

Negative-carbon electrochemical CO₂ capture technology powered by green electricity

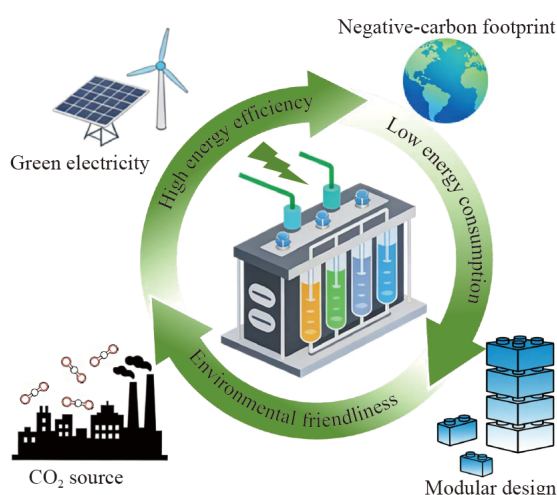
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Abstract: The declining costs of renewable energy are progressively improving the economic viability of employing electrochemical techniques for carbon dioxide capture. Electrochemical carbon capture (ECC) technology utilizes electrical energy to drive electrode reactions, enabling the selective separation of CO₂. The vigorous development of ECC powered by renewable energy offers a promising alternative route to conventional carbon capture methods, overcoming limitations associated with thermally driven capture and release cycles. This approach provides a promising alternative route that is more efficient, flexible, scalable, low-energy-consuming and low-polluting for traditional carbon capture technologies. This review begins by introducing established, large-scale carbon capture technologies, such as pre-combustion capture, post-combustion capture, oxy-fuel combustion, adsorption, membrane separation and the calcium looping process. It then transitions to several rapidly developing ECC technologies, including electrochemically mediated amine regeneration (EMAR), pH-swing-mediated systems, and methods involving redox-active molecules. The pH-swing systems are further categorized into bipolar membrane electrodialysis (BMED), proton-coupled electron transfer (PCET), and membrane capacitive deionization (MCDI). For each method, the underlying principles, technological advancements, advantages, as well as current problems and challenges, are systematically elucidated. It is anticipated that with the widespread deployment of green electricity and persistent innovation in electrochemical materials, ECC technology will emerge as a highly efficient and low-carbon strategy, contributing significantly to the global goal of achieving carbon neutrality.

Key words: carbon capture technologies; electrochemical carbon capture; renewable energy; catalysts



Economic development has driven a surge in energy demand and extraction, leading to concomitant issues of pollution emissions, most notably carbon emissions. In 2024, global energy-related carbon dioxide (CO₂) emissions reached a record high of 37.8 billion tons, reflecting a growth rate of 0.8%. This increase in total emissions contributed to an atmospheric CO₂ concentration of 4.225×10^{-4} in 2024, a rise of approximately 3×10^{-6} compared to 2023, and 50% higher than pre-industrial levels^[1]. The accumulation of CO₂ intensifies the greenhouse effect,

resulting in ecological challenges such as sea-level rise and an increased frequency of natural disasters. Over the past decades, numerous policies have been implemented to mitigate atmospheric CO₂ levels, including the substitution of fossil fuels with renewable energy^[2], and enhancing efficiency in chemical production and energy usage. In such context, Carbon Capture, Utilization and Storage (CCUS), recognized as a sustainable technology^[3], represents one of the most critical measures for the urgent reduction of CO₂ emissions. The International Energy Agency and the

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Intergovernmental Panel on Climate Change (IPCC) have evaluated the global emission reduction potential of CCUS. To achieve nearly net-zero emissions by 2070, CCUS is projected to contribute to mitigating approximately 15% of cumulative emissions. By 2100, the target of 1.5 °C temperature rise control is to be achieved, and the global CCUS will cumulatively reduce 5.5×10^{11} to 1.017×10^{12} tons of CO₂. Under carbon neutrality scenarios, the European Union and its member states are committed to decarbonizing their economy by 2050^[4], and China has announced its ambition to achieve carbon neutrality by 2060, with an estimated CCUS capture capacity of around 1.6×10^9 t of CO₂. Addressing ecological and environmental issues necessitates a concerted global effort, no nation can remain on the sidelines.

Although conventional carbon capture methods, such as post-combustion capture, pre-combustion capture, and oxy-fuel combustion, have become increasingly mature, they are still plagued by critical challenges including high energy consumption, poor economic viability, limited system flexibility, and high integration complexity. With the continuous increase in the scale of renewable energy power generation, the cost of electricity has decreased accordingly. As such, innovative, low-energy consumption and low-cost carbon capture approaches are regarded a key to mitigate the current climate crisis. In some scenarios, these novel approaches can complement or even replace traditional capture technologies. Among these approaches, electrochemical carbon capture (ECC), powered by renewable energy electricity, has emerged with significant potential.

1 Conventional carbon capture technologies

Conventional carbon capture technologies primarily include post-combustion capture^[5], pre-combustion capture^[6], oxy-fuel combustion capture^[7], and direct air capture (DAC)^[8]. Unlike the first three CO₂ capture technologies, DAC is a representative “negative emission” technology where chemical sorbents selectively react with and capture CO₂, directly removing it from the ambient air *via* chemical processes. It has garnered significant attention due to advantages such as flexible deployment and easy of transport. The concept of DAC was first proposed by Lackner et al.^[9] in 1999. Over the subsequent 26 years, DAC technology has emerged as an innovative pathway for addressing climate change and achieving carbon mitigation, demonstrating significant potential and accumulating a substantial body of theoretical knowledge and practical experience. However, due to the low concentration of CO₂ in the air, the cost of DAC remains extremely high, and most of its applications are still in early-stage development.

Since the 1930s, amine-based solvent absorption has emerged as the most mature capture process^[10], featuring high capture efficiency (>90%) and strong processing capacity. Furthermore, it also holds significant application

value at low CO₂ partial pressures, capable of capturing various acid gases (including CO₂, NO_x, and SO_x) from flue gas while simultaneously producing valuable by-products^[11]. Its primary drawbacks, however, lie in the high energy penalty required for solvent regeneration and the potential environmental impacts associated with solvent degradation. Substantial research efforts have been devoted to addressing these issues. To mitigate the high energy consumption for regeneration, solid or liquid absorbents have been proposed, with some showing preliminary success^[11–14]. Nonetheless, most of these materials still rely on complex or costly operations based on temperature or pressure swings. Regarding solvent degradation, Lepaumier et al.^[15] investigated amine degradation mechanisms through both thermal and oxidative degradation pathways, evaluating the degradation of 12 different amines, including ethanolamines and ethylenediamines, under CO₂-rich conditions. The corresponding experimental results indicated that cyclic primary and tertiary amines with greater steric hindrance showcase higher stability. In contrast, compounds containing the –NH–CH₂–CH₂–NH– moiety tend to form significant quantities of imidazolidinones, thereby reducing absorption efficiency. By establishing relationships between molecular structure and degradation performance, this study provides a framework for predicting the relative chemical stability of amines under CO₂ capture conditions and the nature of their degradation products. It suggests that modifying the amine molecular structure (e.g., introducing steric hindrance, hydroxyl groups, or cyclic structures) can enhance degradation resistance, offering a theoretical foundation for developing more efficient and stable absorbents. Despite extensive efforts to optimize absorbent performance, the economic viability of carbon capture is still hampered, primarily due to the high energy consumption of the desorption process and the substantial costs associated with the adsorption process^[16]. For instance, costs for solid adsorbents and the KOH–Ca looping process can range from 100 to 1350 USD per ton of CO₂ captured.

