Breaking Barriers in Carbon Dioxide Removal with Electrochemistry

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Silvan Aeschlimann and Charithea Charalambous, *Breaking Barriers in Carbon Dioxide Removal with Electrochemistry*, RMI, 2024, **https://rmi.org/insight/breaking-barriers-in-carbon-dioxide-removal-with-electrochemistry**.

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Acknowledgments

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RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.

About Third Derivative

Third Derivative, RMI's global climate tech accelerator, is accelerating the rate of climate innovation. Third Derivative's inclusive ecosystem rapidly finds, funds, and scales climate tech globally. By uniting and aligning investors, corporations, and experts with the world's most promising climate tech startups, Third Derivative bridges finance and resource gaps to increase the speed to market. The flexible and highly curated remote accelerator program enables startups to focus on their unique needs and opportunities. Together, we are moving markets to achieve an equitable climate future. Learn more at **www.third-derivative.org**.

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Executive Summary

Electrochemistry stands poised to transform the field of carbon dioxide removal (CDR) by significantly reducing the energy requirements, and therefore costs, of prominent CDR pathways. When powered by clean electricity — which is expected to further decrease in price by as much as half and become more widely available over the next decade[1] — electrochemistry-based CDR systems can be an affordable and durable part of a global CDR portfolio aimed at meeting global temperature targets.

Exhibit ES1 (next page) illustrates the potential of electrochemistry to reduce the projected cost of CDR by over 50% using the example of a 1 megaton (Mt) per year solid sorbent direct air capture (DAC) plant. Similar innovation pathways could be envisioned for other CDR approaches based on electrochemistry, such as indirect water capture (IWC) and hybrid systems (HYB).[i]

Startups and investors are recognizing the potential of electrochemistry in CDR. From 2019 to March 2024, the number of startups leveraging electrochemistry for CDR has increased from three to 24, with many securing initial funding rounds. Despite this growth, the total cumulative investment into electrochemistry-based CDR of $300 million to $400 million remains far below what is necessary for the sector to achieve its full potential. RMI's *Applied Innovation Roadmap*[2] estimates that at least $2.5 billion to $7 billion will be needed over the next 15 to 20 years to demonstrate the viability of known electrochemistry-based approaches at scale.
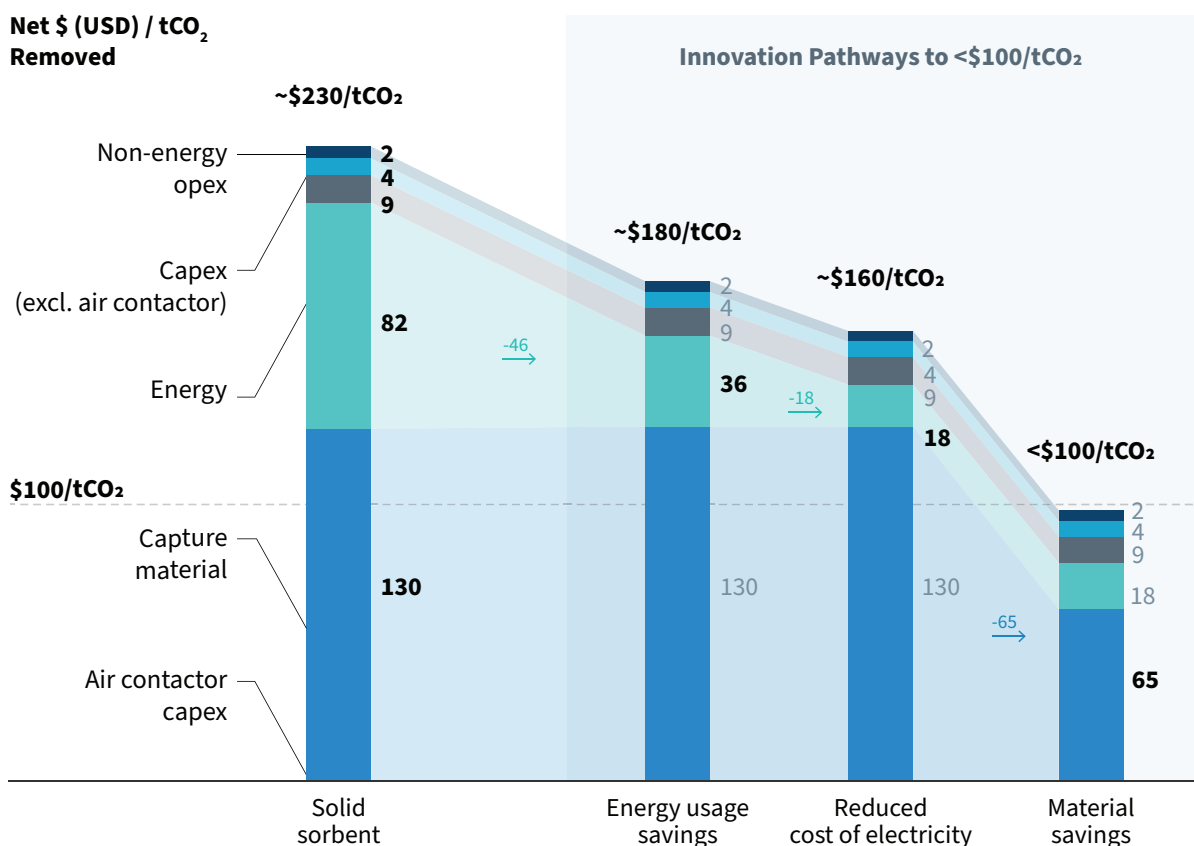
Electrochemistry-based CDR shows high potential to improve the efficiency and cost of engineered CDR systems, but developers will need to tackle key challenges such as manufacturability, system integration, and system longevity in real-world environments. Because startups are in the early stages of addressing these risks and demonstrating system designs, it can be challenging for investors to confidently assess the viability and potential of these technologies.

