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Membraneless and Electrochemical Carbon Capture: Disrupting Traditional Amine-Based Systems for Industrial De-carbonization: A Review

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***Abstract**: Electrochemical carbon capture is emerging as a promising alternative to thermally driven amine scrubbing for decarbonising challenging industrial sectors. This review critically assesses recent advances in membraneless and other electrochemical approaches in comparison to conventional amine-based post-combustion capture. Membraneless electrochemically mediated amine regeneration (EMAR) architectures replace ion-selective membranes with gas-diffusion electrodes, collapsing absorption and desorption into a single electrochemical unit and eliminating ancillary equipment, such as columns and flash tanks. This redesign delivers CO_2 removal efficiencies above 90% at energy consumptions as low as ~60 kJ mol^{-1} CO_2 and levelized capture costs near 70 USD t^{-1}, substantially below conventional EMAR and competitive with state-of-the-art thermal systems. Complementary concepts, including electrochemical pH-swing regeneration of amine solutions, exploit amines as buffers to maintain favorable inorganic carbon speciation and achieve high current utilization with minimum energies near 60 kJ mol^{-1} CO_2 while preserving product purity. Integrated "reaction-swing" schemes directly electroreduce CO_2 captured in tailored amine solvents to syngas, demonstrating high absorption (>84%) and improved Faradaic efficiencies, thereby circumventing separate solvent regeneration and gas compression steps. These developments are contextualised against the chemistry, performance and deployment of incumbent amine scrubbing and emerging electroswing systems for industrial decarbonization. The outstanding issues are to reach industrially relevant current densities and lifetimes, sorbent stability, and to incorporate electrochemical units into large-scale process flows. Convincingly, membraneless and electrochemical carbon capture technologies have a promising future in potentially replacing traditional amine systems through lower energy penalties, reducing process layouts, and allowing a flexible and electricity driven net-zero industrial process.*

Keywords: Carbon capture; Electrochemical separation; Membraneless systems; CO_2 utilization; Industrial decarbonization

1. INTRODUCTION

The rationale behind the rising urgency of climate change may also be justified by an impressive rise in the amount of carbon dioxide (CO_2) in the atmosphere that has reached an unprecedented high of more than 415 ppm due to the emission of greenhouse gases by humans, primarily through industrial production and burning fossil fuels [1, 2, 3]. The Intergovernmental panel on climate change (IPCC) and the major climate models are categorical that the only solution to preventing global warming of 1.5 to 2oC above preindustrial levels will be to decarbonize all sectors at a high rate, and the industry is one of the most frontiers due to the high temperature processes and distributed sources of greenhouse gases [1, 3, 4, 5]. Carbon capture and storage (CCS) has also become a focal point of net-zero policies as it represents a chance to cut down the remaining emissions of the industrial sectors, such as cement, steel, chemicals, and pulp and paper

[4, 6, 7, 8]. The CCS area, including direct air capture (DAC) and bioenergy with CCS (BECCS), is one of the main aspects of the integrated assessment models project through which net-zero goals can be reached by the middle of the century, and up to a quarter of the required emission reductions can be provided by CCS [9, 10, 11, 12]. In addition to making negative emissions possible, CCS offers flexibility to energy systems with large portions of variable renewables [13]. However, the current technologies of CCS, dominated by thermochemical reactions such as amine-based post-combustion capture, are very limiting.

These are high-energy consumption concepts with a lack of flexibility in operation, solvent degradation, corrosiveness and high costs of adoption, which make them hard to use widely [2, 6, 7, 14]. Also, the environmental issues, which accompany the use of solvents and the higher air pollution caused by the use of auxiliary fuels, also undermine their sustainability credentials [7].

To address these issues, the trend is towards the conception of electrified carbon capture technologies. Electrochemical methods use renewable electricity to power CO_2 separation at ambient temperatures, which have the benefit of modularity, scalability, efficiency, and renewable energy system integration [5, 16, 17, 18, 19].

New developments involve electrochemically mediated regeneration of amines, redox-active organic sorbents, including quinones, pH swing technologies using redox-active materials or inorganic nanomaterials, and direct air/ocean capture using electrochemical cells-all of which have shown promising energy savings and operational savings over conventional processes [5, 17, 18, 19]. Although these technologies are currently still maturing as the technology continues to be advanced through research to tackle the issue of stability, selectivity, material costs, and system integration, they are a revolutionizing direction towards sustainable industrial decarbonization in line with ambitious climate objectives [15, 16, 18].

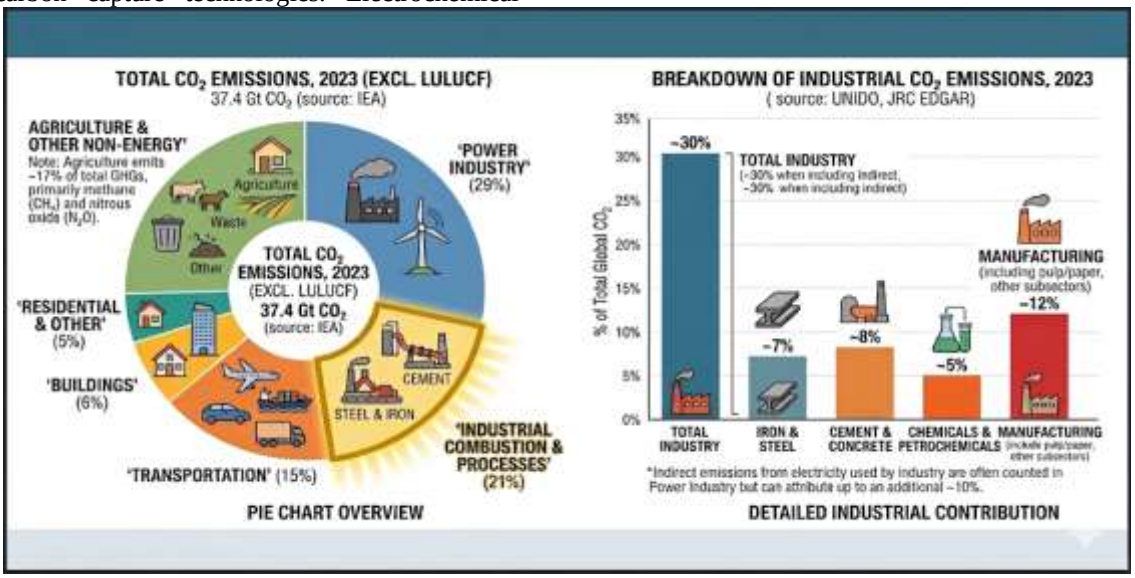

Figure 1: Global CO_2 Emissions by Sector. [19, 20, 21, 22, 23]

2. CONVENTIONAL AMINE-BASED CARBON CAPTURE

The conventional amino scrubbing, usually using aqueous monoethanolamine (MEA), has been the most common technology of post combustion capture of CO_2 in the manufacturing and power plants because it has fast reaction kinetics, high selectivity of CO_2 and has been proven to be successful technologically [24, 25]. In this case, the CO_2 in the flue gas dissolves in an amine solution in an absorber column, and is desorbed in a stripper to reuse the amine solution, enabling the process to be continuously repeated [26, 27]. Irrespective of its widespread use, MEA based capture is constrained by harsh solvent regeneration and solvent degradation, as well as corrosion energy penalties that prompt the ongoing effort of solvent and process development [24, 27].

2.1 Reaction Mechanisms (Carbamate Formation)

Primary and secondary amines capture CO_2 through a carbamate formation reaction through a zwitterionic intermediate. The initial reactant first reacts with the free amine to produce a zwitterion and the protons are then transferred with the help of a second amine or a water molecule to form an alkylammonium carbamate pair. This two-step reaction mechanism with a zwitterion intermediate could be explained by means of molecular dynamics and metadynamics simulations with the emphasis on the significance of the proton transfer by the interactions between molecules [28, 29, 30]. The presence of water has a complex

effect of stabilising the zwitterion and reducing the activation energy of proton transfer, which increases the formation of carbamate [31, 32, 33]. The lifetime of the zwitterionic intermediate is also dependent on the amine type and environment affecting the kinetics of CO_2 capture [30, 34]. Such mechanistic understandings are important to guide the design of more solvents based on amines that may be used in carbon capture [35, 36].

Two primary or secondary amines bind one CO_2 molecule under dry conditions; a process that results in a theoretical maximum capacity of 0.5 mol CO_2 per mol amine [37, 38]. Water in humid systems facilitates other pathways such as bicarbonate formation that can shift the apparent stoichiometry more towards 1 mol CO_2 per mol amine and alter energy needs of regeneration [39, 40, 41, 42, 43, 44]. State of the art simulations and spectroscopic experiments verify that carbamate stability, barrier heights and equilibrium of carbamate, carbamic acid, and bicarbonate species are critically determined by proton transfer reactions, networks of hydrogen bonds and the solvent structure [45, 46].

2.2 Process Design: Absorber–Stripper Configuration.

In the industrial amine plants, they are usually designed as a closed absorber-stripper loop. The cooled and conditioned flue gas is fed to the bottom of a packed absorber, where it comes in contact with downward flowing lean amine, with the depleted CO_2 gas leaving at the top, commonly in a water wash section to minimize solvent emissions [26, 47]. The absorbent bottom solvent is pre heated against lean solvent and pumped to a packed stripper, where steam in a reboiler strips CO_2 to create an overhead CO_2 rich vapour which is condensed and sent to compression and storage [26, 48].

Simulations and optimization experiments highlight how lean loading, liquid to gas ratio, column packing, and operating pressure/temperature affect capture efficiency and energy consumption with the optimized commercial scale MEA plants normally aiming at capturing about 90% of CO_2 [26, 49, 50].

2.3 Energy and Environmental Constraints

The main disadvantage of traditional amine systems is the thermal energy required to regenerate solvents is large, around 3 4 GJ/t -1 CO_2 with a typical baseline MEA, and results in 9-12 percentage point efficiency penalties in coal burned power plants [24, 51, 52]. Up to 3,060 percent of reboiler workload has been saved by the widespread attempts to alter the processes, such as lean vapor compression, cold solvent split, absorber intercooling, internal heat integration and advanced stripper designs [51, 52, 53, 54].

Along with the consumption of energy, the amine processes, in addition, have certain negative environmental and operation characteristics such as the oxidative/thermal degradation of solvents, formation of potentially cancer-causing degradation products, the loss of solvents through volatilization, and the corrosion of carbon steel equipment [24, 55]. The degradation cost increases the makeup requirements, which may be a substantial part of the operating cost, and necessitates reclaiming, compared to the amine emissions and the nitrosamines formation which must be kept within the environmental regulations [24, 56].