Beyond the aforementioned amine scrubbing, other mature, non-electrochemical CO₂ capture technologies—such as pre-/post-combustion capture, oxy-fuel combustion, adsorption, membrane separation, and the calcium looping process—have been widely implemented. Pre-combustion capture refers to a technology where, prior to the combustion and utilization of fuel, the fuel is converted into a syngas containing CO and H₂ through gasification (for coal) or reforming (for natural gas). Subsequently, the CO is converted to CO₂ *via* the water-gas shift reaction, resulting in a high-concentration CO₂/H₂ gas mixture (with a CO₂ concentration of approximately 15%–40%). Finally, CO₂ is separated using methods such as physical absorption (e.g., low-temperature methanol washing) or pressure swing adsorption (PSA), and the remaining H₂ can be used as a clean fuel. Post-combustion capture involves treating the flue gas exhausted after fuel combustion (with a CO₂ concentration of approximately 10%–15%, predominantly

composed of N₂) by first removing impurities such as dust and SO₂ through pretreatment, followed by introducing it into a capture system. CO₂ is selectively separated from the flue gas *via* chemical absorption (e.g., amine solution absorption), physical adsorption, or membrane separation. The purified exhaust gas is discharged in compliance with standards, while the captured CO₂ is stored or utilized after desorption and purification. This technology stands out as the most mature and widely adaptable capture method. Oxy-fuel combustion is a technology that uses pure oxygen or high-concentration oxygen (O₂ content > 80%) instead of air as the combustion aid, combined with flue gas recirculation technology. This enables the fuel to produce high-concentration CO₂ flue gas after combustion. High-purity CO₂ can be obtained directly through condensation and dehydration, eliminating the need for complex separation steps and thereby simplifying the capture process.

Adsorption is a physical or chemical capture technology that achieves the separation and enrichment of CO₂ through an “adsorption-desorption” cycle. It utilizes adsorbents with high specific surface area and selectivity (e.g., activated carbon, molecular sieves, and MOFs materials) to selectively adsorb CO₂, while other gases (e.g., N₂, H₂) pass through. Subsequently, the adsorbent is desorbed by temperature swing adsorption (TSA), pressure swing adsorption (PSA), or purging, to release high-concentration CO₂, and the adsorbent is regenerated for cyclic use. Membrane separation is a physical separation technology that leverages the selective permeability of polymer or inorganic membranes. By applying a pressure difference

across the membrane as the driving force, it achieves the separation of CO₂ from other gases based on the difference in permeation rates of different gas molecules. Calcium looping, also known as calcium-based adsorbent cyclic capture technology, is a method for CO₂ capture and immobilization based on the reversible cyclic reaction of carbonation-calcination of calcium-based oxides (e.g., CaO). In the first stage (carbonation), the calcium-based adsorbent (CaO) reacts with CO₂-containing gas at 600–700 °C to form stable calcium carbonate (CaCO₃), realizing CO₂ capture. In the second stage (calcination), CaCO₃ is fed into a calciner and thermally decomposed at 900–1000 °C to release high-concentration CO₂ (purity > 95%), while regenerating the CaO adsorbent, which is then recycled back to the carbonation stage for reuse. Although these technologies have achieved industrial-scale application, they still suffer from critical limitations, including high energy consumption, poor economic viability, material performance constraints, and high system integration complexity. Their descriptions, respective advantages, and current challenges are summarized in Table 1. With societal advancement and the increasing utilization of renewable electricity, electrochemical carbon capture (ECC) technology is poised to become a core solution for next-generation carbon capture, offering distinct advantages such as low energy consumption, high energy efficiency, flexible modular design, and environmental friendliness. The figure below (Figure 1) compares the advantages and disadvantages of direct electrochemical carbon capture with those of conventional methods.

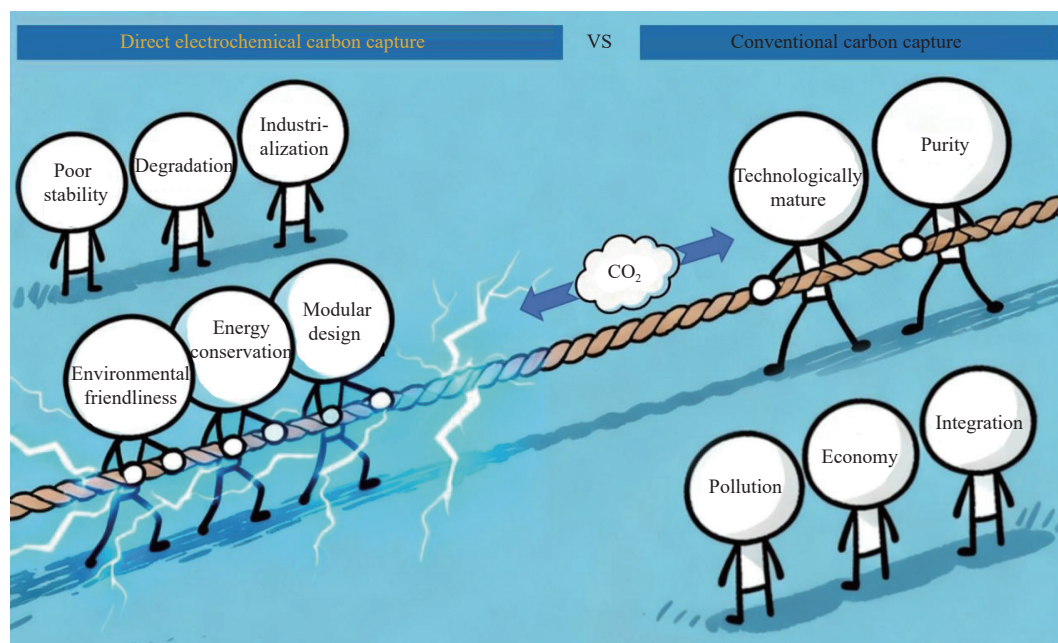


Fig. 1 Comparison of the advantages and disadvantages between direct electrochemical carbon capture and conventional carbon capture

2 Electrochemical carbon capture technologies

“Negative carbon” in electrochemical CO₂ capture refers

to the process of net removal of CO₂ from environmental reservoirs such as the atmosphere and oceans through green electricity-driven systems, followed by permanent

sequestration or low-carbon resource utilization, ultimately reducing atmospheric CO₂ concentration over the full life cycle of the technology. Electrochemical Direct Air Capture (DAC) technologies (e.g., quinone-based redox systems, capacitive deionization-based capture) separate and immobilize free CO₂ in the atmosphere *via* highly selective adsorption/electrochemical conversion, equivalent to directly “extracting” already emitted CO₂ from the environment, thus representing a typical “negative carbon operation.” The use of electrochemical methods for CO₂ capture dates back to the late 1960s, when a research and development team at TRW Inc. in the United States proposed a two-stage electrochemical cell system. This system first employed an alkaline electrolyte (K₂CO₃) to

simultaneously transfer CO₂ and O₂. The CO₂ was carried by HCO₃⁻/CO₃²⁻ migration, while O₂ was carried by OH⁻ migration. In this system, was first used, with CO₂ transported *via* and O₂ migrate *via* OH⁻. In the second-stage development, an acidic electrolyte (H₃PO₄) was employed to reduce O₂ to H₂O at the cathode, yielding high-purity CO₂ (97%–98%). This electrochemical carbon capture system demonstrated excellent long-term stability, energy efficiency, and integrability, establishing itself as a viable solution for CO₂ management in enclosed environments^[17–18]. Currently, electrochemical CO₂ capture methods are versatile, capable of treating gas streams of virtually any CO₂ concentration, with demonstrated use in direct capturing from air, seawater, and flue gases^[19–21].

