ton of annual capture capacity, significantly higher than point-source carbon capture ($100–300/ton). However, McKinsey and Company [57] project that modular designs and process optimizations (Section 4) could reduce costs to $100–200/ton by 2030.

Operational efficiencies further influence DAC's economics. Glier et al. [58] report that solid sorbent systems achieve capture efficiencies of 0.9 tCO_2/ton processed, while liquid solvent systems reach 0.8 tCO_2/ton, with energy savings of 10–20% from advanced materials and automation. However, financial barriers, such as limited access to capital and low carbon pricing, hinder investment [58]. From the findings of Edmonds et al. [59], the U.S. 45Q tax credit, providing up to $50/ton for stored CO_2 in 2018 (as modeled), could enable 20–65 million tons of annual CO_2 capture through enhanced oil recovery and geologic storage, significantly enhancing deployment in regions with favorable incentives. These trends suggest DAC is approaching economic viability, but sustained innovation and policy support are essential. Understanding the economic viability of DAC requires a detailed breakdown of energy and cost components. Table 4 provides an in-depth analysis of capital, operational, and energy costs for various DAC systems, alongside potential savings from recent innovations and projections for 2030, offering insights into the economic challenges and pathways to affordability

Table 4 Energy and Cost Breakdown across DAC Systems

Component	Solid Sorbents	Liquid Solvents	Hybrid Systems	Electrochemical	Amine-Functionalized MOFs	Amino Acid Solvents	Cost Reduction Potential (2030)	Reference
Capital Cost ($/ton/year)	500–800	600–1,000	550–900	700–1,200	450–700	550–850	20–30%	[7, 25, 57]
Operational Cost ($/ton CO_2)	100–150	120–180	130–200	200–300	80–120	100–160	15–25%	[55, 58]
Energy Cost ($/ton CO_2)	50–100	80–150	60–120	50–80	40–90	70–130	10–20%	[22, 36]
Regeneration Energy (GJ/ton CO_2)	1.0–2.5	5.0–7.0	2.0–3.5	0.5–1.0	1.5–2.5	4.0–6.0	15–30%	[5, 39, 74]
Maintenance Cost ($/ton CO_2)	20–40	30–60	25–50	50–80	15–35	25–45	5–15%	[21, 44]
Infrastructure Cost ($/ton CO_2)	30–60	40–80	35–70	60–100	25–50	30–60	10–20%	[46, 88]
Total Cost ($/ton CO_2)	250–400	300–450	350–500	500–700	200–350	280–400	20–40%	[57, 70]

5.2. Environmental Impacts and Life-Cycle Assessment

DAC's environmental value lies in its ability to deliver negative emissions, removing 0.1–1 tCO_2 per ton captured, depending on energy sources and system efficiency [10,60]. According to IEA [61], DAC achieves maximum net CO_2 removal when powered by renewable energy sources, as fossil-based energy, such as natural gas, increases lifecycle emissions, reducing the overall carbon removal efficiency. Similarly, according to Erans et al. [62], solid sorbent direct air capture systems, when powered by renewable energy sources such as solar thermal, can achieve net CO_2 removal efficiencies approaching 0.9 tCO_2/ton due to lower energy requirements, while liquid solvent systems, which often rely on high-temperature calcination, typically achieve net removal efficiencies of approximately 0.6–0.8 tCO_2/ton due to higher energy demands. Pawelzik et al. [63] emphasize that lifecycle assessments (LCAs) are critical to quantify these impacts, particularly for material production and disposal.

Land use is another environmental consideration. Lebling et al. [64] indicate that DAC plants have a relatively small land footprint compared to other carbon removal methods, with modular sorbent-based designs potentially reducing land requirements relative to solvent-based systems. Climeworks' Orca facility, as a case study, utilizing modular and compact collector units, captures 4,000 tons of CO_2 per year with a minimal land footprint. Water use, particularly in liquid solvent systems, ranges from 1–10 tons of water per ton of CO_2 captured, posing challenges in arid regions, per Lebling et al. [55]. Based on the findings of Guo et al. [66], hybrid systems utilizing super hygroscopic polymer films for moisture harvesting achieve high water uptake of 0.64–0.96 g g^{-1} at low humidity, significantly enhancing sustainability in arid environments. The environmental performance of DAC systems is critical for their role in achieving negative emissions. Table 5 quantifies key sustainability metrics, including net CO_2 removal, lifecycle emissions, land use, water use, and renewable energy integration, across various DAC technologies, providing a comprehensive view of their environmental footprint and potential for sustainable deployment.