These difficulties form the basis of the ongoing studies of low energy solvents, blended and water lean amines as well as intensified process configurations that aim to preserve the chemical benefits of carbamate forming amines, but avoid the energy and environmental costs [57, 58, 59, 60].

Table 1. Key Aspects of Conventional Amine Capture

Aspect	Brief Description	Citations
Dominant reaction	Zwitterion pathway to ammonium carbamate; water enables bicarbonate routes	[61, 62, 63, 64]
Core process layout	Packed absorber + packed stripper with heat integration and CO_2 compression	[26, 65, 66]
Main limitation	3–4 $GJ \cdot t^{-1}$ CO_2 reboiler duty, 9–12% efficiency penalty	[67, 68, 69]
Key environmental issues	Amine degradation, corrosion, emissions and nitrosamine risk	[24, 55, 56]

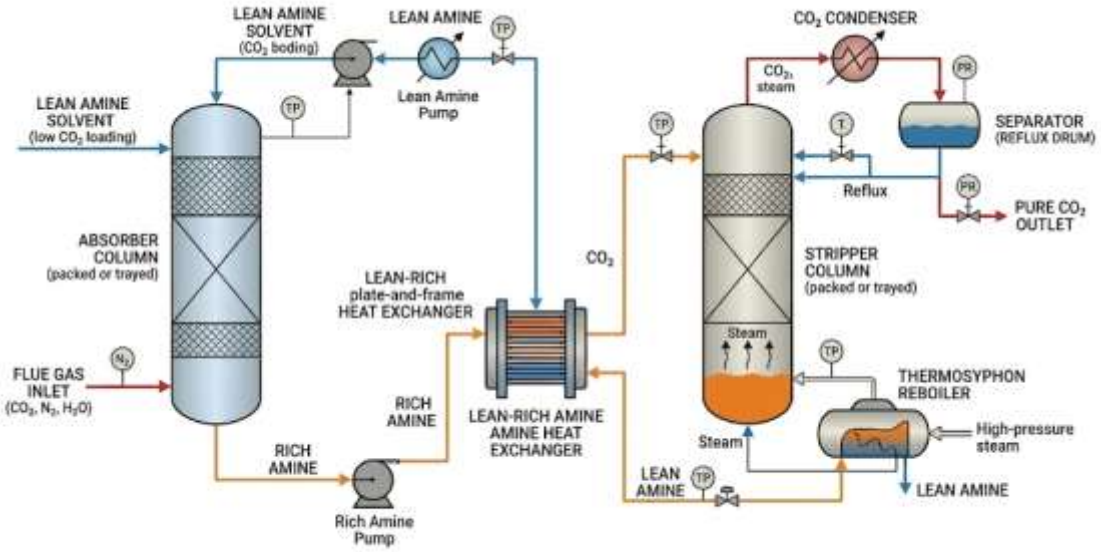

Figure 2: Process Flow Diagram of Amine Scrubbing System [70, 71, 72]

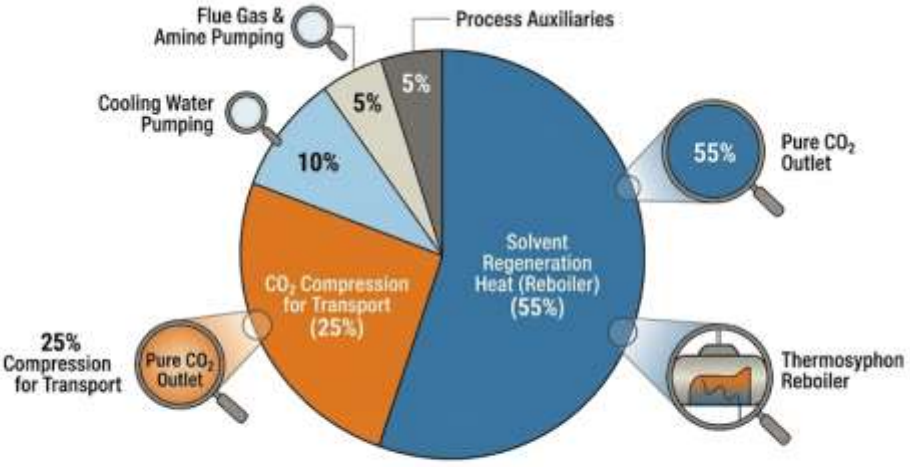

Figure 3: Energy Penalty Breakdown [71, 73, 74].

Table 2: Performance of Common Amine Solvents

Solvent	Capture Efficiency (CO_2 removal / rate)	Energy Demand for Regeneration	Stability (degradation, corrosion)
Monoethanolamine (MEA)	High; benchmark for ≥90% capture in many designs; among	High; typical 3.3–3.8 GJ t^{-1} CO_2 and highest regeneration heat among compared systems [75, 76, 78, 79, 80]	Low–Medium; strong oxidative/thermal degradation and highest corrosivity among

	fastest absorption rates [75, 76, 77]		investigated amines [77,81,82,]
Diethanolamine (DEA)	High; comparable or slightly lower rate vs. MEA; good absorption in blends and membranes [75,78,83]	Medium–High; regeneration heat generally lower than MEA but still significant [78,83]	Medium; less corrosive and more stable than MEA but degradation still relevant [78,81]
Methyldiethanolamine (MDEA)	Medium; slower kinetics; lower specific absorption rate than MEA/DEA, but good loading at equilibrium [76,77,78,83]	Medium; low heat of absorption and lower regeneration energy than MEA; further reduced in blends [77,78,79, 80,84]	High; tertiary amine with good thermal/oxidative stability and lower corrosion [77, 78, 81, 84]
2-Amino-2-methyl-1-propanol (AMP)	High; specific absorption rate AMP < MEA < PZ but higher than MDEA; good CO_2 capacity [76, 78, 85]	Medium; lower reaction/regeneration heat and good cyclic capacity vs. MEA [76, 78, 85]	Medium–High; sterically hindered amine with better thermodynamics; stability depends on blend and make-up rate [85,78,76]
Piperazine (PZ, usually as promoter)	Very High; fastest specific absorption rate; PZ > MEA > AMP > MDEA [76,77,86]	Medium; used in low concentration; blends (e.g., MDEA/PZ, MEA–MDEA–PZ, water-lean PZ-activated) reduce energy by ~10–50% vs. MEA [87, 86, 84,80]	Medium; chemically robust but can increase corrosion; stability managed by low dosage [77, 87, 86, 85]
Advanced mixed / water-lean & biphasic amines (e.g., MEA/2ME or 2EE, MAE/DEGDME or EGME, EMEA/DEEA+PZ, MEA–MDEA–PZ)	High; comparable to 5 M MEA with larger cyclic capacity and good rates [88, 89, 87,84,90]	Low; regeneration energy reduced by ~45–60% vs. aqueous MEA, down to ~1.75 MJ kg^{-1} CO_2 [88, 89,87, 84,90]	Medium; lower degradation via reduced water, but volatility, phase separation and long-term stability are key design issues [86, 87,82,90]

3. MEMBRANELESS CARBON CAPTURE TECHNOLOGIES

Membraneless carbon capture Membraneless carbon capture is a type of carbon capture and separation process that uses liquid-gas or liquid-liquid interfaces, phase behavior or electric fields to cause separation and regeneration, rather than a solid membrane. These ideas are being worked in conjunction to traditional absorption, adsorption, and membrane systems to minimize the energy penalties and equipment complexity in post combustion capture [91, 94, 95].

3.1 Definition and Classification.

Membraneless technologies can be viewed as a sub-category of so-called emerging CO_2 capture systems, re-engineering contactors and regeneration steps, typically focusing on the process electrification and co-purification with the existing capture paths [91, 96, 97].

They can be generally categorized as:

Biphasic solvent systems: This is where CO_2 effects or takes advantage of the liquid-liquid phase separation to concentrate the rich solvent fraction [8, 98].

Liquid liquid extraction systems: CO_2 is extracted with liquid solvents with a solvent barrier (immiscible solvents) [99, 100].

Electrofluidic/electrochemical systems: It takes the potentials applied to trap/release CO_2 or to re-distill solvents without the use of high temperature steam [100, 101].

3.2 System Types

(i) Biphasic systems

The solvent mixtures with biphasic amines and a loading of CO_2 or temperature to trigger the phase segregation allow the regeneration of a CO_2 rich phase in lower volume, lowering circulation rates and regeneration energy [102]. The use of these phase change solvents is being explored as an improved version of the conventional amine absorption of post combustion capture [103, 104, 105].

(ii) Liquid–liquid extraction

Liquid liquid extraction plans are based on the difference in solubility of CO_2 between two immiscible phases (usually an aqueous reactive phase and an organic or ionic liquid phase) that allow gas liquid contact in mixer settlers or columns and phase separation by gravity [104, 106, 107]. State-of-the-art CO_2 capture indicate liquid-liquid and hybrid solvent systems such as ionic liquid-based extractants as potentially offering a path to reduced energy usage and reduced corrosion compared to traditional amines. [108,109,110].

(iii) Electrofluidic systems

Electrochemical carbon capture (ECC) and electrochemical amine regeneration (EMAR), are some of the key electrofluidic techniques that can be configured in either no-membrane or with smaller membrane dimensions [111,112]. More recently, a membraneless EMAR cell has been shown, which employs gas diffusion electrodes and flows through electrochemical contactors in place of ion exchange membranes, and removes CO_2 with a >90% efficiency at energy consumptions as low as -60 kJ $^{-1}$ CO_2 and has estimated capture costs of 70 USD , low in comparison to conventional EMAR [112]. An example of such systems involves the replacement of thermal reboilers with electric fields and redox chemistry to create modular, low temperature and possibly renewable powered capture [111, 112, 113].

3.3 Mass Transfer and Transport Phenomena.

In membraneless systems, overall performance is dictated by coupled diffusion, convection and phase equilibrium as in other solvent based and electrochemical capture technologies. CO_2 diffusion in liquids, diffusion at a gas-liquid or liquid-liquid interface, local reaction rates and approach to equilibrium with CO_2 diffusion in liquids is achieved by diffusion of molecules. Effective diffusivities are highly dependent on the solvent viscosity, temperature, and speciation and therefore design of columns or cells as evidenced by the reviews of captures [111, 114, 115].

Flow fields in a column, mixer or electrochemical channels such as co current/counter current operation, agitation and distribution of residence time are directly dependent on interfacial area as driving forces are being designed to directly impact capture efficiency and specific energy utilization. [114, 115, 116]. The distribution of CO_2 between gas, aqueous, organic and occasionally ionic liquid phases has been termed as a thermodynamic process, which involves physical solubility and chemical reactions [111, 114]. In electrochemical systems, low temperature regeneration pathways are possible, in which either speciation or effective equilibrium with potential is disturbed [112, 115].

