



A Comprehensive Review on CO₂ Capture Technologies: Principles, Progress, and Prospects

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Abstract

The rapid increase in atmospheric CO₂ due to fossil fuel combustion has intensified the need for efficient carbon capture strategies. This review provides a comprehensive assessment of current CO₂ capture technologies, including post-combustion, pre-combustion, and oxy-fuel combustion processes [1–4]. It critically evaluates chemical absorption using amines [2,5], physical adsorption [6], membrane separation [7], cryogenic methods [8], and emerging techniques such as metal–organic frameworks (MOFs) [9] and ionic liquids [10]. Each method is analyzed for efficiency, energy consumption, scalability, and environmental impact. The paper also highlights the techno-economic challenges and future directions for sustainable and scalable CO₂ mitigation [11].

Keywords: CO₂ capture, chemical absorption, adsorption, membrane separation, MOFs, carbon mitigation, energy efficiency

1. Introduction

The intensification of global climate change is largely driven by anthropogenic greenhouse gas (GHG) emissions, with carbon dioxide (CO₂) accounting for approximately 76% of global GHG emissions [1]. The primary contributors to CO₂ emissions are fossil-fuel-based power plants, cement manufacturing, steel production, and other energy-intensive industries [2]. According to the International Energy Agency (IEA), annual CO₂ emissions surpassed 36.8 billion tonnes in 2023, and without mitigation, this figure is expected to rise steadily [3].

To meet the Paris Agreement targets of limiting global warming to well below 2°C, the deployment of carbon capture, utilization, and storage (CCUS) technologies is imperative [1,4]. CO₂ capture is the first and most critical step in the CCUS value chain and involves isolating CO₂ from gaseous streams before it can be emitted into the atmosphere.

Why CO₂ Capture?

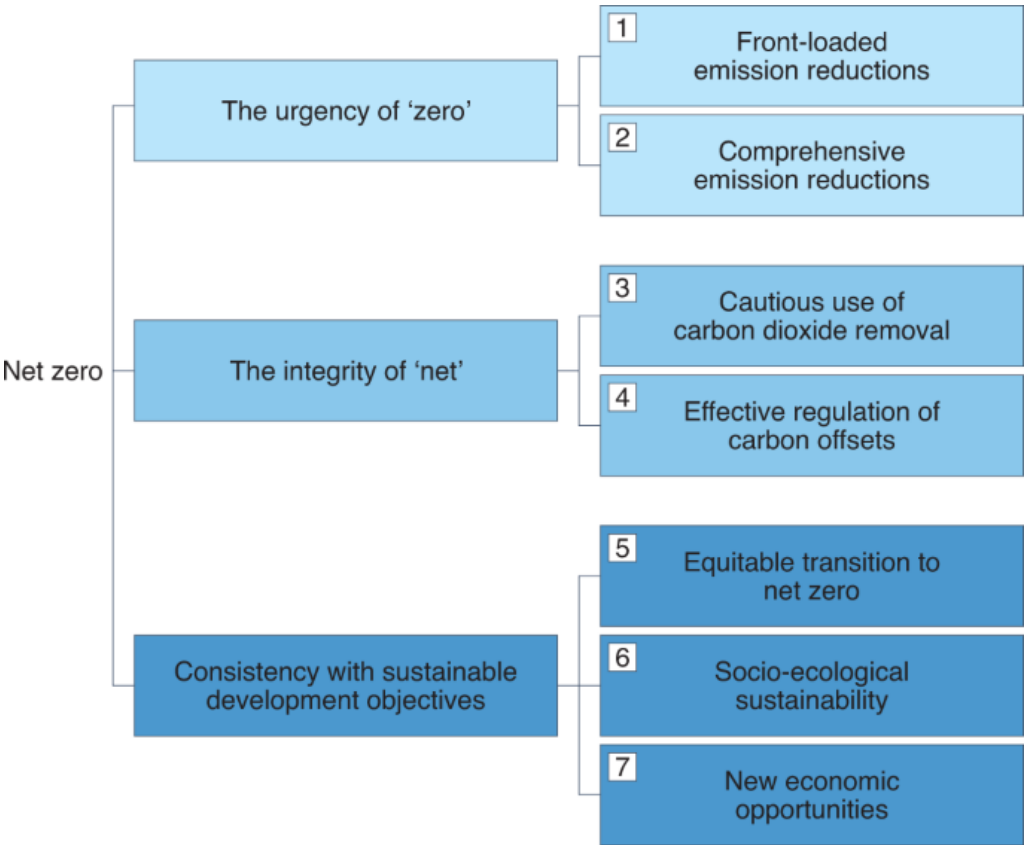
- Enables retrofitting of existing fossil-fuel-based infrastructure.
- Essential for "hard-to-abate" sectors like cement and steel.
- Bridges toward carbon neutrality, especially when integrated with renewable energy or bioenergy (BECCS) [5].