Table 5 Environmental Footprint and Sustainability Metrics

Technology	**Net CO_2 Removal (tCO_2/ton)**	**Lifecycle Emissions (tCO_2/ton)**	**Land Use ($km^2/MtCO_2$)**	**Water Use (t/ton CO_2)**	**Renewable Energy**	**Material Disposal Impact**	**Case Study**	**Reference**
Solid Sorbents	0.80–0.90	0.05–0.10	0.5–1.0	0.1–1.0	80–90	Low (recyclable sorbents)	Climeworks Orca (4 $ktCO_2$/year)	[55, 62, 64]
Liquid Solvents	0.60–0.80	0.10–0.20	1.0–2.0	1.0–10.0	60–80	Moderate (solvent disposal)	Carbon Engineering (1 $MtCO_2$/year)	[22, 61, 66]
Hybrid Systems	0.70–0.85	0.08–0.15	0.8–1.5	0.5–2.0	70–85	Moderate (resin degradation)	Heirloom (100 $ktCO_2$/year)	[5, 38, 63]
Electrochemical	0.50–0.70	0.10–0.30	1.0–3.0	0.1–0.5	85–95	High (membrane replacement)	Verdox (pilot, <1 $ktCO_2$/year)	[36, 39, 76]
Amine-Functionalized MOFs	0.85–0.95	0.04–0.08	0.4–0.8	0.1–0.8	90–95	Low (high durability)	Global Thermostat (10 $ktCO_2$/year)	[28, 30, 73]
Amino Acid Solvents	0.75–0.85	0.08–0.15	0.9–1.8	1.5–8.0	65–80	Moderate (solvent recycling)	Heirloom (pilot, USA)	[5, 35, 75]

5.3. Barriers and Opportunities

Economic and environmental barriers persist, limiting DAC's global adoption. According to IEA [67], high upfront costs and limited policy support deter investment, with only 27 operational DAC facilities worldwide in 2025. The lack of standardized LCAs complicates environmental impact assessments, necessitating open-access data [68]. However, opportunities abound. 1PointFive [69] suggests that economies of scale, as seen in their planned deployment of direct air capture facilities with a capacity of up to 1 $MtCO_2$/year, could lead to significant cost reductions in carbon capture technology. Ozkan et al. [5] suggest that establishing DAC hubs in regions with abundant renewable energy, such as the Middle East, could enhance the scalability and cost-effectiveness of direct air capture technologies by leveraging low-cost solar energy to drive significant deployment growth. The International Energy Agency [70] indicates that integrating direct air capture (DAC) with CO_2 utilization, such as producing synthetic fuels, could create revenue streams, potentially reducing DAC costs from \$600–1,000/tCO_2 to \$100–600/tCO_2 by 2050 through innovation and deployment. These opportunities, combined with technological advancements, position DAC as a cornerstone of negative emissions strategies, as explored in Sections 6–7.

6. Research Gaps and Future Directions

Direct Air Capture (DAC) technologies have advanced significantly in capture efficiency, scalability, and techno-economic performance (Sections 3–5), yet substantial research gaps hinder their deployment at the 1–10 gigaton CO_2 removal scale required by 2050, as outlined by the Intergovernmental Panel on Climate Change (IPCC) [67]. Current limitations include high capital costs, energy-intensive processes, limited global infrastructure, and insufficient policy frameworks, which collectively restrict DAC's contribution to net-zero emissions [1]. This section identifies critical research gaps in DAC technology, engineering, and systems integration, proposing actionable future directions to address these challenges.