This brief aims to equip investors, entrepreneurs, and research funders with critical insights for making well-informed decisions on CDR technologies that employ electrochemistry. It seeks to fill the gap in independent evaluations of technologies' effectiveness and scalability. The brief provides an overview of the state-of-the-art applications of electrochemistry in CDR, highlights the critical trade-offs in various electrochemistry-based CDR systems, and offers practical guidelines on avoiding biased or inaccurate assessments.

Based on the review of the CDR startup landscape, this brief identifies eight electrochemical CDR system archetypes currently being pursued. CDR systems are grouped based on (1) the core electrochemical process used, (2) the specific CDR approach, and (3) the role of the electrochemical cell in the CDR system. Exhibit ES2 (page 9) outlines these eight system archetypes and illustrates their comparative advantages.

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i   DAC refers to approaches that use machines to directly remove carbon dioxide from the atmosphere in a concentrated form; IWC refers to approaches that indirectly remove carbon from the air by altering water chemistry. HYB approaches merge multiple CDR approaches, such as combining DAC with enhanced rock weathering.

Electrochemistry's Innovation Pathways to Cost Reduction by 2050

Net $ (USD) / tCO_2 Removed

Innovation Pathways to <$100/$tCO_2$

~$230/$tCO_2$

Non-energy opex — 2

4

9

Capex (excl. air contactor)

82

Energy

-46 →

~$180/$tCO_2$

2

4

9

36

-18 →

~$160/$tCO_2$

2

4

9

18

<$100/$tCO_2$

$100/$tCO_2$

Capture material — 130

130

130

2

4

9

18

-65 →

65

Air contactor capex

Solid sorbent   **Energy usage savings**   **Reduced cost of electricity**   **Material savings**

Notes: Cost values are from the National Academy of Sciences (NAS) and correspond to solid sorbent-based DAC technologies based on a 1Mt/year scale. Electricity is $0.06/kWh. All other capital expenditures (capex) and operating expenses (opex) are the midpoints of the range reported by NAS, with a 12% fixed charge factor to determine annualized capital expenditures. Innovation pathways consider: energy savings due to electrochemistry-based DAC values reported by companies (from about 5 gigajoules per ton of CO_2 [GJ/tCO_2] to about 2 GJ/tCO_2); reduced cost of electricity (from $0.06/kWh to $0.03/kWh); and 50% material savings due to cheaper materials used, longer durability and stability, material recyclability, and reducing manufacturing costs.

RMI Graphic. Sources: *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, National Academy of Sciences*, 2019; and for the solid sorbent cost component, Eve Hanson and John Matson, *Direct Air Capture: Capitalizing on the Defining Decade for Technology Development*, Third Derivative, 2021.

This information can be used to map electrochemistry-based CDR system archetypes to investors' profiles and industry partnerships.

When conducting due diligence on electrochemistry-based CDR startups, RMI encourages potential investors to follow these four best-practice principles to help distinguish companies with competitive and realistic performance projections from those unlikely to scale:

1. **Review the latest literature for up-to-date benchmarks on electrochemical technologies and costs:** Regularly check for comprehensive independent performance assessment and techno-economic analysis (TEA) for technologies of interest.