The best way to optimize membraneless capture is thus to tune simultaneously solvent chemistry (capacity and kinetics), hydrodynamics (mixing and flow architecture) and thermodynamics (favorable CO_2 loading and readily reversible binding) to achieve deep decarbonization goals at reasonable costs [113, 114, 115, 116].

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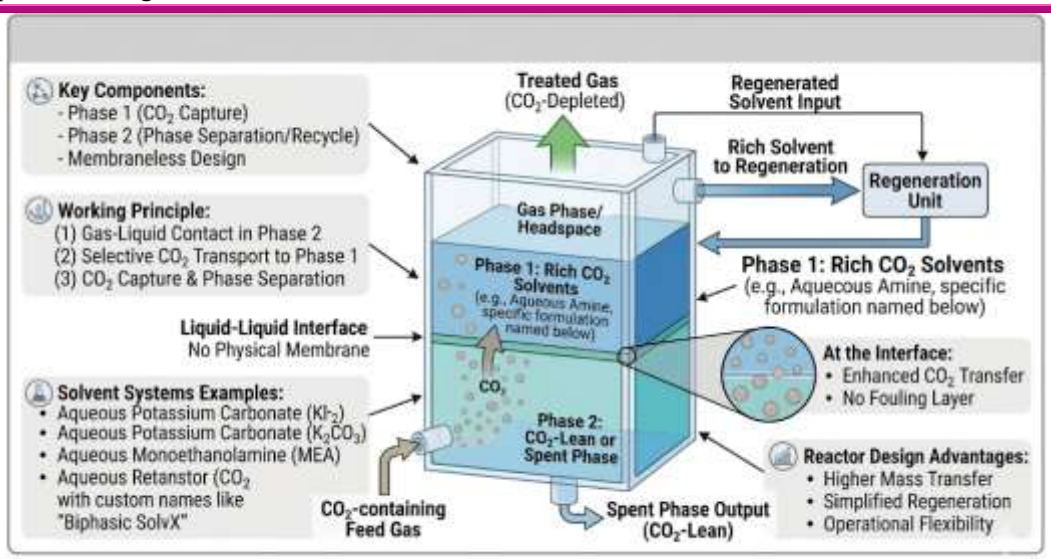

Figure 4: Schematic of a Membraneless Biphasic System

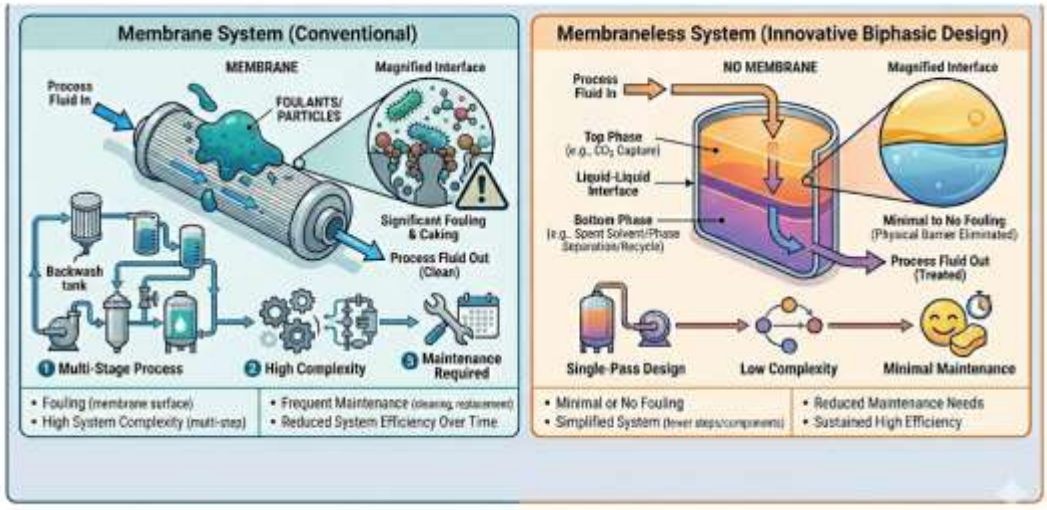

Figure 5: Comparison of Membrane vs Membraneless Systems

Table 3. Summary of Membraneless Technologies

System Type	Mechanism (Gas / Species Separation)	Efficiency	Advantages	Limitations	Citations
Laminar-flow membraneless electrolyzer	Co-flowing electrolytes; product gases separated by stable laminar flow profile	Comparable cell voltages to PEM; efficiency limited by mixing and bubble loss	Simple design, no membrane cost, easy scale-down for microdevices	Gas crossover, bubble management, lower purity vs. membrane systems	[117, 118]
Flow-through electrode ME	Electrolyte forced through porous electrodes; bubbles swept	Improved mass transport; higher current densities than planar	Higher productivity, better bubble removal, potential compact reactors	Complexity of porous structures, pressure drop,	[117,118]

	and separated by flow	laminar-flow designs		purity still an issue	
Gas-diffusion / bubble-free electrode ME	Gas generated at gas-diffusion electrodes; products removed through gas channels	High faradaic efficiency; reduced ohmic losses	High current density, reduced bubble blockage, compact architecture	Electrode stability, fabrication cost, control of two-phase interfaces	[117]
Organic-assisted ME	Organic additives modify solubility / phase behavior to aid product separation	Can lower required cell voltage; context-dependent efficiency gains	Reduced overpotentials, tunable electrolyte properties	Additive cost, contamination, separation of organics from product stream	[117]
Microbial electrolysis cell (MEC, no membrane)	Biocatalytic anodic reactions; product gases separated by flow and reactor design	Lower overall efficiency than PEM; can operate at low energy input	Uses waste organics, low-grade streams; adds valorization of wastewater	Low current densities, slow kinetics, gas mixing	[117]
Membraneless micro fuel cell (co-laminar)	Parallel laminar oxidant/fuel streams; interface acts as “virtual membrane”	~12% higher power density vs. PEM micro FC; 20–40% system cost reduction	No Nafion cost, no fuel crossover membrane losses, simple microfabrication	Limited to low Reynolds number, fuel crossover by diffusion, scaling up	[119,120]
Membrane-free macro fuel cells	Various: laminar co-flow, redox mediators, flow-segregated electrodes	Highly system- and design-dependent; promising efficiencies demonstrated	Lower material cost, robustness, less chemical degradation	Still emerging; durability and long-term performance under study	[119]

4. ELECTROCHEMICAL CARBON CAPTURE

Electrochemical carbon capture (eCC) is a redox based faradaic process that capture and release CO_2 with the use of electricity instead of heat, enabling isothermal, modular systems that could potentially have less specific energy consumption than heat-based amine scrubbing [121, 122, 123].

4.1 Electrochemical Principles

eCC involves redox active molecules or electrodes the oxidation state of which controls local pH, nucleophilicity or specific CO_2 binding reactions [124,125,126]. Aqueous pH swing systems use proton coupled electron transfer of organic mediators such as phenazines, pyridinium or aminopyridinium species with higher or lower concentration of hydroxide transportation of dissolved inorganic carbon speciation as CO_2, HCO_3^- and CO_3^{2-}. DSPZ and 1 aminopyridinium, which are molecular mediators, have demonstrated electron utilization up to 1.25 mol CO_2 per mol and capture flue gas under relevant and direct air capture conditions [127, 128, 130].

Motivating work in eCC is the faradaic reaction between redox electrodes, and the ion transportation that is assisted by supporting electrolytes and redox active electrolytes, respectively [122,131]. Faradaic electro swing reactive adsorption (ESA) uses quinones complex on surfaces that can react with CO_2 in a reversible reaction when reduced and release CO_2 after oxidation without any coupling between capture and solvent vapour loss under enabling isothermal operation. [132, 133, 134]. Alternatively, solid electrolyte reactors couple oxygen reduction/evolution reactions with carbonate formation and neutralization. [122, 135].

Table 4. Research consensus on effectiveness of electrochemical CO_2 capture

Results	Recency	Methods	Journals	Search
Yes 80% 8 papers — High-quality, recent studies in top journals with experimental validation and strong energy efficiency data support electrochemical pH-swing carbon capture. [130,134, 136, 137, 138, 139, 140, 141].	2024-2025 avg.	0 tier one studies	Q1 avg.	327 total
Possibly 10% 1 paper — A perspective review highlights potential but notes practical limitations and dependency on renewable electricity, lacking direct experimental evidence [136].	2025 avg.	0 tier one studies	Q1 avg.	44 total
Mixed 10% 1 paper — A simulation-based study in a mid-tier journal shows efficiency depends on operational parameters and highlights design challenges for real-world application [136].	2025 avg.	0 tier one studies	Q2 avg.	6 total

No 0%	—	—	—	—

4.2 Technology Pathways

(i) Electro swing adsorption (ESA).

In ESA structures, redox active CO_2 carriers usually quinones are fixed on high surface area carbon or porous polymeric electrodes. [132, 142, 143]. The negative potential decreases the redox centers, and this enhances their affinity to CO_2 and the opposite happens when the potential is reversed and a stream of pure CO_2 is liberated [144, 145, 146]. Experiments and simulations demonstrate selective capture of low concentration feeds (<1% CO_2) with energy consumptions as low as -0.6 MWh-t^{-1} CO_2 and high sensitivity of productivity to applied potential, flow rate, and transport in ionic liquid or polymeric matrices [147,148, 149].

Porous polymeric electrodes are of great benefit in improving the transport of gases and utilization of redox sites (~90%), which allows continuous flow through ESA with a high Faradaic efficiency and stability [142,150].

(ii) pH swing systems

Homogeneous redox mediators such as phenazine sulfonates, pyridinium derivatives, and neutral red systems in aqueous electrolytes are cycled in redox mediated pH swing cells, producing reversible changes in pH which intermittently absorb and release CO_2 [130,136,151]. Cell with a cation exchange membrane and phenazine-mediators obtain CO_2 at -32 kJmol -1 and capture rates of 50 percent and capture efficiency above 90 percent [136,152]. Systems with DSPZ capture CO_2 of flue gas to very dilute partial pressures, and measured work of 61 kJ mol^{-1} CO_2 to separate 0.1 bar CO_2 to 1 bar CO_2 and 121 to 237 kJ mol -1 to natural conditions at 20 mA cm^{-1} [153, 154]. Similar pH swing principles can also be applied to amine solvent regeneration using hydrogen oxidation/evolution or anion exchange membrane cell, with up to 63 kJ/mol-1 of energy savings being possible when regenerating MDEA at >99% CO_2 purity [155].