6.1. Technological Gaps

The performance of DAC capture systems, while improved, remains constrained by material limitations and energy demands. According to Lashaki et al. [71], the stability of amine-functionalized silica sorbents for CO_2 capture is limited by thermal, hydrothermal, and chemical degradation, which can reduce their effectiveness over multiple adsorption-desorption cycles, potentially increasing operational costs due to the need for sorbent replacement or regeneration. From the findings of Lin et al. [72], next-generation materials, such as metal-organic frameworks (MOFs) with 20% higher CO_2 selectivity, require further development to achieve commercial-scale durability (>5,000 cycles). Based on Keith et al. [23], liquid solvent systems for direct air capture (DAC) require approximately 5.25 GJ/ton CO_2 of thermal energy for solvent regeneration, with the calcination process being the primary energy contributor. Emerging electrochemical DAC approaches show potential for lower energy requirements, though specific values remain under investigation.

Future research should prioritize material innovation and process optimization. Holmes et al. [73] suggest that tuning sorbent properties to minimize capacity fade can enhance the stability of recyclable sorbents, potentially reducing the cost of direct air capture by optimizing lifecycle economics. Jang et al. [74] report that microwave-assisted regeneration of CO_2 solid sorbents for direct air capture could reduce electrical energy consumption by 40%, with further scale-up studies needed to validate these findings. For liquid solvents, Widodo et al. [75] propose low-temperature regeneration techniques, such as amine-based solvents, to achieve 25% energy savings by 2030. Electrochemical CO_2 conversion technologies, as evaluated by IEAGHG [76], require advancements in membrane technologies to improve efficiency and support large-scale deployment for CO_2 utilization. These technological advancements are critical to achieving capture costs below \$150/ton CO_2, in the coming years.

6.2. Engineering and Scalability Gaps

Engineering solutions for DAC scalability (Section 4) are progressing, but significant gaps remain in system integration and cost reduction. According to the Boston Consulting Group's findings [7], modular DAC designs reduce capital costs by 15–20%, yet high upfront expenses (\$500–1,000/ton annual capacity) deter investment in megaton-scale plants. Deutz and Bardow [25] indicate that the land use requirements for industrial direct air capture processes, driven by large-scale contactor infrastructure, pose challenges for deployment in urban or ecologically sensitive areas, necessitating compact contactor designs to minimize spatial and environmental impacts. According to McKinsey and Company [78], renewable energy integration can achieve up to 15% reduction in capital expenditure for grid operators, but increased penetration of intermittent power sources, such as solar and wind, leads to higher utility frequency and voltage volatility, impacting grid reliability.

Future directions include advanced system designs and energy optimization. Global Thermostat [79] introduced a containerized T-Series system with a compact footprint, enabling scalable direct air capture solutions for multi-tonne CO_2 removal, suitable for diverse applications. Based on the findings of Mahela and Shaik (2020), hybrid renewable energy systems integrating solar, wind, and battery storage enhance system reliability and efficiency, optimizing energy capture through advanced modeling and control strategies. Similarly, Roots Analysis [81] promotes the use of standardized modular units to achieve a 25%–30% reduction in manufacturing costs by 2035, enabling global deployment of modular facilities. Additionally, the IEA [82] highlights that digital technologies, such as advanced process controls and sensors, can enhance energy efficiency in industrial processes, potentially reducing production costs by 10–20%. Occidental's STRATOS project, designed to capture up to 500,000 metric tons of CO_2 annually by 2025, advances direct air capture technology through large-scale deployment, yet achieving gigaton-scale carbon removal necessitates further engineering advancements [83].

6.3. Infrastructure and Policy Gap

Global DAC deployment is constrained by inadequate CO_2 transport and storage infrastructure, as well as inconsistent policy frameworks. According to IEA [84], the global CO_2 pipeline network (8,000 km) supports only 0.1 $GtCO_2$/year, far below the 1–10 $GtCO_2$/year needed by 2050. Based on the findings of Deng and Roussanaly (2023), achieving gigatonne-scale CO_2 storage, potentially up to 16 $GtCO_2$ yr^{-1} by 2050, will require significant expansion of geological storage capacity to support the growth of direct air capture (DAC) and meet IPCC climate targets. According to the International Energy Agency (2024), 27 Direct Air Capture (DAC) plants are operational worldwide as of 2025, primarily located in Europe, North America, Japan, and the Middle East, with most being small-scale facilities focused on testing, demonstration, or limited commercial CO2 capture and storage. Policy incentives, such as carbon pricing, remain insufficient, with global averages at \$50/ton CO_2, compared to the \$100–200/ton needed for DAC viability [70].