Table 1 Non-electrochemical carbon capture methods^[6,22–28]

Capture method	Description	Advantage	Problem and challenge	Example
Post-combustion carbon capture	Post-combustion capture refers to the process of capturing CO ₂ from the flue gas produced by fuel combustion. It is widely recognized as the technology with the greatest near-term potential for mitigating CO ₂ emissions	• The technology is mature and has reached commercial deployment • It allows for high-purity CO₂ recovery, making it suitable for separating high-concentration CO₂ streams • It requires minimal modifications to existing infrastructure	• Treatment of impurities in the flue gas • Gas treatment from a large volume of fossil fuel power plants • The partial pressure of CO₂ in the flue gas • The temperature of the incoming flue gas stream • The targeted efficiency for CO₂ removal • The intended end-use of the captured CO₂ • Solvent loss due to volatility and thermal/chemical degradation, which leads to equipment corrosion and negative environmental impacts from solvent emissions	[24]
Pre-combustion capture	Pre-combustion capture involves the separation of CO ₂ from syngas streams prior to fuel combustion and power generation. This approach is particularly suitable for Integrated Gasification Combined Cycle (IGCC) power plants. In this process, fuel first undergoes gasification to produce syngas primarily composed of carbon monoxide (CO) and hydrogen (H ₂). Subsequently, CO in the gas stream is converted to CO ₂ and then separated from the system, while the remaining hydrogen-rich stream serves as a clean fuel source for energy production	• Low separation difficulty • Low cost	• The syngas stream must undergo drying prior to CO₂ capture • For non-gaseous feedstocks (e.g., coal or crude oil), the syngas requires cleaning due to impurities originating from the gasified materials • IGCC systems are associated with substantial capital investment and operational costs • Retrofitting this technology into existing power plants is both cost-prohibitive and technically challenging	[6]
Oxy-fuel combustion capture	Oxy-fuel combustion capture is a process specifically designed for systems where CO ₂ is generated during combustion. In this approach, fuel is burned in pure oxygen rather than air, producing a flue gas characterized by high CO ₂ concentration and absence of nitrogen-based pollutants	• Rapid and secure combustion process • Exceptionally high CO₂ concentration in the combustion products	• Substantial energy cost for oxygen production • High susceptibility to air in-leakage within the system • Greater challenges in retrofitting existing infrastructure compared to post-combustion capture • Requirement for specialized materials resistant to high flame temperatures	[25]

Table 1 Non-electrochemical carbon capture methods^[6,22–28] (continued)

Capture method	Description	Advantage	Problem and challenge	Example
Adsorption	This process involves the adsorption of gaseous CO ₂ onto solid materials, with recovery achieved <i>via</i> desorption driven by temperature, pressure, or vacuum swings	• The equipment is simple and the automatic operation is reliable • Adsorbents are diverse in types, low in cost and easy to regenerate • Effective for capturing low-concentration CO₂	• Requires pretreatment of flue gas to remove impurities such as NO_x, SO_x, and H₂O, as well as to lower the gas temperature • Gradual loss of adsorption capacity in the adsorbent following desorption cycles • Degradation of the adsorbent during cyclic operation	[26]
Membrane gas separation	This process is driven by the partial pressure difference of the gas molecules to be separated. Separation occurs as molecules permeate through the membrane based on their size, diffusivity, and solubility	• Compact and simple design with a small area • Low operating costs and minimal energy consumption	• Limited effectiveness for gas streams with low CO₂ partial pressure and concentration • A large membrane surface area is required to accommodate the high flow rates of industrial flue gases • Susceptibility to humidity variations • Current research is focused on developing novel membrane materials with high selectivity and permeability	[27]
Calcium looping	This process represents a variation of chemical looping (combustion) that involves carbonation and calcination reactions. In oxy-fuel combustion applications, metal oxide carriers such as CuO, Mn ₂ O ₃ , NiO, and Fe ₂ O ₃ are utilized in place of O ₂	• Low cost and wide availability • High thermal storage density	• The CO₂ capture capacity of the sorbent (limestone) deteriorates rapidly after multiple reaction cycles • Environmental concerns arise from limestone mining and the disposal of waste materials (spent CaO) • High-temperature operation • An air separation unit is necessary to supply pure oxygen for the calcination step	[28]

Compared to conventional CO₂ capture technologies, electrochemical CO₂ capture offers practical advantages: it typically requires no additional thermal input, high-pressure, or vacuum conditions during operation, and the adsorbing materials resist degradation. Furthermore, it can be readily integrated into existing operational processes^[29]. Such attributes makes this technology highly suitable for real-world applications^[30].

Common ECC methods mainly include: (1) Electrochemically Mediated Amine Regeneration (EMAR): First proposed by Stern et al.^[31] in 2013, EMAR is a hybrid technology that integrates an electrochemical process with traditional amine-based carbon capture. Similar to thermally driven post-combustion methods, it employs amines to capture CO₂^[32]. (2) pH-Swing-Mediated Systems: These systems utilize electrochemical reactions to alter the pH within an aqueous electrolyte or across ion-exchange membranes. The resulting increase or decrease in pH drives carbonation/decarbonation reactions, thereby facilitating CO₂ capture or release^[33]. (3) Methods Involving Redox-Active Capture Molecules: This approach uses the ability of certain redox-active molecules to directly bind or release CO₂ upon a change in their oxidation state, independent of bulk pH swings. The foundational work on such molecules was conducted by DuBois et al. in 1988^[34].

2.1 Electrochemically mediated amine regeneration

Currently, the most mature technology for CO₂ capture is thermal amine scrubbing. Its principle relies on the nucleophilic characteristic of amine compounds to absorb CO₂ from flue gas, followed by a temperature-swing process for solvent regeneration^[33,35]. Notwithstanding the high CO₂ absorption capacity and rapid reaction kinetics are achieved, the commercial application of amine scrubbing suffer from the high energy consumption from solvent regeneration and low absorption efficiency^[36–37]. In contrast, electrochemically mediated amine regeneration (EMAR) systems, which operate near ambient temperature, effectively circumvent thermal degradation issues and demonstrate notable advantages in energy efficiency. The EMAR system is ideally suited for large-scale industrial point source. It can be directly integrated into existing emission infrastructure in settings that demand high-volume CO₂ treatment, such as coal-fired power plants and steel mills. By coupling with grid-connected green electricity or on-site renewable energy sources (e.g., waste heat-powered photovoltaics), it enables low-cost and large-scale carbon capture. To date, the EMAR process is one of the most comprehensively studied electrochemical systems. This system is mediated by copper, facilitating CO₂ release by electrochemically regulating the dissociation of the amine-

CO₂ complex. A typical EMAR process comprises three core units: an absorption column, an electrochemical reactor, and a desorption unit. The desorption reactor, being the core of the entire system, directly influences the overall system performance. As illustrated in Figure 2^[38], the process of an EMAR system consists of two primary stages: (1) chemical absorption of CO₂ from a gas stream using an amine absorbent in the absorption column; and (2) electrochemically driven CO₂ desorption and absorbent regeneration^[39]. The absorption step is analogous to the thermal amine process, however, its desorption mechanism is fundamentally different. Herein, regeneration is driven electrochemically using an electrode assembly where both the anode and cathode are made of metallic copper. Specifically, when the CO₂-rich amine solution enters the electrolyzer, it interacts with copper ions (Cu²⁺) generated from the oxidation of the copper anode. This interaction promotes the release of CO₂. Subsequently, the Cu²⁺ ions in the solution are reduced and deposited onto the cathode surface, thereby regenerating the free amine and recycling the metallic copper.

Fan et al.^[40] conducted a systematic comparison of monoethanolamine (MEA) and ethylenediamine (EDA), the most frequently discussed amines in the EMAR process. Their study revealed that EDA exhibits superior CO₂ absorption performance compared to MEA. Furthermore, the Cu(II)-EDA complex demonstrated higher stability than its MEA counterpart, alongside a lower CO₂ desorption energy of 42.4 kJ/mol. This combined attributes enhance the efficiency of CO₂ release in the EMAR regeneration cycle. Mao et al.^[41] performed a comprehensive investigation of various Cu-polyamine systems. They identified diethylenetriamine (DETA) as an outstanding absorbent for EMAR applications, characterized by high stability, low corrosivity, high CO₂ absorption capacity, and low energy consumption.