(iii) Redox carriers and hybrid reactors.

A wide range of redox tunable carriers such as quinones, phenazines, pyridinium salts, aminopyridinium ions and other organic redox agents are being design to maximize solubility, stability, binding strength, and oxygen tolerance either in the dissolved form or immobilized form [156, 157, 158]. Solid electrolyte reactors combine O_2 /H_2O redox chemistry with the formation of carbonates at a high alkaline cathode, neutralization, and high purity (>99) CO_2 at a central solid electrolyte, with carbon removals efficiencies exceeding 98% and start-up energy consumptions of approximately 150 kJ mol^{-1}

CO_2 at high current/voltage.

Table 5. Representative Electrochemical Capture Routes

Pathway / system type	Key mechanism	Typical performance	Citations
Quinone ESA (parallel channels)	Solid redox carriers toggle CO_2 affinity with voltage	Capture from low-% CO_2, ≈0.6 MWh·t^{-1} CO_2 in models	[132, 160, 161]
Porous polymer ESA electrodes	Gas-permeable, redox-active polymeric electrodes	~90% material utilization, high Faradaic efficiency	[142]
Phenazine pH-swing	Homogeneous mediator + CEM	32 kJ·mol^{-1} CO_2 at 39 mmol·m^{-2}·min^{-1}	[136, 152]
DSPZ pH-swing	PCET mediator, electro-rebalancing	61 kJ·mol^{-1} (0.1→1 bar CO_2); 121–237 kJ·mol^{-1} (DAC extrapolated)	[128].
Amine regeneration pH-swing	H_2/H^+ redox + AEM	63 kJ·mol^{-1} to regenerate MDEA at >99% purity	[137]

4.3 Materials and Electrodes

(i) Carbon electrodes

Carbon materials are also popular inert conductive supports in ESA. The material is highly porous, tunable in its porosity, and electrically conductive to immobilized quinones and other redox polymers [162, 163, 164]. Conductive carbon structures are embedded in redox functional polymers in porous polymeric electrodes to form all in one gas permeable electrodes with high redox site utilization and good mechanical stability [142]. Principles of carbon based supercapacitors and pseudocapacitors such as the control of porosity, self-discharge and Faradaic versus non Faradaic behavior are used to optimize the eCC electrode architectures. [165, 166, 167].

(ii) Inorganic and metal oxides electrodes.

Metal oxide nanomaterials, including manganese oxides and Bi/BiOCl or Ag/AgCl, have been used as redox active electrodes in pH swing systems developed to selectively de-intercalate protons without causing significant perturbations

to other ions, and remove CO_2 selectively in flue gas, or dissolved inorganic carbon in seawater [127]. These inorganic electrodes offer insensitivity to sodium, high-energy efficiency and operation with ocean or brine chemistries [127, 141]. Oxygen reduction and evolution ceramics like noble metal or transition metal oxides are used as catalysts to rapidly cycle O_2/H_2O redox in high current densities in solid electrolyte reactors, and can be stable in strongly alkaline or acidic environments [168].

(iii) Electrolytes

Electrolyte selection regulates the stability of the mediators, conductivity, pH window, and oxygen tolerance. Aqueous electrolytes that include dissolved organic mediators are favored in pH swing designs since they are environmentally friendly and can be readily scaled [127, 169, 170]. ESA utilizes ionic liquids and customized supporting salts to balance CO_2 and redox reactions and solubility [171, 172, 173]. Aqueous electrolytes that contain amines allow electrochemical regeneration to be directly coupled to the mature solvent based capture cycles, to minimize thermal duty without compromising CO_2 loading capacities [174, 175]. In systems, resistance to lateral reactions like oxygen crossover, decomposition of mediators, carbonate precipitation is a key design consideration [155, 175, 176, 177].

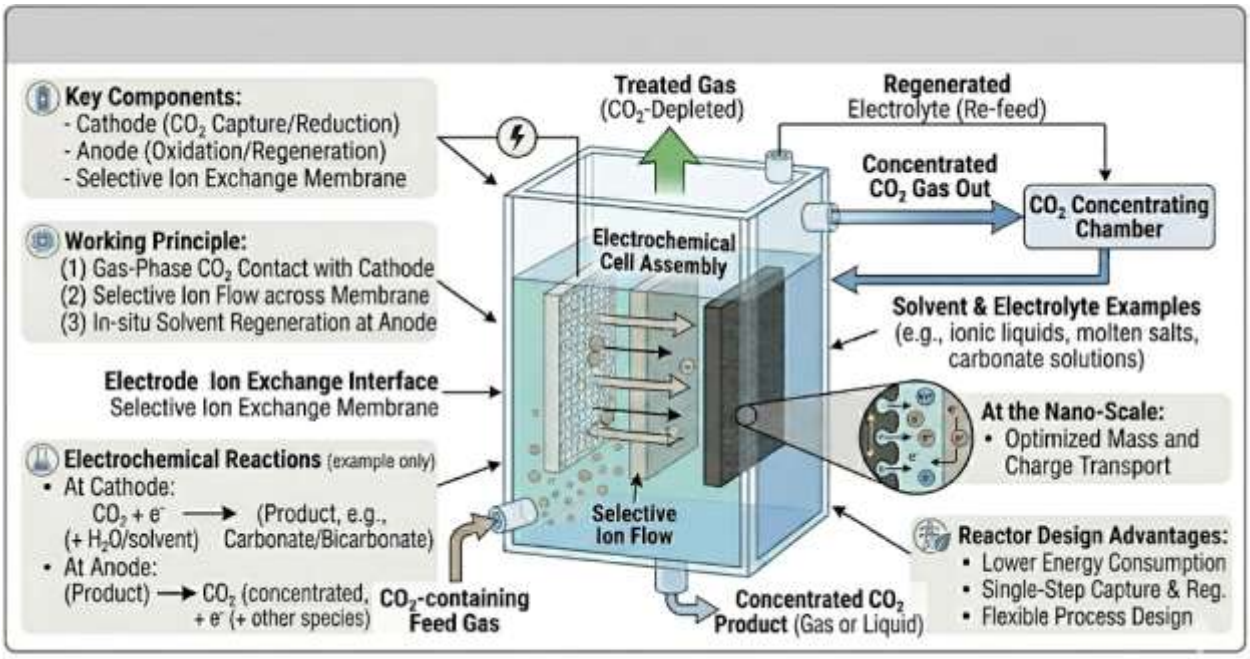

Figure 6: Electrochemical CO_2 Capture Cell

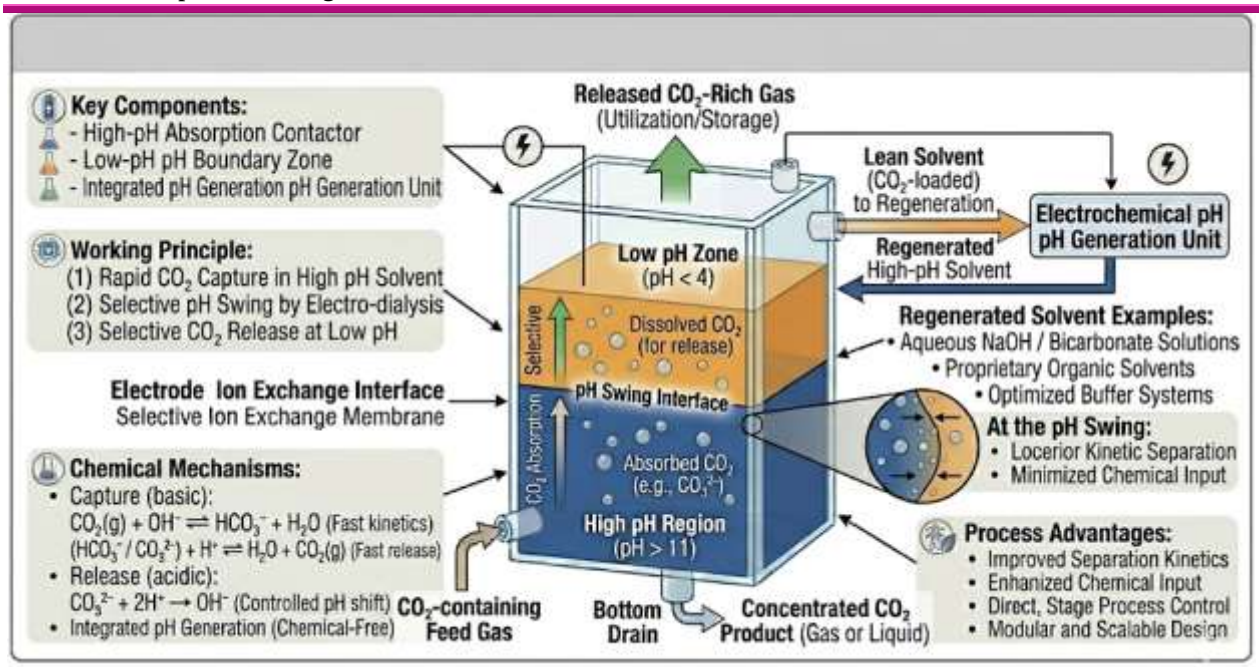

Figure 7: pH Swing Mechanism

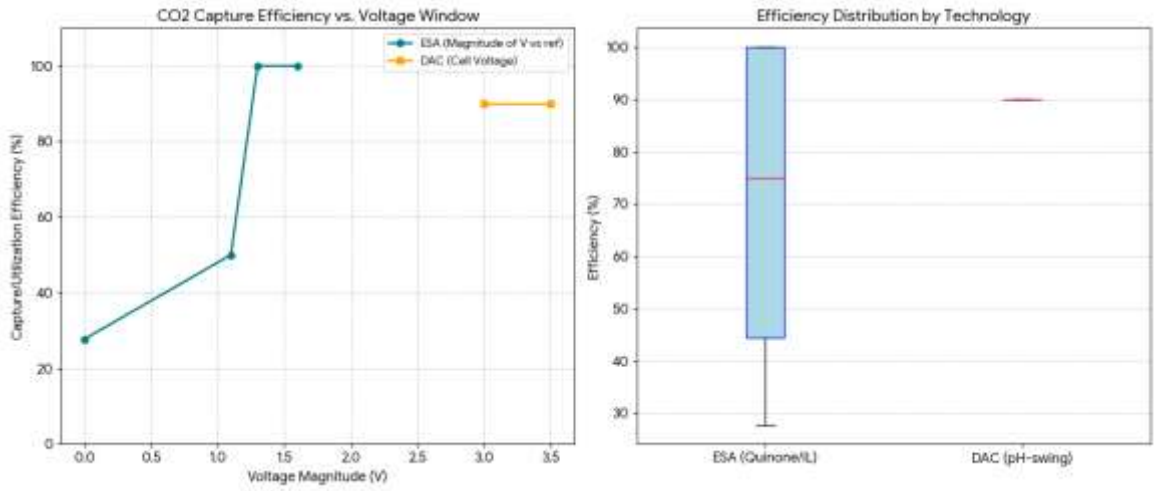

Figure 8: Voltage vs CO_2 Capture Efficiency Curve

The ESA Curve (Teal) exhibits a typical behavior of activation. The efficiency which is a reflection of the physical absorption at the base level is low at 0 V. At 1.1 V to 1.3 V, the efficiency shoots dramatically upwards as the electrochemical redox process is triggered. Increasing voltage past 1.3 V, the curve levels off, which means that increasing voltage only causes power consumption to rise without seizing more CO_2[178, 179, 180].