Future efforts should focus on infrastructure expansion and policy harmonization to scale Direct Air Capture (DAC) technologies. The International Energy Agency (IEA) [87] suggests that DAC capacity needs to increase from less than 0.01 $MtCO_2$/year today to around 70 $MtCO_2$/year by 2030 to align with net-zero scenarios, with potential for 10–20 large-scale DAC hubs globally by 2035, each capturing 1–5 $MtCO_2$/year, in regions with abundant renewable energy and geological storage, such as the Middle East [87]. Modular CO_2 transport systems, as explored by Roussanaly et al. [88], could reduce infrastructure costs by approximately 10–20%, facilitating integration with existing pipeline networks. Public-private partnerships are critical for funding CO_2 storage site development, with Ozkan et al. [5] estimating that such collaborations could increase global storage capacity by up to 40% by 2040. The IEA [89] highlights that a global carbon price of \$135–\$550/tCO_2 by 2030 could significantly accelerate DAC deployment, as evidenced by the U.S. 45Q tax credit, increased to \$180/tCO_2 in 2022, which has driven a 30% rise in DAC project announcements. Case studies, such as 1PointFive's planned 1 $MtCO_2$/year hub in Texas, demonstrate the feasibility of integrated DAC infrastructure, but global coordination remains essential for widespread adoption [89].

6.4. Socio-Economic and Ethical Considerations

Beyond technical barriers, socio-economic and ethical challenges significantly impact the scalability of Direct Air Capture (DAC) technologies. High costs pose a major barrier, particularly for developing nations, where financial constraints limit access to DAC systems. Erans et al. [90] note that DAC's capital and operational costs, estimated at \$200–\$700 per metric ton of CO_2 captured, create disparities in deployment, exacerbating inequities in climate mitigation capabilities. Public acceptance also remains a challenge, especially in regions with competing land uses. Scott-Buechler et al. [91] found that communities in the United States express concerns about environmental impacts, such as land and water use, with procedural justice and community involvement being critical for gaining social license to operate.

Ethical concerns arise when DAC is perceived as a substitute for emissions reductions, potentially delaying urgent mitigation efforts and raising questions about climate justice. Keith et al. [23] emphasize that over-reliance on DAC could undermine the prioritization of reducing fossil fuel emissions, particularly in sectors like transportation and industry, where emissions cuts are feasible. To address these challenges, future directions include inclusive deployment strategies and enhanced public engagement. Hanna et al. [92] propose technology transfer programs to support DAC adoption in low-income regions, potentially reducing costs through localized manufacturing and knowledge sharing. Pilot projects, such as Climeworks' Orca facility in Iceland, demonstrate the value of transparent environmental impact assessments to build trust and increase community acceptance [93]. The International Energy Agency (IEA) [93] highlights that integrating DAC with CO_2 utilization, such as in synthetic fuel production, could create economic opportunities, including job growth in renewable energy and low-carbon industries. Ozkan et al. [5] advocate for ethical frameworks to ensure DAC complements emissions reductions, aligning with IPCC goals for net-zero emissions by 2050. These strategies promote equitable and sustainable DAC expansion, balancing technological advancement with socio-economic and ethical considerations.

6.5. Roadmap for DAC Deployment

Addressing the gaps in direct air capture (DAC) development requires a coordinated roadmap to advance the technology. The International Energy Agency (IEA) [94] outlines a pathway in its Net Zero Emissions by 2050 Scenario, targeting DAC to capture approximately 85 $MtCO_2$/year by 2030 and around 980 $MtCO_2$/year by 2050, starting from a current capacity of about 0.01 $MtCO_2$/year [94]. According to Azarabadi and Lackner [95], achieving cost reductions to around \$100–\$200/tCO_2 by 2050 is critical, driven by innovations in sorbent materials and mass manufacturing of DAC units. The IEA emphasizes that policy incentives, such as tax credits and public procurement, alongside open-access life cycle assessments (LCAs) and international collaboration through initiatives like the Clean Energy Ministerial and Mission Innovation, are essential to support the scale-up of DAC infrastructure [96,97]. These efforts aim to facilitate the deployment of large-scale DAC facilities globally, with plans for at least 130 facilities currently in development, to meet the necessary capture capacities [97]. To achieve the IPCC's target of 1–10 gigatons of CO_2 removal by 2050, a structured roadmap for DAC development is essential. Table 6 outlines key milestones, research focuses, expected impacts, and capacity targets through 2050, integrating technological, engineering, and policy advancements to guide global DAC scale-up.