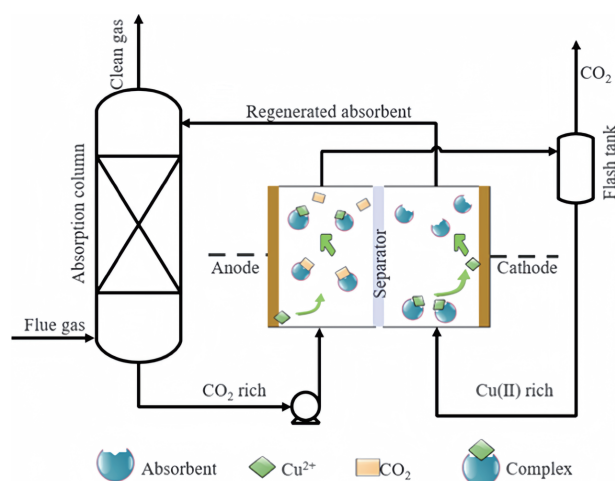


Fig. 2 Schematic diagram of the CO₂ capture process via electrochemically mediated amine regeneration (EMAR)^[38]
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The CO₂ desorption energy for the DETA system was reported to be 36.67 kJ/mol, indicating the potential of EMAR technology for industrial applications.

Despite the promising potential, the practical application of EMAR systems using these absorbents faces several limitations that require further optimization. Notably, research shows that critical challenges related to volatility, corrosivity, and electrode stability can be addressed by introducing additives or mixing absorbent. Rahimi et al.^[42] blended EDA with 2-(2-aminoethylamino)ethanol (AEEA), which has lower vapor pressure but a comparable CO₂ absorption capacity. They found that a 50/50 mixture achieved the lowest energy consumption, approximately 10% lower than pure EDA, while maintaining good stability. In a recent research, Hassan et al.^[39] moved beyond the conventional metal-amine complex limitation, providing new insights into the mechanism of EMAR with mixed amine systems. Their research showed that a mixture of EDA and methyldiethanolamine (MDEA) reduced the charge transfer resistance (R_{ct}) by 40% and increased the heterogeneous electron transfer rate constant by three-times compared to pure EDA. In lab-scale evaluations, the EDA-MDEA mixture achieved a desorption energy of 37 kJ/mol CO₂, representing a 34% reduction compared to the pure EDA system (56 kJ/mol CO₂). This breakthrough offers critical guidance for developing next-generation, low-energy CO₂ capture absorbents. Additionally, the presence of acidic gases like CO₂ and H₂S in natural gas streams poses a challenge for the selective capture of CO₂. Addressing this, de Meyer et al.^[43] proposed an electrochemical regeneration system utilizing EDA as the absorbent and iron as the active electrode. This system enables amine solvent regeneration through electrochemical redox reactions while simultaneously achieving selective CO₂ separation and the direct conversion of H₂S into solid sulfur and hydrogen. This technology allows for the simultaneous treatment of CO₂ and H₂S with 100% separation selectivity, reducing the need for subsequent treatment. Fan et al.^[40] and Mao et al.^[41] sequentially addressed the central question of “which amine solvent enables EMAR to achieve minimal energy penalty, high capacity and long life”. The former established EDA’s comprehensive thermo-electrochemical superiority among mono-amines; the latter demonstrated that among poly-amines, DETA offers the optimal balance of CO₂-displacement efficiency, the lowest desorption energy and acceptable corrosivity, thereby closing the absorbent-selection loop from mono-amine to poly-amine.

Although the EMAR system has been extensively studied, it is still in laboratory-scale operation. Currently reported systems typically suffer from low operating current densities and poor long-term electrode stability. Moreover, the internal resistance within the reactor leads to an energy consumption for CO₂ capture that far exceeds the theoretical value.

2.2 pH-swing-mediated systems

By cycling solution pH, the pH-swing-mediated system drives CO₂ captures and releases and manipulates the carbonate equilibrium. In aqueous systems, pH is the primary determinant of CO₂'s thermodynamic equilibrium. Under acidic conditions, CO₂ tends to remain molecular form. As pH increases, the equilibrium progressively shifts towards bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions^[44]. This pH-dependent speciation forms the fundamental underlying pH-swing CO₂ capture systems. This approach represents a promising electrochemical CO₂ capture technology due to its operational simplicity, absence of toxic or expensive chemicals, and ability to function at ambient temperatures. Inexpensive, non-toxic, non-corrosive, and non-volatile salt solutions such as NaCl, KCl and KHCO₃ can be employed in this process. This method is applicable to the flexible capture of industrial point sources with medium-to-high CO₂ concentrations, such as blast furnace gas from steel mills, kiln tail flue gas from cement plants, chemical synthesis off-gases, landfill gas, and anaerobic digestion gas from livestock and poultry breeding. The precise regulation of pH enables compatibility with various capture agents (e.g., amines, carbonates), allowing flexible adjustment of the system according to flue gas compositions. Additionally, it can be employed in clustered food fermentation plants and breweries. This system eliminates the need for high-pressure equipment, offers high operational safety, and enables the centralized treatment of scattered emissions from multiple small-scale enterprises. Furthermore, the captured high-purity CO₂ can be recovered for food preservation and carbonated beverage production, thereby

realizing a synergistic integration of emission reduction and resource recovery. The required pH swing can be achieved through various reactions, including electrolysis, bipolar membrane electro dialysis (BPMED)^[45–46], proton-coupled electron transfer (PCET), and membrane capacitive deionization (MCDI).

Taking the MCDI system as an example, CO₂ enters the system in the form of carbonic acid. During the charging and discharging cycles, protons (H⁺) and bicarbonate/carbonate ions (HCO₃⁻/CO₃²⁻) are adsorbed/desorbed on porous electrodes through cation exchange membranes (CEMs) and anion exchange membranes (AEMs), respectively. This ion removal perturbs the reaction equilibrium, leading to the absorption or release of CO₂^[47]. Building upon this, Rahimi et al.^[48] introduced a novel method utilizing an electrochemical cell based on proton concentration, which employs manganese dioxide for CO₂ capture (Figure 3(a))^[48]. As shown in Figure 3 (b), the CO₂ desorption energy required for this process is approximately 33.2 kJ/mol CO₂. This value is comparable to the EMAR process (31.3 kJ/mol CO₂) and about 30% lower than that of the MCDI capture system (49 kJ/mol CO₂). This is the first time that proton-embedded electrodes have been adopted to replace the traditional metal dissolution/deposition strategy, segregating the capture and release of carbon dioxide into a reversible pH swing environment. The method provides an amine-free, low-corrosivity, and long-service-life carbonate-proton platform, thereby expanding the industrial application potential of electrochemical CO₂ capture. The following sections will focus on introducing the systems based on BPMED and PCET.