Table 1: Global CO₂ Emissions by Sector (2023)

Sector	% Contribution to CO ₂ Emissions
Power Generation	42%
Industry (cement, steel)	23%
Transport	15%
Residential & Commercial	10%
Agriculture & Others	10%

Source: International Energy Agency, 2024 [3]

Figure 1: Carbon Capture in the Context of Net-Zero Goals (Insert a flowchart showing: energy generation → CO₂ emission → Capture → Utilization/Storage → Climate Impact Reduction)



Scope of the Review This review paper presents a comprehensive assessment of CO₂ capture technologies, focusing on their classification, operational principles, efficiency, scalability, and economic feasibility. It covers:

- Post-combustion, pre-combustion, and oxy-fuel combustion
- Chemical absorption, physical adsorption, membrane separation, cryogenic methods, and advanced materials
- Emerging trends such as MOFs, ionic liquids, and hybrid processes

This paper aims to serve as a decision-support tool for researchers, policymakers, and engineers by identifying key research gaps, techno-economic challenges, and future directions for sustainable implementation.

Key Review Objectives:

1. Compare current and emerging CO₂ capture technologies.
2. Identify material and energy efficiency bottlenecks.
3. Analyze cost and environmental impacts.
4. Highlight advancements in simulation and integration techniques.

2. Classification of CO₂ Capture Technologies

CO₂ capture techniques can be classified as follows:

2.1 Post-Combustion Capture

Occurs after fossil fuels are burned. CO₂ is separated from flue gases. Common in retrofitting existing plants.

- **Technology:** Amine-based chemical absorption (e.g., MEA)
- **Advantage:** Compatibility with existing infrastructure
- **Limitation:** High energy penalty due to solvent regeneration [2]

2.2 Pre-Combustion Capture

CO₂ is removed before combustion by gasifying the fuel to produce a synthesis gas (CO + H₂), which is then shifted to CO₂ + H₂.

- **Technology:** Physical solvents like Selexol, Rectisol
- **Advantage:** High CO₂ concentration stream, energy-efficient
- **Limitation:** Not suitable for retrofitting [3]

2.3 Oxy-Fuel Combustion

Fuels are combusted in pure oxygen instead of air, resulting in a flue gas rich in CO₂ and H₂O.

- **Advantage:** Easier CO₂ purification
- **Limitation:** Expensive air separation unit [4]

3. Capture Techniques

3.1 Chemical Absorption

Most mature method using alkanolamines like monoethanolamine (MEA).

- **Reaction:** $\text{CO}_2 + \text{RNH}_2 \rightleftharpoons \text{RNHCOO}^- + \text{H}^+$
- **Drawbacks:** Corrosion, solvent degradation, high energy use [2]
- **Improvement:** Use of mixed amines, novel solvents like AMP and MDEA [5]

3.2 Physical Adsorption

Uses solid sorbents such as zeolites, activated carbon, MOFs.

- **Advantages:** Regenerable, low energy input
- **Challenges:** Moisture sensitivity, low selectivity at high temperature [6]

3.3 Membrane Separation

Employs polymeric or inorganic membranes to separate CO₂.

- **Types:** Dense polymeric, mixed matrix membranes
- **Advantages:** Compact, modular design
- **Drawbacks:** Low selectivity, membrane fouling [7]

3.4 Cryogenic Distillation

Separates CO₂ by liquefying it at low temperatures.

- **Advantage:** High purity
- **Limitation:** Energy-intensive cooling required [8]

3.5 Emerging Techniques

- **MOFs:** Porous crystalline materials with high surface area and tunability [9]
- **Ionic Liquids:** Non-volatile, thermally stable solvents with tunable properties [10]

4. Techno-Economic Analysis

The techno-economic viability of CO₂ capture technologies hinges on capital investment, energy consumption, and long-term operational costs. Understanding levelized cost of CO₂ captured (LCOC), payback periods, and return on investment is essential for large-scale deployment [21,27].