The DAC Window (Orange) is the technology that works in a wider cell voltage range (3.0 V to 3.5 V) yet still has a highly stable and high efficiency (85 to 95%). The boxplot shows that, although ESA is more efficient (baseline to peak), DAC systems are more efficient at keeping the output at a high level most of the time [181,182,183].

Table 5. Electrochemical System Performance

Electrochemical CO_2 Capture	Energy (kWh/ton CO_2)	Efficiency	Cycle Life	References
Electrochemically mediated amine regeneration (EMAR)	90–150	50–70% (vs. thermal baseline)	1,000–10,000 (projected lab-scale)	[184, 185]
Redox-active quinone systems (pH-swing, flow cell)	100–250	40–60%	1,000–5,000 (lab-scale)	[186, 187]
Bipolar membrane electrodialysis (BPMED) for CO_2 capture	150–300	30–50%	5,000–20,000 (membrane stacks, projected)	[188, 189]
Capacitive deionization / supercapacitive swing adsorption	50–150	40–70%	10,000–100,000 (electrodes)	[190, 191]
Molten carbonate electrolysis (CO_2 to CO/O_2)	200–400 (as capture + conversion)	30–50% (electrical to chemical)	5,000–20,000 (cells, projected)	[192, 193]
Alkaline electrochemical air capture (NaOH/KOH cycles)	150–250	35–55%	3,000–10,000 (cells, projected)	[194, 195].

Table 7. Electrode Materials Comparison

Material	Conductivity	Stability	Relative Cost
Carbon paper (GDL, standard)	High in-plane electronic conductivity [196, 197]	Prone to flooding; limits long-term CO_2RR stability [196, 197]	Low–moderate (commodity carbon) [197, 198]
ePTFE (hydrophobic membrane)	Very low (insulating) [196]	Excellent flooding resistance; mechanically robust [196]	Low–moderate polymer cost, simple film [196]
Hierarchically conductive ePTFE (Cu-wired)	High (embedded Cu conductors) [196]	Maintains ePTFE stability; stable up to 50 cm^2 scale [196]	Moderate (extra Cu wiring, but scalable) [196]
Porous polymeric quinone electrodes	Moderate (polymer + carbon network) [199]	High Faradaic efficiency; >100 cycles stable operation [199]	Low (polymer and carbon fillers) [199]
Carbon cloth / textile with immobilized PCET polymer	High (woven carbon fibers) [200]	Remarkable chemical stability vs dissolved PCET; stable in air and seawater [200]	Moderate (textile carbon + polymer) [200]
YP80F activated carbon (supercapacitor)	High (conductive porous carbon) [201]	>12 000 cycles with minimal degradation 3 [201]	Low (commercial activated carbon) [201]
Metal-based GDE backings (e.g., Cu mesh, foams)	Very high metallic conductivity [202, 203]	Good mechanical stability; may corrode in some media [202, 203]	Moderate–high (metal content, fabrication) [202, 203]

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5. COMPARATIVE TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS

5.1 Energy Consumption

Direct air capture is very energy-consuming as it isolates carbon dioxide in the atmosphere (~420 ppm). The typical current plants have total energy requirements of about 2,000-3,000 kilowatt hours (kWh) of CO_2 per tonne of gas, including energy used in the fans, and regeneration of the sorbent [204, 205]. The energy requirements of 1.4-3.7 mega joules per kilogram (MJ/kg^{-1}) of CO_2 (=390-1030 kWh/t^{-1}) of aqueous scrubbing and solid sorbent DAC are simulated through process simulation and optimization studies. These indicate that advanced solid sorbents can achieve high productivity (3.8-10.6 kg CO_2). Electrochemical processes can theoretically reduce energy consumption, but it requires sufficiently low equivalent cell voltages and high current efficiencies. Techno economic analysis (TEA) indicates only a few electrochemical DAC designs to compete or even outperform thermal processes at realistic voltages and power cost [207, 208].

5.2 Cost (Capital and Operating Expenditures)

Both capital expenditure (CAPEX) and operating expenditure (OPEX) have a significant impact on the levelized cost of capture (LCOC).

The LCOC estimates of DAC currently range between 80-1133 €/tCO_2 with long term aspirational estimates of 34-260 €/tCO_2 under optimistic learning and integration conditions [209].

Detailed process TEA Capital cost is the cost driver in most cases; all major DAC concepts can achieve less than 200 US dollars -1 CO_2 in ideal cases, only solid sorbent DAC is cost-effective in a broad parameter space [206].

Scenario analyses of high temperature (HT) aqueous DAC and low temperature (LT) solid sorbent DAC indicate that LT DAC can drop down to levels of about 32-54 €/tCO_2 by 2050 when supplemented by hybrid photovoltaic (PV)-wind-battery systems using waste heat [210].

Combination modeling of electrochemical and non-electrochemical DAC discovers that electro swing adsorption (ESA) and electrochemical absorption can only be competitive when both CAPEX and specific electricity demand decrease along experience curves [207].

Learning curve projections with full DAC with CO_2 transport and storage (DACCS) suggest that probable mid-century net removal costs are in the 300 to 400 USD [211, 212].

Table 8. Cost (CAPEX & OPEX)

Metric	Typical findings	Citations
LCOC vs scale	From 12.5 to 7.6 $·t$⁻¹ CO_2 when plant size increases 54→543 MW	[205]
Cost split	OPEX dominates LCOC; CAPEX/OPEX per t fall with scale	[205, 212]
DAC	Often 100–200 $·t$⁻¹ CO_2 in simplified TEA; capital cost main driver	[213, 214]
Transport/storage	Liquefaction OPEX is largest share in ship chains; optimal ~15 bar	[207, 212]
Industrial CCS	Different CO_2-avoidance cost formulae give divergent results if assumptions differ	[215]

5.3 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an assessment of the environmental impact in the entire DAC value chain as construction, energy, chemicals, and storage.

Comprehensive LCA of DAC with geological storage (DACCS) driven with low carbon electricity and heat demonstrates negative greenhouse gas (GHG) emissions and a GHG removal efficiency of 7997% at different locations, systems layout, and energy mix [216]. A comparative analysis of temperature swing adsorption (TSA) versus high temperature aqueous (HT Aq) DAC proves that TSA is always superior in all categories of impact by 1.310 times, and can be

used to recover up to a high of net carbon removal of 86 with low carbon energy [217].

Combined reports of DAC LCA/TEA show extremely broad carbon removal efficiency (CRE), of <10 to well above 95, and are primarily dependent on the carbon content and amount of energy used [209, 215]. Off grid DACCS powered by high temperature heat pumps with PV and batteries can achieve CRE values of about 88–93, however, at high cost and requiring heavy burden of mineral resources and land area [214].

5.4 Carbon Footprint

The energy source and design of the system are crucial to the carbon footprint; the net life cycle GHG emissions per tonne of CO_2 captured and stored.

Low carbon electricity and waste heat based DACCS systems have the potential to eliminate up to 0.79-0.97 tonnes of CO_2 equivalent (tCO_2 eq) per tonne of captured gas, but when deployed in areas with fossil intensive power mixes can result in net positive GHG emissions [215, 216].

Comparative LCA indicates that TSA DAC route, with storage, has a higher net carbon removal and a lower total carbon footprint than HT Aq DAC with the same capture rates [217].

Co assessment wherein TEA is combined with LCA highlights the idea of tradeoffs. DACCS can deliver high climate benefits, but may cause other environmental impacts, such as land use with PV, battery and sorbent mineral resource use, and the importance of integrated indicators, such as CRE and

multi impact scores, is highlighted [209,214, 215].