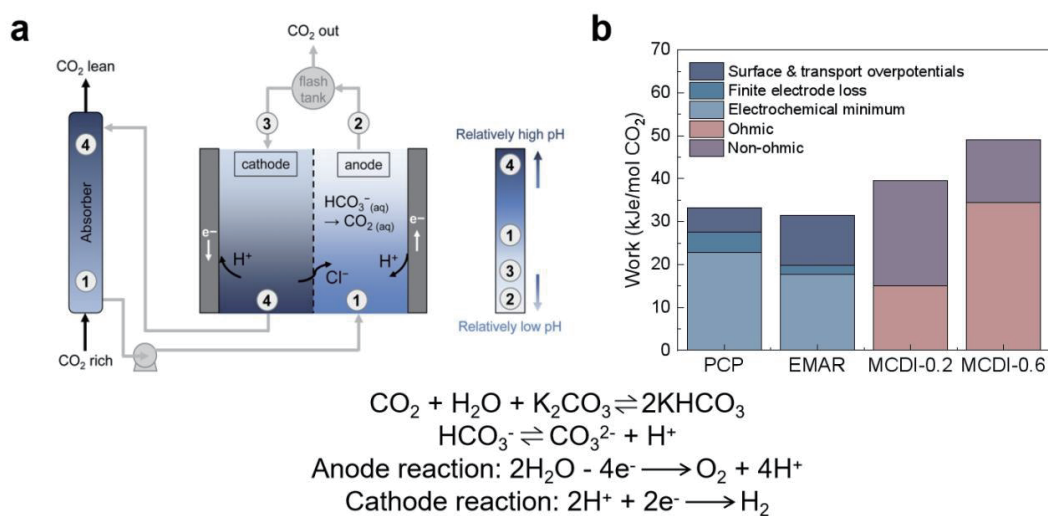


Fig. 3 (a) Schematic illustration of the electrochemical cell for CO₂ capture and release via proton concentration swing (In the absorber, CO₂ is selectively absorbed by a K₂CO₃ solution, with KCl serving as the background electrolyte); (b) Comparison of the energetics for the proton concentration process against other electrochemical CO₂ capture systems^[48]

PCP: Proton Concentration Process, EMAR: Electrochemically Mediated Amine Regeneration,

MCDI: Membrane capacitive deionization.

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2.2.1 Bipolar membrane electrodialysis

Bipolar membranes (BPMs) have demonstrated great potential in fields such as seawater desalination, wastewater treatment, and resource recovery^[49–50]. With continuous advancements in membrane technology, the relevant research and applications have grown increasingly extensive^[51–52]. The integration of bipolar membranes with electrodialysis, known as bipolar membrane electrodialysis (BPMED), exhibits unique advantages for CO₂ capture, particularly in extracting CO₂ from seawater^[53–54]. This process utilizes an electric field to drive water dissociation into OH[−] and H⁺ ions, which are subsequently used for CO₂ capture and release.

Of all the CO₂ emitted, approximately 23% is absorbed by the ocean through a series of chemical reactions, designating it as a massive carbon reservoir. In fact, the ocean holds for more carbon compared to the atmosphere. While the increase in dissolved inorganic carbon (DIC) leads to ocean acidification, it makes the ocean a major potential sink for CO₂ capture. One current strategy to harness this is pH-swing technology. While most research has focused on extracting gaseous CO₂ from acidic gas streams, CO₂ can also be captured and stored in solid form through seawater alkalization. By regulating the pH of seawater, it realizes the net transfer and sequestration of CO₂ between the ocean and the atmosphere, simultaneously achieving negative emissions and mitigating ocean acidification. The captured CO₂ can be directly injected into the deep sea for sequestration *via* subsea pipelines, or converted into bicarbonate minerals for permanent immobilization, exhibiting extremely low carbon leakage risk throughout the entire process. Studies have shown that when pH > pK_{a2}, CO₃^{2−} becomes the dominant species and reacts with dissolved Mg²⁺ and Ca²⁺ ions in water^[55–56]. The concentrations of Mg²⁺ and Ca²⁺ in seawater are far higher than that of DIC, theoretically allowing for the removal of all DIC. However, the ensuing issue of membrane scaling leads to slow reaction kinetics. Zhao et al.^[57] adopted an innovative technique combining a bipolar membrane electrodialysis system with a crystallizer. This system utilizes BPMED to generate base (OH[−]) *in situ* for immediate reaction with CO₂, while the addition of seed crystals to the crystallizer promotes CaCO₃ growth. This strategy reduces supersaturation, minimizes the precipitation of Mg(OH)₂ and CaCO₃ on membrane surfaces, and thus avoids membrane fouling. Recently, Aliaskari et al.^[58] reduced the energy consumption by 20% through the introduction of a novel electrolyte solution, thereby enhancing the efficiency and reducing the cost of the BPMED system in pH-mediated carbon capture.

In addition, differing from systems that rely on natural carbon sources and seawater containing Mg²⁺ and Ca²⁺, Direct Air Capture (DAC) systems face challenges such as high air flow rates and low CO₂ partial pressure (~4.0×10^{−4}), potentially requiring additional energy consumption to facilitate air contact with the electrolyte.

Eisaman et al.^[59] conducted a comprehensive study on CO₂ regeneration from aqueous potassium carbonate/bicarbonate solutions using BPMED. Their system comprised seven cells connected in series, each containing an anion exchange membrane (AEM) and a bipolar membrane (BPM), with electrode compartments at both ends using a 2 mol/L KOH solution as the electrode solution (Figure 4(a))^[59–60]. This system successfully regenerated pure CO₂ from the carbonate/bicarbonate solution with a desorption energy of approximately 100 kJ/mol CO₂. Since capturing CO₂ from the atmosphere into a hydroxide solution requires about 200 kJ/mol CO₂, the entire process demands roughly 300 kJ/mol CO₂. They also observed that in conventional electrodialysis, gas bubble formation on membrane surfaces increases electrical resistance, leading to higher energy consumption and reduced membrane lifespan^[60]. To address this, they proposed a high-pressure BPMED approach. By elevating the system pressure (up to 20 atm), CO₂ remains completely dissolved in the solution, thereby preventing bubble formation, lowering resistance and energy consumption. Performance testing under different current densities (22–139 mA/cm²) and pressures (1.5–10.2 atm) revealed that higher current densities improve CO₂ desorption efficiency. Under high pressure (>6 atm) and high current density (139 mA/cm²), the CO₂ desorption energy consumption was reduced by 29% compared to operation at ambient pressure (Figure 4(b))^[59–60]. This is attributed to the dissolved CO₂ which prevents an increase in resistance and eliminates membrane damage caused by bubble formation. Datta et al.^[61] also explored a method combining *in situ* electrochemical pH control with resin wafer deionization for capturing CO₂ from flue gas. This system utilized a configuration of bipolar and cation exchange membranes, integrated with resin wafers to enhance ion conduction and gas-liquid contact. Electrochemical water dissociation controlled the pH, enabling CO₂ conversion to carbonate/bicarbonate in an alkaline capture chamber. A phosphate buffer (Na₂HPO₄/NaH₂PO₄) neutralized H⁺ ions, maintaining reaction equilibrium. As such, CO₂ capture and release were realized by continuous switching of the solution's pH environment, with carbonic anhydrase added to accelerate reaction kinetics at neutral pH. Using a simulated flue gas (15% CO₂, flow rate 50 sccm per cell pair), a single-pass CO₂ capture efficiency of 80% with a purity >98% was achieved operating at 2.5 A for 6 h. The aforementioned studies address “electrochemical, low-energy regeneration of CO₂ from dilute streams”. Eisaman introduced carbonate–bipolar-membrane electrodialysis to overcome the high thermal demand and bubble-induced resistance of conventional regeneration; pressurization further showed that a “dissolution–release” route lowers energy while protecting membranes. Datta integrated resin-wafer electrodeionization with *in situ* pH swing, combining capture and stripping in one unit and demonstrating that electrochemically generated protons can displace vacuum or steam. Together, they establish pH-swing electrochemistry as a versatile, amine-free, low-temperature platform for modular CO₂ separation.