Table 4: Techno-Economic Performance of Selected CO₂ Capture Technologies

Technology	LCOC (\$/ton CO ₂)	Energy Penalty (%)	Maturity Level	Reference
MEA Absorption	60–90	25–30	Commercial	[27]
Oxy-fuel Combustion	50–80	20–25	Pilot Scale	[28]
Membrane Separation	40–70	15–20	Emerging	[29]
Solid Sorbents (MOFs)	30–60	10–15	Lab/Pilot	[30]
Cryogenic Separation	80–120	30–40	Demonstration	[31]

- *Note: Costs vary with scale, location, and feed gas composition.*
- **Figure 2: Flowchart of Techno-Economic Evaluation Process** (*Flowchart depicting: Technology Selection → CAPEX & OPEX Estimation → Energy Analysis → LCOC Calculation → Feasibility Assessment*)

5. Environmental and Operational Challenges

Despite significant advancements, several environmental and operational challenges hinder large-scale adoption of CO₂ capture technologies:

- **High Energy Penalty:** Most capture systems (e.g., amine scrubbing) require significant energy for solvent regeneration, increasing overall process inefficiency [22].
- **Corrosion and Material Degradation:** Chemical absorbents like monoethanolamine (MEA) can corrode equipment and degrade over time, leading to higher operational costs and frequent maintenance [23].
- **Waste Management:** Spent solvents and solid adsorbents require environmentally safe disposal or recycling, which remains a poorly addressed area [24].
- **Water Usage:** Solvent-based systems consume large volumes of water, posing problems in arid regions or where water stress is high [25].
- **Process Complexity:** Integrating CO₂ capture into existing industrial systems increases design complexity and requires customized retrofitting [26].

Table 3: Summary of Environmental and Operational Issues

Issue	Impact	Reference
Energy Consumption	Reduces net power plant efficiency	[22]
Corrosion	Increases capital and maintenance costs	[23]
Waste Management	Hazardous by-products pose disposal challenges	[24]
Water Usage	High demand in solvent regeneration processes	[25]
Integration Complexity	Difficult to retrofit older systems without major upgrades	[26]

Addressing these challenges through technology optimization, robust material development, and integrated process modeling is crucial for commercial viability and long-term environmental sustainability.

6. Future Perspectives and Recommendations

The future of CO₂ capture lies in overcoming current technological, economic, and environmental barriers. Innovations in material science (e.g., amine-functionalized MOFs, hybrid membranes), machine learning-based process optimization, and renewable-powered regeneration systems will be key [16,17]. Policy interventions such as carbon taxation and investment in demonstration projects can catalyze industrial deployment [18]. Integration with hydrogen production and bioenergy systems (BECCS) also holds significant potential.

Table 2: Recommendations for Scaling Up CO₂ Capture Technologies

Focus Area	Recommendation
Material Innovation	Develop low-energy, high-selectivity sorbents and membranes [17]
Process Efficiency	Use AI and digital twins for dynamic optimization [19]
Integration	Combine capture with H ₂ , BECCS, and renewables [20]
Policy & Economics	Introduce carbon pricing, subsidies, and investment support [18]
Techno-Economic Analysis	Establish global benchmarks for LCA and cost-effectiveness [21]

By implementing these strategies, CO₂ capture technologies can move from pilot-scale to full industrial integration, ensuring a critical role in global decarbonization efforts.

7. Conclusion

CO₂ capture technologies have become a pivotal focus area in addressing climate change and meeting global decarbonization goals. Among the various approaches, chemical absorption—particularly using amine solvents—remains the most mature and widely applied technology for post-combustion scenarios [2,5]. However, its high regeneration energy, solvent degradation, and corrosion issues necessitate improvements or alternative methods [5,11].

Emerging technologies such as **metal–organic frameworks (MOFs)** and **ionic liquids** present promising avenues due to their high selectivity, tunable properties, and lower environmental impact [9,10]. **Membrane-based separation** also shows potential for compact and modular applications but still faces challenges in permeability and fouling [7].

The **integration of capture systems with renewable energy sources** (e.g., solar-assisted regeneration or hybrid systems using waste heat) could significantly reduce the energy penalty associated with current techniques [11]. Moreover, the **development of carbon capture and utilization (CCU)**, where captured CO₂ is converted into fuels, chemicals, or construction materials, offers an economically viable alternative to long-term geological storage [11].

From a policy and economic standpoint, there is an urgent need for:

- Incentivized deployment through **carbon pricing mechanisms**
- Investment in **pilot-scale demonstration projects**

- Standardization of **life-cycle assessments (LCA)** and **techno-economic analysis (TEA)** for benchmarking technologies [1,11]

In conclusion, while no single technology currently meets all industrial, economic, and environmental criteria, a **hybrid and multi-disciplinary approach**—integrating advances in materials science, process engineering, and renewable integration—will be key to realizing scalable, sustainable CO₂ mitigation strategies in the near future [6,9,11].

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