2. **Ask startups for data that enables unbiased comparisons across systems.** That includes requests for:
   a. Clearly defined system boundaries for any TEA or life-cycle assessment (LCA) data they share.
   b. Metrics underlying their reported energy requirements.
   c. A detailed comparison between their electrochemical process/system and a benchmark process/system.
   d. Relevant data to assess the scalability of their system, including a list of major components, current material costs and expected cost trajectories, the rate of by-product generation, patents they hold, and targeted sites.

3. **Compare similar system contexts:** Only compare cost and energy data for systems using the same system boundaries.

4. **Contextualize startup performance data:** Given all electrochemistry-based CDR systems are at an early stage of technology readiness, do not overly rely on the nominal values of TEAs.

Exhibit ES2 — Comparison of Electrochemistry-Based CDR System Archetypes

		Archetypes					
Role of cell	**CDR approach**	**Electrochemical process**	**Comparative advantage among archetypes**				
Electrochemical CO$_2$ capture & release (ECCR)	Direct air capture (DAC)	1 Proton-coupled electron transfer (PCET) with metal oxides	⚡	⚙	💡			
		2 Redox organic carriers (ROC)	⚡	⚙	💡			
Electrochemical CO$_2$ release (ECR)		3 Electrolysis (EL)			💡	⤴	⧗	
		4 Bipolar membrane electrodialysis (BPMED)			💡	⤴	⧗	
Electrochemical preprocessing of inputs (EPOI)	Indirect water capture (IWC)	5 BPMED for CO$_2$ stripping				⤴		👥
		6 BPMED for ocean alkalinity enhancement (OAE)		⚙		⤴		👥
	Hybrid (HYB)	7 EL			💡	⤴		👥
		8 BPMED			💡	⤴		👥

⚠	⚙	💡	⤴	⧗	👥
Energy use	System engineering simplicity	Measurement, monitoring, reporting, & verification simplicity	Technological maturity	Material lifespan	Potential co-benefits

Notes: The eight electrochemistry-based CDR system archetypes are based on: (1) the core electrochemical process used: PCET, ROC, EL, BPMED; (2) the specific CDR approach: DAC, IWC, HYB; and (3) the role of the electrochemical cell in the CDR system: ECCR, ECR, EPOI. A description of these terms can be found in the *Glossary* section.

RMI Graphic. Source: RMI dataset

Glossary

Term	Abbreviation	Description
Applied (cell) potential		The voltage that must be applied to an electrochemical cell to initiate the reaction.
Bioenergy with carbon capture and storage	BECCS	CDR approaches that use photosynthesis as the CO_2 capture step but then rely on combustion or gasification to produce energy and to convert that biomass to CO_2, which is then stored.
Biogenic carbon dioxide removal	bCDR	CDR approaches that rely on plants, using naturally occurring biogenic carbon fixation mechanisms to capture carbon dioxide from the atmosphere. The most important of these mechanisms is photosynthesis. Prominent examples include afforestation or BECCS.
Bipolar membrane electrodialysis	BPMED	An electrochemical process that uses bipolar membranes, composed of laminated anion and cation exchange layers that selectively transfer ions to the anode and cathode, effectively controlling the pH of the cell.
Carbon dioxide removal	CDR	Any activity to specifically remove carbon dioxide from the atmosphere or ocean and store it in Earth's biosphere or lithosphere.
Cell separator		A component of the electrochemical cell used to promote increased selectivity, limited unwanted reactions, and increased product purity.
Current density		The amount of electric current passing through a cell per unit area of the electrode surface. Current density describes the intensity of the reaction or the quality of the electrode catalyst. The higher the current density, the more intense the reaction. However, a greater current density also requires a higher voltage to sustain the process, leading to an increased power demand.
Direct air capture	DAC	Approaches that capture CO_2 directly from the atmosphere to deliver it in a concentrated stream.
Electrocatalysts		A material that participates and accelerates electrochemical reactions at the surface of an electrode or as the electrode surface itself.
Electrochemical cell		A device that generates electrical energy from chemical reactions or uses electrical energy to drive chemical reactions.
Electrode		A component of the electrochemical cell that provides the physical interface between the electrical circuit and the electrolyte.
Electrode potential		The potential difference between the metal electrode and the solution, a measure of the driving force for a given electron transfer reaction.
Electrolysis	EL	An electrochemical process that directly splits water molecules to facilitate a pH swing near the two electrodes, often by generating H_2 and O_2 gases at the cathode and anode, respectively.
Electrolyte		A substance containing free ions that carry electric current between electrodes or a reactant in the chemical processes.
Electrolytic cell		An electrochemical cell that uses electricity from external sources to cause chemical reactions and produce desired chemicals.
Electronic conductivity		The ability of a material to carry electrical current, e.g., the movement of electrons in a metallic conductor (electrons conduct electricity in solid conductors or semiconductors).