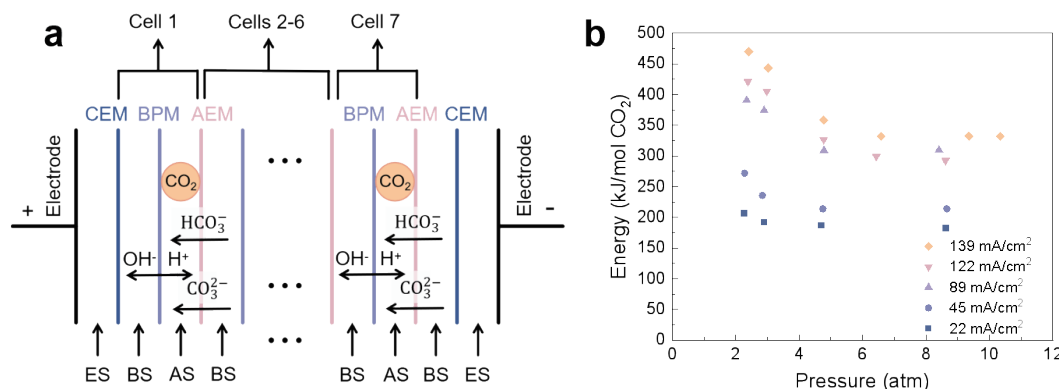


Fig. 4 (a) Schematic diagram of a bipolar membrane electrodialysis (BPMED) system for CO₂ regeneration (ES: Electrode solution (KOH/NaOH); AS: Acid solution (KH₂PO₄ + H₃PO₄); BS: Base solution (mixtures of KHCO₃, K₂CO₃ and KOH); CEM: Cation exchange membrane; AEM: Anion exchange membrane; BPM: Bipolar membrane); (b) Energy (kJ/mol CO₂) as a function of pressure at current densities ranging from 22 to 139 mA/cm², using 0.5 mol/L KHCO₃ as the electrolyte^[59–60] (with permission from Royal Society of Chemistry Publications)

2.2.2 Proton-coupled electron transfer

The synergy between compounds possessing proton-coupled electron transfer (PCET) capability and pH-swing technology has also demonstrated significant promise in the field of electrochemical CO₂ capture. Through electrochemical control, this process modulates the redox state of a mediator and pH swings to facilitate reversible capture and release of CO₂^[32]. An ideal PCET compound should exhibit the following characteristics: (1) high stability of the redox mediator, (2) high solubility under both acidic and alkaline conditions, (3) a substantial pK_a difference between its redox states, and (4) distinct structural differences between the reduced and oxidized states to enable a large amplitude in the pH swing. Currently, widely studied compounds primarily include quinones^[62–63], phenazines^[64–65], inorganic compounds^[48,66], and riboflavin derivatives^[67].

A typical PCET system contains three stages. First, a CO₂-containing gas stream is contacted with an alkaline solution, where CO₂ is captured in the form of dissolved inorganic carbon (HCO₃⁻, CO₃²⁻, CO₂(aq)). Second, an electrical potential is applied to oxidize the mediator, triggering a deprotonation process that locally acidifies the solution. This shifts the carbonate equilibrium, promoting the release of CO₂ gas. Finally, a cathodic potential reduces the mediator to complete the cycle, leading to protonation and regenerating solution alkalinity, which enables subsequent CO₂ capture. Building on this foundation, researchers have explored various compounds.

Watkins et al.^[68] utilized PCET reactions of quinones (e.g., benzoquinone and naphthoquinone) in a two-electrode configuration. A hydrophilic porous polypropylene membrane, forming a supported liquid membrane with an aqueous solution containing the quinone redox couple in a 1 mol/L NaHCO₃ buffer, created a gas-liquid interface. Using platinum/palladium/ruthenium as catalysts, a pH gradient was established across the membrane *via* the redox processes of hydroquinone/benzoquinone and 2,6-

dimethylbenzoquinone/2,6-dimethylhydroquinone, enabling CO₂ separation from flue gas. This study demonstrated electrochemically driven CO₂ capture process using a quinone-mediated PCET mechanism, providing a novel approach for ECC. However, challenges remain regarding the long-term stability of quinone mediators and the optimization of system integration. Addressing such issues, Pang et al.^[69] reported a dual-chamber flow battery based on a phenazine (C₁₂H₈N₂) derivative, using platinum as a catalyst. They used the PCET characteristics of the phenazine derivative to drive pH swings for CO₂ capture and release. The phenazine derivative exhibited ultra-high aqueous solubility (>1.35 mol/L across pH value 0–14) and chemical stability. A 0.1 mol/L solution showed no capacity decay over 550 cycles (16 days), overcoming the challenges of degradation and precipitation common in traditional redox mediators. Furthermore, this system combined efficient CO₂ capture with electrical energy storage, achieving a CO₂ capture capacity of 1.4 mol/L at a 0.8 mol/L mediator concentration, comparable to industrial amine-based methods.

As shown in Figure 5(a)^[70], Huang et al.^[70] employed a three-electrode system with graphite electrodes, using 4,5-dihydroxy-1,3-benzenedisulfonic acid disodium salt (QH₂) as the pH-swing mediator, whose redox reaction alters the solution pH. Na₂Q (prepared from QH₂ and NaOH in a 1:2 molar ratio) hydrolyzes to generate OH⁻. The released ions subsequently react with CO₂ to form HCO₃⁻, effectively promoting CO₂ capture (Q²⁻ + H₂O = QH⁻ + OH⁻; QH⁻ + H₂O = QH₂ + OH⁻; OH⁻ + CO₂ = HCO₃⁻). In the anode compartment, Q²⁻, QH⁻ and QH₂ present in the CO₂-saturated Na₂Q solution are oxidized to Q. This process triggers the release of H⁺ with lower pH, and also leads to HCO₃⁻ decomposition, thus releasing the absorbed CO₂. Finally, in the cathode compartment, Q is reduced back to Q²⁻, restoring the solution alkalinity for subsequent CO₂ absorption. Figure 5(b)^[70] shows that at a current density of 18 mA/cm², the CO₂/Q²⁻ molar ratio approached 1 (in 0.1–0.7 mol/L solutions), indicating highly efficient CO₂ capture capacity.

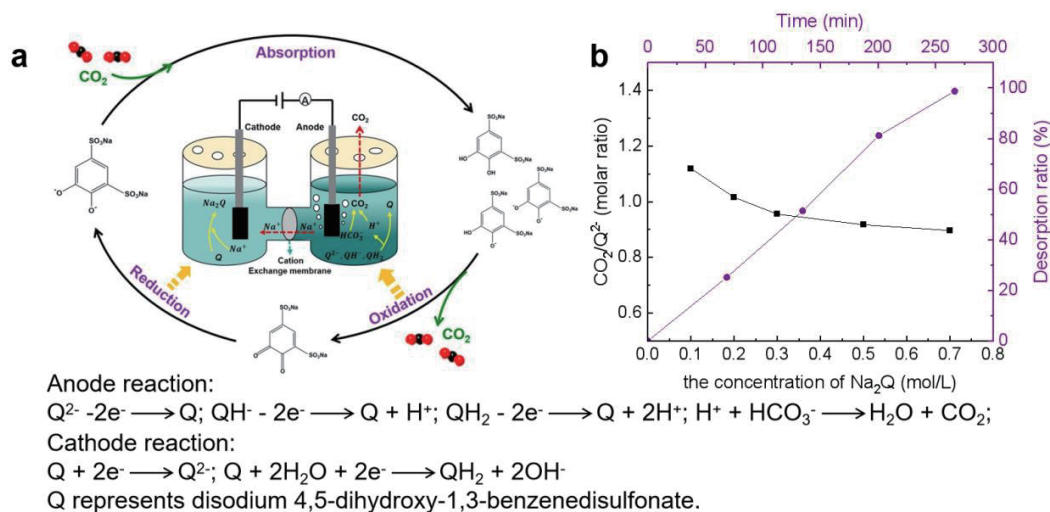


Fig. 5 (a) Schematic diagram of the experimental setup; (b) Molar ratio of CO₂ to Q²⁻ at different Na₂Q solution concentrations and the corresponding CO₂ desorption rate over time^[70]
 (with permission from American Chemical Society Publications)

After 260 min of reaction, with a coulomb number reached approximately 4000 C, the CO₂ desorption rate reached 100%. Because the redox potential of QH₂ lies consistently between the potentials for water oxidation and hydrogen evolution, the system operates without side reactions (such as O₂ or H₂ evolution). This study further demonstrates that a PCET-mediated pH swing enables CO₂ capture and decoupled regeneration under ambient pressure and low temperature. The high aqueous solubility and robust redox reversibility of tiron establish a foundation for closed-loop flow-battery carbon-capture systems, outlining a technical pathway toward industrial-scale, low-energy upgrading and offering a promising alternative to traditional amine-based methods.