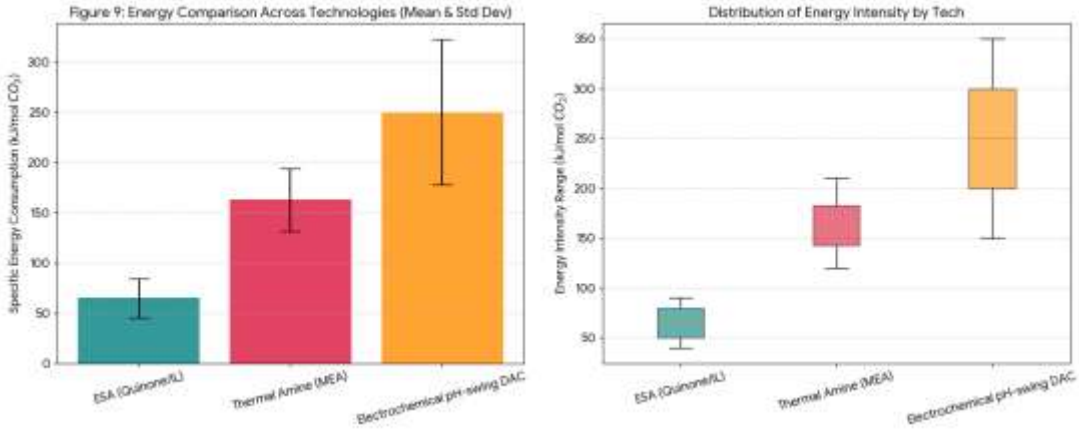

Figure 9. Energy Comparison across Technologies

Table 9. Comparative Technology Assessment

Parameter	Amine (thermal post-combustion)	Membraneless (EMAR)	Electrochemical (general ECC / integrated)
Technology maturity (TRL)	Commercial, largest industrial deployment, benchmark CCS [205,208, 213, 218]	Emerging, lab→pilot; redesign of EMAR cell [209, 215]	Emerging to pilot; various chemistries and configurations under development [204, 210, 211, 212, 217].
Main driving force	Thermal regeneration of rich solvent (steam reboiler) [205, 208, 210,218]	Electrical potential regenerates amine, minimal thermal duty 1 4 11 [206 ,215]	Electrical potential; redox-mediated sorbents or reactive capture media 2 5 9 10 11 19 20 [204, 210, 211, 219]
Typical energy use	High: several GJ·t^{-1} CO_2 for solvent regeneration [205, 214, 210,218]	Low: down to ~60 kJ·mol^{-1} CO_2 (membraneless EMAR); ~40–80 kJ·mol^{-1} CO_2 EMAR [215]	Competitive with amines; some chemistries approach or outperform best amines [204, 210, 219]
Capital cost / complexity	Large columns, heat exchangers, solvent handling; well-known designs [205, 210, 214, 218]	Simplified flowsheet; no membranes, fewer auxiliaries, smaller footprint [206, 215]	Cell-stack plus balance-of-plant; membranes or GDEs often required; integration can reduce units [204, 210, 219]
Capture efficiency	High (often >90% in practice) [205, 214, 218,]	>90% CO_2 removal demonstrated with optimized GDEs [206]	High separations possible; efficiency depends on cell design and chemistry [204, 210, 212, 219]
Operating conditions	Near-ambient pressure, 40–120 °C; flue-gas tolerant [205, 214, 218]	Similar gas conditions; moderate temperatures; electrochemical cell constraints [206, 209, 215]	Wide range; from near-ambient to elevated T, various solvents and supports [204, 210, 212, 218, 219]
Environmental / degradation	Solvent degradation, corrosion, waste handling issues [205, 214, 218]	Reduced solvent handling; still amine-based but lower thermal stress [206, 209]	Degradation of redox carriers/electrolytes and membranes a key challenge [204, 210, 212, 219, 220,221]
Integration with utilization	Typically separate capture then compression and conversion [204, 210, 218]	Can be coupled to downstream utilization but mainly a capture step [206, 209]	Enables direct “reactive capture” and integrated CO_2 conversion in capture media [204, 210, 222, 223]

6. INDUSTRIAL INTEGRATION AND SCALE-UP

The integration and scale up of carbon capture, utilization and storage (CCUS) and direct air capture (DAC) in industries will rely on the ease of retrofitting systems, modular deployment and the ability to integrate them with the low carbon energy. Effective routes have to be a trade-off between engineering constraints, economics and system level flexibility [224, 225, 226].

6.1 Retrofitting Existing Plants

Emissions can be reduced by retrofitting established fossil fuel and waste to energy (WtE) plants with carbon capture and storage (CCS), without creating stranded assets, and making coal and gas dominated systems switch justly [227, 228, 229].
U.S. fossil power plant front end engineering design (FEED) studies indicate that there are three prevalent retrofit determinants.
Site specific considerations like availability of water, land limitations and access to new equipment greatly influence capture design and cost [230].
Integration level and capture efficiency are under the control of host plant characteristics such as flue gas composition, permissible steam extraction and operating mode [231, 232].
Constructability and modularization which is the number and offsite fabrication choices influence the schedule and capital expenditure [233].
The China system level modeling indicates that extensive retrofitted CCS on coal and gas fired plants decreases future capacity by up to 605 gigawatts and decreases cumulative decarbonization costs by 6.2-8.2% in 2060 and also reduces the cost of electricity supply by an average of 2-3 percent relative to a system which has not been retrofitted [234].
Amine-based post combustion capture in waste to energy retrofit in China reduces net electrical efficiency by 13-17 percentage points at 85-95% capture, and increases the avoided costs of CO_2 to an approximate of 153-236 €/tCO_2, but still contributes substantially to national climate targets when coupled with complementary policy frameworks [235, 236]. Comparable WtE reviews emphasize that currently, few large scale plants use CCS, but numerous feasibility and pilot projects in northern Europe have shown developed retrofit capacity [237].
There is also industrial integration to co firing biomass with CCS; bioenergy with carbon capture and storage, BECCS. Co firing of biomass with 10 percent of the overall pulverized coal in an Indonesian pulverized coal plant results in virtually carbon neutral operation, but increases the levelized cost of electricity (LCOE) by approximately 164 percent, which highlights the tradeoff between deep decarbonization and affordability [238].

6.2 Modular Deployment

Modularity has also been considered as one of the fundamental facilitators to allow quick and distributed scale up of DAC and smaller post combustion capture systems [238, 239, 240].
One view of modular, solid sorbent DAC estimates that a 1 gigatonne (Gt) CO_2/year would need approximately 20 million modules of current 50 $tCO_2 \bullet yr^{-1}$ capacity, which can be effectively realized by manufacturing capacity of the scale of the annual combined vehicle production of large non-Chinese automakers [238].

In order to sustain such factories (DAC factories), the following highlights were established.

(i) Standardized module designs in order to take advantage of learning through doing and supply chain efficiencies [241, 242].
(ii) New financing tools such as carbon purchase agreements (CPAs), to give long term demand signals [238].
(iii) Sorbent, fan, casing and balance of plant integrated supply chains which are globally replicable [243].

In smaller scales, modular DAC units in laboratories have shown the effectiveness of process intensification and digitalization of results. The improvement of CO_2 removal efficiency by 32%, power usage by 32.7 percent, and manufacturing cost of approximately 180 USD per unit of a 3D printed, stationary mixer-enhanced solid sorbent DAC module with built-in Internet of Things (IoT) monitoring demonstrated how low cost, plug and play modules could be used to distribute applications [244].

A new algae-based coating of DACCS which is direct air carbon capture and storage also makes use of modularity as hydrogel based microalgal coating on polymer surfaces can be deployed in large arrays, with modeled carbon removal efficiencies of 44 to 73% and costs of 702 to 1,585 US/tCO_2 and reliant on solar energy and biochar generation to store carbon [245].
Wider reviews on CCUS emphasize that adsorption based capture units, integrated capture conversion (ICCU) module and CO_2 hub concepts in terms of shared capture-transport-storage infrastructure are also advantaged by modular design hubs and designs, which save unit costs and ease integration into existing industrial clusters [246, 247, 248]. An example of a techno economic analysis of a Brazilian coal complex demonstrates, based on CO_2 hubs, is that levelized costs of avoided emissions can be reduced by a factor of 60 and that the emission factors can be reduced by 88 to 90 percent compared to standalone retrofits, despite higher total expenditures [249].

6.3 Coupling with Renewables

By coupling CCS and DAC with variable renewable energy (VRE) solar, wind and occasionally geothermal or bioenergy,

lifecycle emissions can be reduced, grid services can be offered, and capture systems can be autonomous with host plants [250, 251, 252, 253].

An overview of renewable integrated CO_2 capture reveals that solar, wind, bioenergy and geothermal integration can:

(i) Provide low carbon heat and electricity to capture to reduce the net emission of greenhouse gases (GHG)and in some cases, achieve net zero or net negative operation [254, 255].

(ii) Reduce renewable intermittency with flexible operation of capture during off peak periods or use capture and downstream utilization as an indirect form of energy storage (power to fuels/chemicals) [256, 257].

(iii) Minimize the use of steam that is extracted out of power plants hence retaining or even enhancing the efficiency of the plant in certain designs [258, 259].

Specific idea of renewable integrated flexible carbon capture (RIFCC) demonstrates that with renewables to power capture units on fossil plants, an economical grid decarbonization and intermittency approach can be achieved, especially in systems that have high VRE content and still have fossil capacity [260, 261]. Smart energy system studies show that flexible CCU (carbon capture and utilization) facilities can take excess renewable energy by turning CO_2 and hydrogen into synthetic fuels and chemicals, which is a good way to store energy and stabilize the grid [262, 263].

Another example is the coupled integrated energy systems. With added power to gas (P2G) and CCS, a hybrid concentrated solar power-combined heat and power (CdSW) system would decrease CO_2 emissions by 72.4% and would significantly improve wind power accommodation by utilizing the captured CO_2 to produce synthetic gas and by increasing dispatchability [264].

In the case of DAC, renewable coupling can be a common requirement to realize real negative emissions. According to reviews and case studies, DACCS when run on low carbon renewable has the potential to achieve net removal of up to -0.9 tCO_2 per tonne captured, but when operated on fossil intensive grids there is the risk of eroding or reversing climate benefits [265, 266]. Designs of Modular DAC can be incorporated with hybrid solar wind battery systems that can cut down on the energy cost as well as the capital cost by 15 to 20% and enhance the reliability of the weak grids [267].

A more sociotechnical perspective of CCUS highlights that the combination of capture and renewables and the combination of capture and a circular utilization pathway of CO_2 which is either synthetic fuels, polymers or building materials is not only essential to technical operation and economy, but also to societal acceptance and compatibility with goals of just transition and circular economy [268, 269].

Table10. Key Integration Strategies for Scale-Up

Strategy	Main industrial role	Key challenges	Citations
Retrofitting existing plants	Avoid stranded assets, fast abatement in power/WtE	Efficiency loss, site constraints, high costs	[270, 271, 272]
Modular deployment	Mass manufacturing, distributed capture and hubs	Supply-chain scale-up, standardization, finance	[273, 274, 275]
Coupling with renewables	Deep decarbonization, grid flexibility, net negative	Intermittency, land/water use, integration complexity	[276, 277, 278]