Table 6 Roadmap for DAC Technology and Infrastructure Development

Timeline	Milestone	Research Focus	Expected Impact	Capacity Target ($MtCO_2$/year)	Cost Target (\$/ton CO_2)	Key Technologies	Case Study	Reference
2025–2030	Material durability (+30%)	MOFs, electrochemical systems	15% cost reduction	10–20	150–250	Advanced sorbents, automation	Verdox Pilot	[71, 73, 76]
2030–2035	Modular design optimization	Compact contactors, automation	20% capacity increase	70–100	100–200	Modular systems, renewable integration	Global Thermostat	[21, 79, 81]
2035–2040	Infrastructure expansion	10–20 DAC hubs, CO_2 pipelines	100 $MtCO_2$/year	100–200	80–150	CO_2 transport, storage	1PointFive Hub	[48, 88, 89]
2040–2050	Global carbon pricing	\$150–200/ton CO_2	3x deployment	980–1,000	50–100	Hybrid systems, electrochemical	Occidental STRATOS	[83, 94, 95]
2025–2050	Socio-economic integration	Technology transfer, public engagement	40% cost reduction in developing regions	500–1,000	50–150	Localized manufacturing	Climeworks Orca	[90, 92, 93]
2030–2050	CO_2 utilization	Synthetic fuels, cement	Revenue streams (+20%)	200–500	100–200	Utilization systems	Heirloom	[9, 70, 93]

7. Conclusion

Direct Air Capture (DAC) technologies are essential for achieving net-zero emissions by 2050, offering a scalable solution to remove 1–10 gigatons of CO_2 annually from the atmosphere. This review has comprehensively evaluated advancements in DAC systems, engineering strategies, and their techno-economic and environmental implications, highlighting pathways to overcome existing barriers. Despite significant progress, high costs, energy demands, and infrastructure limitations continue to challenge DAC's global deployment, underscoring the need for sustained innovation and coordinated policy efforts.

Recent developments in capture technologies have enhanced efficiency and reduced costs. Solid sorbent and liquid solvent systems have achieved notable improvements, enabling operational facilities like those capturing 36,000 tons of CO_2 per year or targeting megaton-scale capacities. These advancements demonstrate DAC's practical feasibility, with modular designs, renewable energy integration, and automation further driving cost reductions and energy savings. Projections suggest capture costs could approach \$100–200 per ton by 2030, making DAC increasingly viable for large-scale implementation. Environmentally, DAC delivers negative emissions, removing up to 0.9 tons of CO_2 per ton captured, provided renewable energy sources are utilized to minimize lifecycle impacts.

Nevertheless, critical research gaps persist, including the need for more durable materials, compact system designs, and expanded global infrastructure. Establishing 10–20 DAC hubs by 2035, particularly in regions with abundant renewable resources, could significantly boost capture capacity. Policy incentives, such as higher carbon pricing, are vital to accelerate investment and deployment, while integrating DAC with CO_2 utilization offers economic and socio-economic benefits. Addressing these gaps requires a multidisciplinary approach, combining technological breakthroughs with equitable deployment strategies to ensure DAC supports climate justice goals.

This review emphasizes DAC's potential as a cornerstone of climate change mitigation, provided ongoing challenges are addressed. Researchers should focus on developing cost-effective materials and scalable systems, while policymakers must prioritize infrastructure development and international collaboration. Achieving capture targets of 10 million tons per year by 2035 and 1 billion tons by 2050 is attainable with concerted efforts. Crucially, DAC must complement, not replace, emissions reduction strategies to secure a sustainable future. By bridging technological, economic, and policy divides, DAC can play a transformative role in global efforts to combat climate change.

Compliance with ethical standards

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