2.3 Methods Involving redox-active molecules

In contrast to conventional chemisorption techniques reliant on thermal or pH swings, CO₂ capture using redox-active molecules operates by electrochemically modulating the redox state of a mediator, which then reversibly binds or releases CO₂. In their reduced state (such as radicals or anions), these molecules with strong nucleophilicity transform into stable complexes by combining with CO₂. After oxidation, the density of the molecular electron cloud decreases, weakening its CO₂ binding affinity and thereby triggering CO₂ release. This method is applicable to DAC, such as urban ambient air and confined spaces. Redox-active molecules (e.g., polyanthraquinone) possess specific adsorption capacity for CO₂, enabling highly efficient discrimination between CO₂, N₂ and O₂ even at low concentrations. Additionally, it can be employed for the capture of small-scale, low-concentration CO₂ emission sources, such as laboratories and small commercial buildings. Characterized by a compact volume, flexible start-stop operation, and no risk of chemical agent leakage, the captured CO₂ can be utilized for plant cultivation or

small-scale industrial applications. The redox-active carriers are typically organic molecules with reversible redox properties, among which quinone derivatives represent one of the most prominent classes. It has been reported that quinone compounds can facilitate CO₂ enrichment and selective separation^[21]. This approach is potentially more energy-efficient than traditional temperature- or pressure-swing processes. This efficiency stems from the strong nucleophilicity of the oxygen anions generated upon electrochemical reduction of quinones, which enables effective CO₂ binding—a property that is lost in the oxidized state. Hemmatifar et al.^[71] reported a method leveraging the affinity of redox-active quinones for CO₂ molecules. This design employs a stackable bipolar cell that achieves low-energy, modular CO₂ capture and release driven solely by electrical potential. However, quinones are often sensitive to oxygen, it is necessary to develop oxygen-tolerant electrode materials. Furthermore, the physical dissolution of CO₂ in the electrolyte will influence the dynamic capacity, and its solubility needs to be reduced to enhance mass transfer.

As with most emerging techniques, while research on redox-active molecules has achieved considerable progress at the laboratory scale, their practical application still faces limitations related to solvent systems and carrier materials. Regarding solvent optimization, ionic liquids and salt-concentrated aqueous electrolytes demonstrate great for large-scale application^[21]. Concerning the carrier materials, one approach involves directly immobilizing quinone compounds onto electrodes to form solid-state quinone electrodes for electrochemical CO₂ capture. However, quinones in conventional organic solvent systems often suffer from poor electrochemical cycling stability, leading to capacity degradation. To address this challenge, Voskian et al.^[72] innovatively developed a composite electrode material composed of polyanthraquinone and carbon nanotubes. In the CO₂ capture phase, anthraquinone acquires two electron under a reducing potential, and

simultaneously undergoes a carboxylation reaction with two molecules of CO₂, forming a dicarboxylated anthraquinone anion to achieve CO₂ capture. Ferrocene (Fe) undergoes electron loss in this process (being oxidized to Fe⁺), acting as an electron donor for the reduction reaction of the outer-layer anthraquinone. In the CO₂ release phase, the dicarboxylated anthraquinone anion loses two electrons, and concurrently decomposes with release of two molecules of CO₂, reverting to the initial anthraquinone structure. Fe⁺ undergoes electron acquisition and is reduced to the original ferrocene, accomplishing the electron recycling process. This system maintained over 70% of its initial capacity after 7000 cycles, demonstrating improved stability (Figure 6)^[72]. Furthermore, Clarke et al.^[73] employed thermodynamic modeling to assess the performance limits of soluble redox-active species for CO₂ separation. Their analysis, which considered the influence of tunable molecular and electrolyte properties on both thermodynamic efficiency and Faradaic efficiency, led to the proposal of a new metric—comprehensive efficiency. This work provides a theoretical framework to guide molecular design and electrolyte optimization. To overcome the solubility limitations of quinones in non-aqueous solvents, Lida et al.^[74] synthesized an ion-functionalized quinone derivative. This modification increased its solubility in dimethyl sulfoxide by 360-times. Simultaneously, these quinone

derivatives also function as supporting electrolytes, enhancing ionic conductivity and offering an alternative effective strategy for large-scale CO₂ separation. Nevertheless, the aforementioned polymer electrodes generally face issues such as complex synthesis procedures and the high cost of coupling agents, highlighting the need to develop more novel, easily synthesized, and low-cost quinone-functionalized electrodes. Regarding the integration of quinone-based materials into carbon capture devices, Hartley et al.^[75] proposed a novel electrochemical CO₂ capture method by immobilizing quinone molecules onto porous carbon surfaces *via* a diazonium radical reaction. Their research demonstrated that quinone functionalization significantly enhanced the electrochemical charge storage capacity, improving the CO₂ capture and energy storage capability of the solid-state electrode.

The advantages and deficiencies of several common electrochemical carbon capture methods are briefly summarized in Table 2^[76].

Additionally, a brief comparison has been made between the CO₂ capture efficiency of traditional methods and electrochemical methods (Table 3)^[77–85]. It should be noted that some electrochemical technologies are still in the laboratory or pilot scale, and their practical application performance may vary.

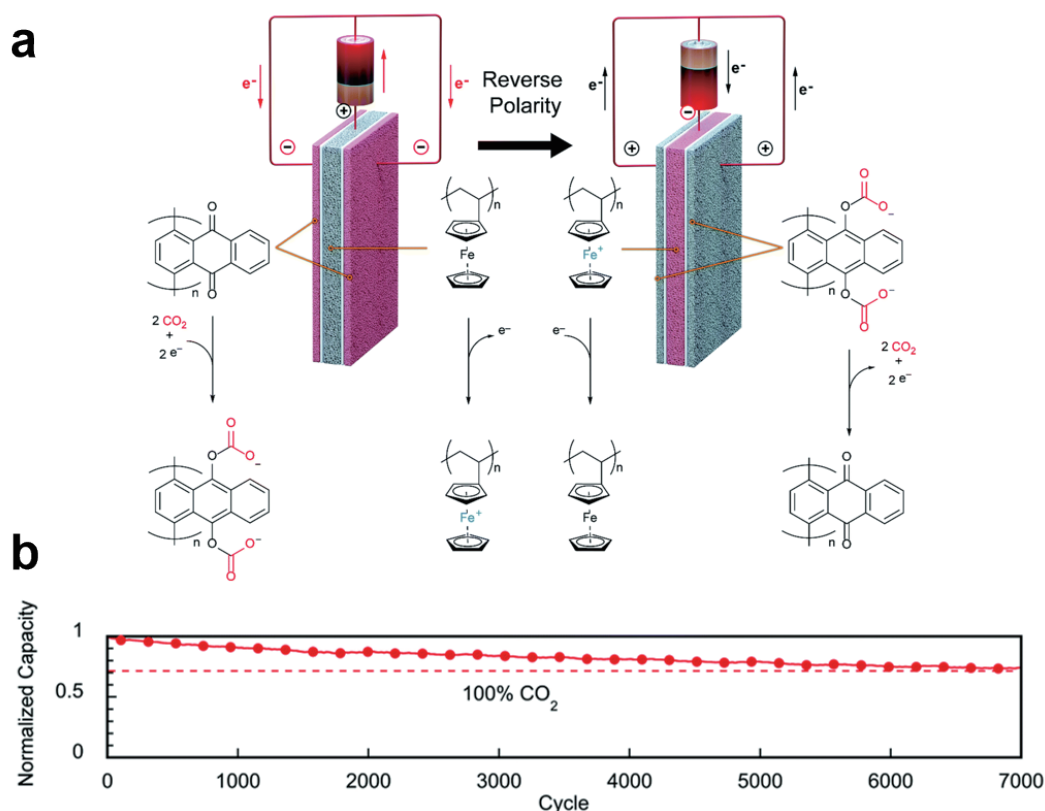


Fig. 6 (a) Schematic diagram of a single-cell swing adsorption electrochemical cell with porous electrodes and an electrolyte separator; (b) Cell capacity retention after 7000 charge-discharge cycles^[72]
(with permission from Royal Society of Chemistry Publications)