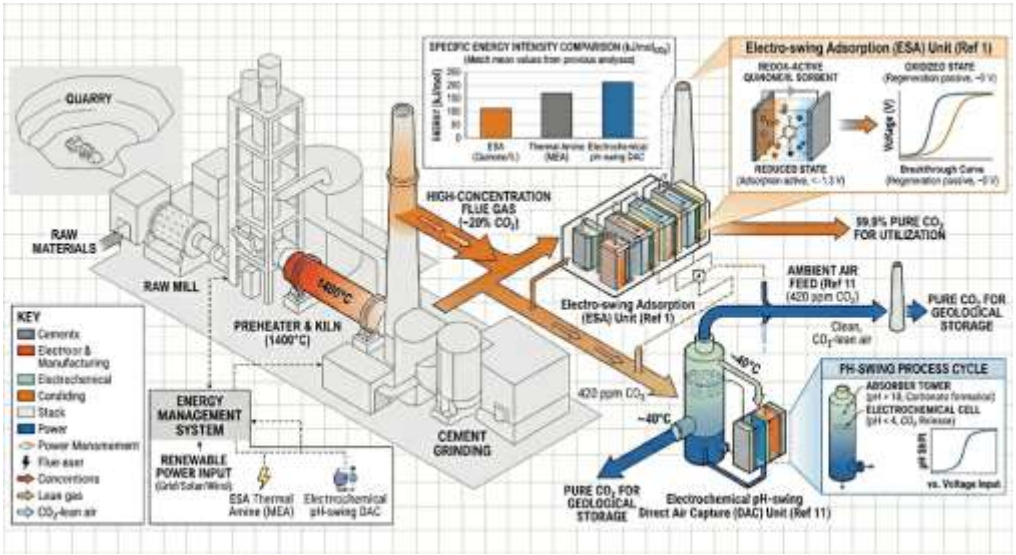

Figure 10. Integration into Industrial Plant

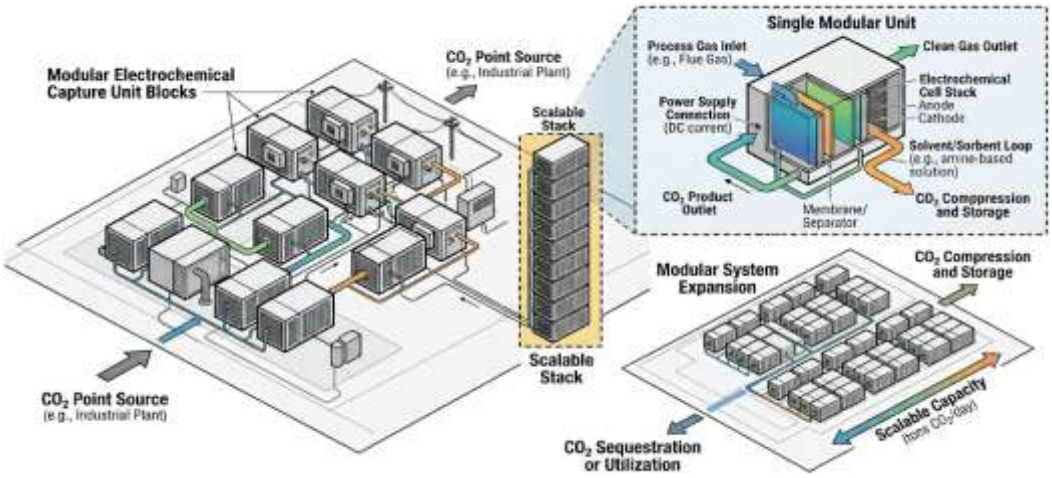

Figure 11. Modular Electrochemical Capture Units

7. HYBRID AND NEXT-GENERATION SYSTEMS

More and more carbon capture systems are being developed as hybrids and next generation systems that integrate membraneless electrochemical architectures and artificial intelligence (AI)-based control in an effort to achieve reduced costs, increased efficiency, and resilience to variable operating conditions. There are three methods to integrate Membraneless and Electrochemical Systems:

7.1 Membraneless and Electrochemical Systems.

Electrochemical carbon captures (ECC) separates carbon dioxide (CO_2) coupled to redox reactions that are powered by electricity instead of energy-intensive thermal regeneration. One of the most developed ECC routes is electrochemically mediated amine regeneration (EMAR), which has conventionally been based on ion selective membranes, which introduce significant capital expenditure and minimize longevity [279].

Recent studies have shown that membraneless EMAR can be done with gas diffusion electrodes (GDEs) on the anode and cathode to present gas-liquid interfaces, and remove the polymer membrane [197, 279]. This redesign eliminates not just the membrane but also the absorber column, flash tank, and circulation pumps, reducing capital costs by about 40% compared to traditional EMAR and reducing plant area [91]. This configuration reached over 90% CO_2 removal, using less than 60 kJ•mol $^{-1}$ CO_2 and an estimated levelized cost of capture of around 70 US -1 tCO_2, which is projected to be even lower, around 50 US -1 tCO_2, with further CO_2 removal such, further enhances the energy performance [284]. An example of this strategy is a dual functional electrocatalytic membrane (eCatMem): a gas is converted by laser induced graphene into a conductive, catalytically active membrane which is able to separate CO_2 (CO_2/N_2 selectivity of approximately 20) and electrochemically reduce it to formate with a Faradaic efficiency of approximately 70% at 1050 mA/. The goal of these membraneless and hybrid and energy consumption reduction achievable through increased current density and efficiency.

This was further developed into a two stage stackable membraneless EMAR platform with a broad selection of CO_2 sources which is between 20% flue gas down to 0.04% direct air and with high CO_2 selectivity, and techno economic potential at scale of about 5070 US dollars/tCO_2 [92].

The capture and electrochemical conversion are also included in hybrid designs. Capture conversion system distinguish three broad classes of architecture.

(i) Independent capture and electrolysis trains,

(ii) Single cell coupling with the capture medium directly electrolyzed, and

(ii) two cell architecture, such as bipolar membrane electrodialysis (BPMED) to liberate CO_2 and a CO_2 reduction cell [96, 280, 281].

Techno economic comparisons show that these combined electrochemical capture conversion systems can eliminate solvent re-generation and compression stages with significant reduction in the overall energy and production costs as long as a high Faradaic efficiency and low cell voltage is ascertained [282, 283].

Beyond solution based systems, combination of membrane or adsorption based capture and gas diffusion electrode CO_2 reduction is also coming into play as a next generation. Conceptual designs incorporate selective membranes or solid sorbents as part of the GDE architecture, such that the captured CO_2 is in situ delivered to the catalyst layer and that the separate chemical capture is thus avoided, and as electrochemical systems is compact, modular and stackable capture units that can be flexibly deployed at point sources or in direct air capture and ocean capture systems [91, 286].

7.2 Intelligent Systems using Artificial Intelligence Control.

To make smart, self-optimizing systems, AI is becoming integrated throughout the carbon capture, utilization and

storage (CCUS) value chain. There are three primary identified functions:
(1) Process monitoring and fault detection,
(2) Real time optimization and scheduling, and
(3) Materials and system design [287, 288, 289].
In oil and gas CCS facilities to gain operational control, AI powered automation processes machine learning (ML) and neural networks on sensor data at the plant to optimize solvent circulation, energy utilization, and compressor operation, and provide predictive maintenance, minimizing downtime costs and increasing CO_2 sequestration rates [290]. In power systems, an artificial intelligence scheduling strategy is used to coordinate post combustion capture facilities with variable renewable generation: a deep belief neural network is used to model the complex carbon-heat-electricity interactions, and particle swarm optimization is used to identify operating profiles that minimize costs and emissions and renewable curtailment.
The system was able to detect a leakage 28 times faster, injection performance 31 times higher, and ecological risk 18 times less in simulations and withstand sensor faults [289].
On the system design level, AI and machine learning are suggested to be:
•Hybrid mechanistic-data driven optimization of CCUS network structure, location and operation to minimize lifecycle costs [287].
•ML Generative and interpretable ML can quickly discover improved capture solvents, sorbents, and membranes with higher CO_2 capacity and stability [293, 294]. Digital twins and federated learning on combined CCS-hydrogen infrastructures, which allow predictive control and sharing of cross project knowledge without violating the privacy of data [295]. Collectively, these developments point to the fact that Having a real data case study, the decrease in renewable curtailment was 51% and the total CO_2 emissions were captured by means of excess renewable power, proving the value of AI in the flexible capture functioning [291].
In new CCU biotechnologies, artificial neural networks, support vectors machines, random forests, and least squares boosting (LSBoost) artificial intelligence models were used on a moving bed biofilm reactor with algal photobioreactor system. LSBoost reached high predictive accuracy (0.97) with CO_2 and hydrogen sulfide emissions, making it useful in monitoring and controlling emissions, unlike the traditional statistical tools [292]. Offshore and ocean based CCUS are also being developed using smart AI systems. One suggested model is a combination of Internet of Things (IoT) sensors, autonomous vehicles, satellite imaging, and sophisticated AI models such as convolutional neural networks, long short term memory networks, generative adversarial networks, and reinforcement learning into a digital twin control loop.
next generation hybrid capture technologies in particular the membraneless electrochemical systems are likely to be implemented as AI-supervised smart modules, with machine learning based controllers constantly adjusting currents, flows, and operating modes in reaction to real time energy prices, renewable availability, and performance diagnostics [296, 297, 298].

Table 11. Summary of Hybrid Next-Generation Features

Feature	Technical role in capture systems	Example benefits	Citations
Membraneless EMAR and electrochemical capture–conversion	Remove membranes, absorbers and pumps; couple capture to redox and CO_2 reduction	~50% lower capture cost; compact, stackable, multi-source operation	[91, 299]
AI-driven smart control (ML, DL, RL)	Real-time monitoring, optimization, scheduling, digital twins	20–50% reductions in curtailment, faster leak detection, higher capture efficiency	[300, 301]

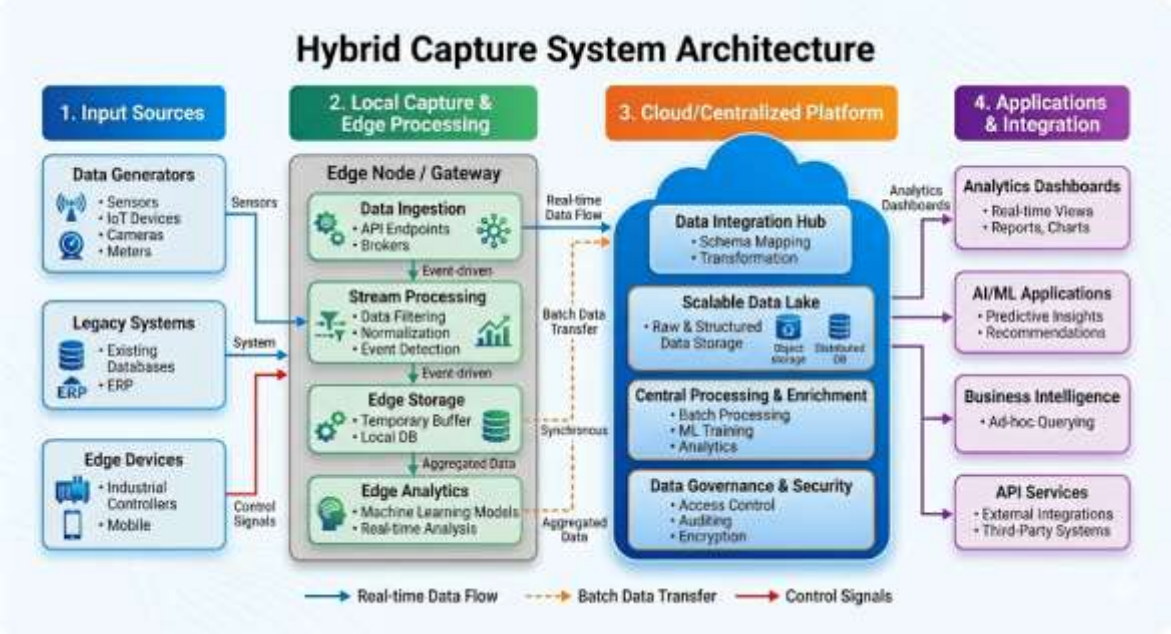

Figure 12. Hybrid Capture System Architecture

8. CHALLENGES AND RESEARCH GAPS

8.1. Material Degradation

Capture materials. Broadly applied amine solvents have disadvantages of evaporation, oxidative decomposition, and corrosion, increasing operation costs and reducing lifespan [302]. More advanced alternatives like ionic liquids, solid adsorbents and membranes can be used to enhance performance but are typically costly, synthetically complicated, and not very stable over time or selective to CO2 in real flue gas environments with steam and impurities [303, 304,305].