Table 2 Electrochemical carbon capture methods^[76]

Capture method	Advantage	Deficiency
Electrochemically mediated amine regeneration	• CO₂ desorption and amine regeneration can be powered by renewable electricity • The energy requirement for CO₂ desorption is comparable to that of conventional thermal swing processes used in amine-based systems • Modular design • It can be incorporated into existing power plants with minimal retrofitting • Oxygen tolerance	• It remains confined to post-combustion CO₂ capture scenarios • Concentration gradients between the bulk solution and the electrode surface can lead to significant transport overpotential • Further research is essential to identify optimal metal-amine combinations for enhanced performance, stability, and energy efficiency • Oxidation by dissolved oxygen electrodeposition/passivation cycles, and degradation of amine absorbents
Bipolar membrane electro dialysis	• It can efficiently capture CO₂ from seawater on a large scale • H₂ is generated at the cathode, promoting the coupling between the capture system and the utilization system	• The energy input required for CO₂ capture from simulated seawater remains exceptionally high • The use of monopolar ion-exchange membranes leads to the problematic scaling of calcium and magnesium on electrode surfaces • Bipolar membranes are susceptible to delamination and increased electrical resistance over prolonged operation • The use of multiple membrane types incurs significant expenses • A lack of experimental research exists utilizing natural seawater within carbonate/bicarbonate buffer systems • Waste management requirement
Proton coupled electron transfer	• Modular scalability • The precisely tunable structures of redox intermediates provide a pathway for optimizing key parameters including redox potential, solubility, stability, scalability, and cost-effectiveness • Mild operating conditions • Rapid kinetics	• Excessive overpotential leads to low CO₂ capture rates • Operation at high current densities results in increased energy consumption • Quinone and phenazine mediators are sensitive to common flue gas impurities such as oxygen • There is a lack of experimental studies on the lifetime and long-term stability of PCET mediators • A shortage of tunable redox sorbents possessing high solubility, processability, and resistance to impurities • Difficulty in effectively fixing tunable redox compounds onto electrode surfaces • Challenging separation of the electrochemical reaction from the absorption process
Methods involving redox-active capture molecules	• Quinone compounds have the effect of enriching and selectively separating CO₂, which is more energy-efficient than conventional thermal or pressure-swing processes	• Significant progress has been achieved only at the laboratory scale • The synthesis of polymer-based electrodes remains complex and relies on costly coupling agents

Table 3 Comparison of CO₂ capture efficiency between traditional methods and electrochemical methods

Capture method	Capture efficiency	Reference
Post-combustion carbon capture	35%–99%	[77]
Pre-combustion capture	85%–90%	[78]
Oxy-fuel combustion capture	70%–90%	[79]
Adsorption	> 85%	[80]
Membrane gas separation	70%–90%	[81]
Calcium looping	65%–85%	[82]
Electrochemically mediated amine regeneration	> 90%	[83]
pH-swing-mediated systems	> 90%	[84]
Methods involving redox-active capture molecules	> 90%	[85]

3 Conclusion and outlook

This review first outlined conventional CO₂ capture methods. While some systems have matured and been deployed, they generally suffer from drawbacks such as high energy consumption, high costs, and complex integration. In contrast, electrochemical CO₂ capture (ECC) technology, as an emerging approach, has garnered widespread attention due to its advantages of high selectivity, modular design, potential for low energy consumption, and compatibility with renewable energy sources. This article systematically reviewed three mainstream ECC technologies and the corresponding research achievements. While these accomplishments provide considerable confidence, they also underscore several scientific challenges, such as the long-term stability of electrode materials, electrolyte degradation, and system scale-up. Although electrochemical methods are still in their early developmental stages, they are expected to evolve into mature, scalable industrial technologies within the next decade. Future development directions are likely to include: (1) Developing highly efficient, low-cost, and stable electrocatalysts and electrode materials to improve capture efficiency and cycling stability. Specifically, the design and synthesis of catalysts should focus on enhancing the density of active sites (e.g., metal single atoms, bimetallic interfaces, or defect-rich carbon matrices) that facilitate the adsorption and activation of CO₂ molecules. For cost reduction, research should prioritize earth-abundant transition metals (e.g., Fe, Co, Ni, Cu) or carbon-based materials as alternatives to scarce noble metals, and explore low-cost precursors and scalable preparation processes (e.g., hydrothermal synthesis, electrospinning, or mechanochemical methods) to lower manufacturing costs; (2) Optimizing electrolyte systems to minimize side reactions and degradation issues. Promising candidates include functionalized ionic liquids (ILs) with high CO₂ absorption capacity and thermal stability, deep eutectic solvents (DESSs) with low volatility and cost-effectiveness, or polymer electrolytes. For aqueous electrolytes, modifying the composition (e.g., adding CO₂-philic additives, adjusting pH buffers) can enhance CO₂ dissolution and stabilize reactive intermediates, reducing the occurrence of side reactions; (3) Scaling up electrochemical reactors to achieve larger reaction capacities and engineering feasibility. The promising design strategies include modular flow-through reactors with parallel electrode arrays, microchannel structures that enhance gas-liquid-solid three-phase contact, and stacked cell configurations to maximize reaction area per unit volume; (4) Exploring direct integration with renewable energy sources (e.g., wind, solar photovoltaic) address the intermittency of energy supply, enhance energy utilization efficiency, and greenify the carbon capture process.

Increased investment in research, development, and industrial support for electrochemical system innovation holds the potential for breakthroughs in combating climate

change. From a societal perspective, reducing CO₂ levels will inevitably require a combination of diverse capture technologies rather than reliance on a single approach. Furthermore, this integrated strategy can facilitate the effective storage of renewable energy in the form of hydrogen, oxygen, CO₂ and waste heat, which can subsequently be utilized for applications like district heating. This contributes to building a larger national energy reserve and constructing a low-carbon, sustainable energy system.

Declaration of Competing Interest

The authors declare no conflict of interest.

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基于绿色电能的负碳二氧化碳电化学捕集技术

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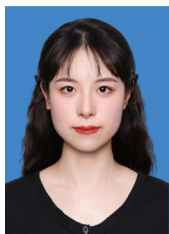
摘要: 随着可再生能源的发展, 绿电成本逐渐下降, 利用电化学技术来捕集二氧化碳的经济性逐渐提高。电化学碳捕集技术是利用电能驱动电极反应, 选择性分离二氧化碳。大力发展以可再生能源为动力的电化学碳捕集技术可以规避以温度驱动捕获和释放的局限性, 为传统的碳捕集技术提供了一种更高效、更灵活、可拓展、低能耗、低污染的有前景的替代路线。本综述介绍了目前已规模化应用的传统碳捕集技术, 例如燃烧前捕集、燃烧后捕集、富氧燃烧、吸附、膜分离和钙循环, 然后过渡到几种正在大力发展的电化学碳捕集技术, 包括电化学介导的胺再生、pH 介导系统、依靠氧化还原活性分子的过程, 其中, pH 介导系统又包括双极膜电渗析、质子耦合电子转移和膜电容去离子等。对于每种方法, 都将系统阐述其原理、技术进展及优势、当前面临的问题与挑战。希望在不久的将来, 通过绿电的普及和电化学材料的创新, 电化学碳捕集技术可以以高效低碳的解决方案助力实现全球碳中和的目标。

关键词: 碳捕集技术; 电化学碳捕集; 可再生能源; 催化剂

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