Impurities (H_2O, SO_2, H_2S, O_2) in dense phase CO_2 can form separate liquid phases containing strong acids or elemental sulfur, causing severe corrosion of steels and degradation of polymers in pipelines and wells [306]. In the field, CO_2 rich brines cause carbonation-induced cement degradation, microcracking, and zonal isolation loss; field scale testing protocols are not standardized and there is limited field scale data on durability of new cement systems [307].

8. 2. Scale Up Limitations

Although some of the capture routes are technically mature, there are only dozens of large CCS/CCUS projects in operation worldwide, which is much less than the number required to meet climate targets [308].

Major highlight include:

•Continued lack of demonstration between lab/pilot and million tonne scale plants, attributed to high capital cost, energy penalty, and solvent/sorbent make up rates [308, 309].

•Many promising materials and hybrid processes stuck at low TRL; screening all options at pilot scale is infeasible without better multi scale modeling and high throughput tools [310, 311].

On storage, the saline aquifer exploration and characterization is limited, and multi-source storage hubs have not been well coordinated to scale to gigatons [310,312, 313].

Table 12. Technology Readiness and Scale-Up

Aspect	Mature (TRL 8–9)	Low–mid TRL & gaps	Citations
Capture	Amine post-combustion, NG processing	Oxy-fuel, advanced adsorbents, membranes, DAC	[314, 315]
Storage	EOR, some saline sites	Large saline aquifers, mineralization, hubs	[316, 317]

8. 3. Lack of Long-Term Data

Storage, long term measurement, monitoring and verification (MMV) of leakage risk, caprock integrity, and induced seismicity is not fully developed; most of the schemes are at an early stage, with unpredictable performance over the lifetime, and societal acceptance [318, 319, 320].

In the case of material and systems, the majority of the information is obtained in short term laboratory experiments; decades scale performance of new solvents, sorbents, membranes, and CO_2 resistant well cements under realistic (cyclic) conditions are lacking [321, 322, 323]. It is also in life cycle assessment studies where the lack of primary data is highlighted and where integrated environmental and techno economic data over complete project lifetimes are desired [324, 325].

Key, interconnected research gaps that slow the implementation of CCUS include material degradation in real-world situations, the challenges of scaling promising technologies to the level of multi million tonne systems, and the unavailability of long term operational and field data. This will be tackled through coordinated large scale demonstrations; standardized durability tests, improved multi scale models, and increased long horizon observations.

9. FUTURE PERSPECTIVES FOR CARBON CAPTURE SYSTEMS

9.1 Capture Technology Electrification.

Carbon capture in the future is likely to move away from thermal processes to electrified capture, with renewable electricity rather than steam or fossil energy. Electrically heated and electrochemical systems are able to reduce penalties on energy, work with less harsh conditions and integrate more readily with more variable renewable energy like wind and solar [122, 326,327,328].

In electrochemically mediated carbon capture (EMCC), temperature or pressure swings are substituted with redox-based cycles allowing modular designs that can be based on direct air capture or point sources [6, 328]. Joule, microwave, or induction heating of temperature swing adsorption is also developing at a very fast pace, but there are still problems in terms of heating the bed uniformly, cycling quickly and technology economic evaluation [329, 330]. With the decarbonization of electricity, electrified capture is gaining popularity as a method of providing deep emissions reductions [331,332].

9.2 Decentralized Carbon Capture

Decentralized carbon capture uses smaller modular units that are configured at distributed emissions or in regional bioenergy systems, and not just at large centralized facilities. Carbon dioxide removal and local heating, electricity, or hydrogen can be produced by decentralized bioenergy with carbon capture and storage (BECCS), especially in rural or remote regions [333, 334, 335]. Simulations indicate that small scale BECCS with local residues such as wheat straw and waste wood has the potential to provide significant negative emissions and offset a significant portion of national removal goals, the effectiveness of which is highly dependent on operation decisions and policy incentives [333]. The advanced decentralized control and flexible operation of distributed post combustion plants to deal with varying levels of flue gas flow also suggests that future capture infrastructure must be both modular and dynamically controllable [336, 337]. The resulting decentralization would enhance biomass use in the region, decrease transportation requirements and coordinate the capture placement with the local energy infrastructure [333].

9.3 Integration with Carbon Capture and Utilization (CCU)

Future directions in the integration of capture with CCU are closer integration to establish a system of circular carbon and enhance project economics. Integrated carbon capture and utilization (ICCU/ICCC) seeks to couple capture with catalytic or biological conversion in the same process or location, which lowers the costs of conditioning and compression and allows on site generation of fuels and chemicals like methanol, methane, and formate [338,339,340]. New ideas are bio integrated CCU, in which methanogenic microorganisms then use the captured CO_2 and renewable hydrogen to produce synthetic methane to the exclusion of energy intensive thermal desorption steps [341]. Regenerated power to renewables such as H_2, CCU, and synthetic fuels can demonstrate how coupled systems can provide fuels to industries and also significant indirect emission reductions [341, 342]. Reviews of the CCUS systems point out that these integrated capture utilization storage systems, with facilitating policy and ongoing innovation, are the focus of achieving large scale mitigation and the journey towards carbon neutrality [15, 246,343].

Table 13. Future Directions

Future direction	Key idea	Citations
Electrified capture	Use renewable electricity for CO_2 separation	[6, 326; 328; 329]
Decentralized capture/BECCS	Modular units and regional biomass for CDR	[333; 336; 337]
Integrated capture with CCU/ICCU	Direct coupling of capture with conversion	[232, 341, 345; 338]

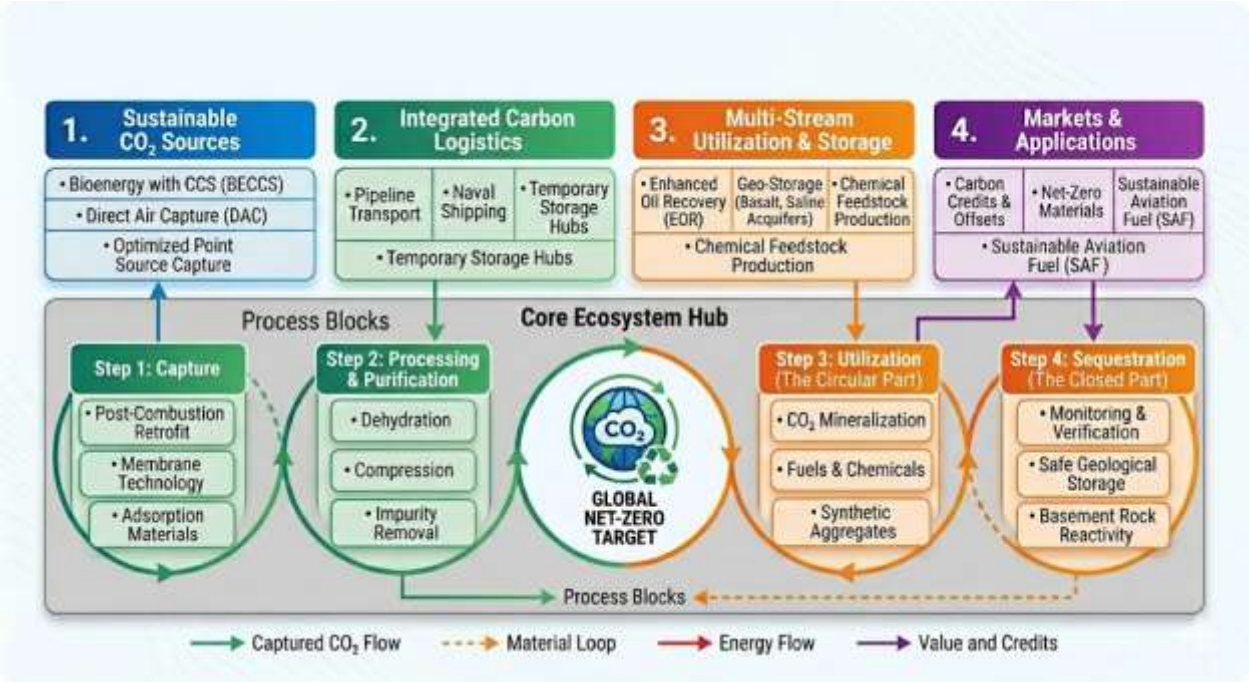

Figure 13. Future Carbon Capture Ecosystem

10. CONCLUSION

The development of carbon capture, utilization, and storage (CCUS) is indicative of a technological transition of isolated purpose, post combustion capture systems to a diversified portfolio of advanced solvents and sorbents, membranes, cryogenic and chemical looping, and at-system scale integration with utilization and storage. More mature techniques like amine absorption and pre combustion capture have already been deployed commercially and new hybrid and novel techniques are underway to seek lower energy penalties and costs. In recent reviews, CCUS is shifting towards proof of concept to industrial deployments, and there is a definite trend of standalone capture units into integrated chains of CCUS, focusing on optimization of the system, techno economic performance, and specific solutions to the sector. The highest technology readiness is post combustion and pre combustion capture and the lowest is the membranes, electrochemical and some DAC routes, though these are rapidly developing For industry, CCUS has become a cornerstone option in hard to abate industries including steel, cement and chemicals, where there are few deep decarbonization options. Nevertheless, high cost of capital and operations, energy demand, infrastructure requirements and social acceptance are significant hurdles to large scale implementation. As noted in reviews, the roll out of industrial applications will rely on enabling policy (carbon pricing, tax credits, subsidies), risk sharing schemes, and the co-ordination of transport and storage networks Most studies agree that CCUS should be rolled out at a very high rate and scale to achieve mid-century climate targets, but that the reality is much slower than the modeled paths. Short term adoption will concentrate on high purity and low cost uses and in areas with good policy backing, whereas more widespread diffusion will be dependent on decreased cost due to innovation, learning by doing, and the formation of enduring CO_2 markets and regulatory frameworks.

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