Electrosynthesizer		A device that uses electrical energy for the synthesis of chemical compounds.
Energy requirement		The amount of energy needed to run a system completely.
Faradaic efficiency		How effectively an electrochemical process converts electrical energy into chemical products. A higher faradaic efficiency indicates lower energy waste.
Geochemical carbon dioxide removal	gCDR	CDR approaches that rely on minerals. They use naturally occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert carbon dioxide from the atmosphere into solid carbonate minerals or dissolved bicarbonates. Prominent examples include terrestrial and coastal enhanced weathering.
Hybrid systems	HYB	CDR approaches that merge multiple CDR approaches, such as combining DAC with enhanced rock weathering.
Ionic conductivity		The electrical conductivity from the movement of ions through an electrolyte (as ions conduct electricity in solutions).
Indirect water capture	IWC	CDR approaches that indirectly remove carbon from the air by altering water chemistry.
Life-cycle assessment	LCA	The method for assessing the environmental impacts associated with all stages of a process, product, or service.
Limiting current		The limiting quantity of current needed so that the concentration of the reactant at the surface falls to zero, indicating that the reaction cannot take place at a current higher than this value.
Mass transport		Mass transport in electrochemistry refers to the movement of materials, such as CO_2, to or from an electrode during an electrochemical reaction, which involves either consumption or generation of these materials. This transport of mass is a critical factor in determining the rate and efficiency of the reaction. Efficient mass transport is essential for the reaction to occur quickly and effectively.
Ocean alkalinity enhancement	OAE	A CDR approach that involves adding alkaline substances to seawater to accelerate the ocean's natural process of sequestering carbon.
Overpotential		Losses that occur in electrochemical cells: **Charge transfer:** the part of the cell voltage that is lost to maintain the required rate of reaction on the electrodes **Resistive losses:** losses due to electronic and ionic conduction **Mass transport:** evident at high current densities and refers to losses resulting from mass transport limitations. The higher the losses, the greater the voltage required to initiate and sustain the reaction, leading to a decrease in the process's efficiency.
Proton-coupled electron transfer with metal oxides	PCET	An electrochemical process in which metal-based electrodes release or consume ions (H^+ or OH^-) through redox reactions, altering the pH around the electrodes.
Redox organic carriers	ROC	Redox organic carriers are chemical substances that bind to or release target species through reduction and oxidation (redox) reactions, respectively, in an electrochemical process.
Synthetic carbon dioxide removals	sCDR	CDR approaches that use engineered systems powered by low-carbon energy to directly separate carbon dioxide from the air and capture it, or to alter water chemistry to indirectly remove carbon dioxide from the air. Prominent examples include a range of DAC and IWC technologies.
Techno-economic analysis	TEA	A method for modeling and predicting the technical and economic performance metrics of a systems.

Technology readiness level	TRL	An empirical assessment of the technology maturity of a technological approach.
Thermodynamic minimum		The state of a system where it has the lowest possible energy or is in its most stable configuration, according to the principles of thermodynamics.
Voltage		In the context of electrochemistry, voltage is the amount of electrical potential required to drive a desired chemical reaction. It depends on the reaction's thermodynamic properties and the need to overcome internal losses within the cell. Essentially, a higher voltage indicates that more energy is necessary to initiate and sustain the reaction.

Introduction

Although reducing emissions from power, mobility, buildings, and industry is the critical and immediate priority, these efforts must be complemented by CO_2 removal to enable a sustainable climate future. Scientific consensus indicates that to stay within a 1.5°C temperature increase and avert the most catastrophic consequences of climate change, billions of tons of CO_2 will need to be removed annually by 2050 — in addition to significant emissions reduction.[3]

As explored in RMI's *Applied Innovation Roadmap*,[4] a diverse portfolio of CDR approaches is necessary because no method alone can fulfill the extensive need for carbon dioxide removal, and different approaches will be favorable in different geographies and industries. RMI currently tracks 29 distinct CDR approaches across three categories,[ii] each offering unique advantages and challenges.[5,iii] Approximately half of these methods either already use electrochemistry or could be transformed by breakthroughs in electrochemistry. Adopting a diverse portfolio of CDR strategies helps reduce the risks associated with each individual method, provides the flexibility to customize CDR approaches to fit specific geographic and environmental conditions, and unlocks a diverse set of co-benefits.

RMI's first DAC insight brief (published on our Third Derivative platform)[6] identified electrochemical DAC as a promising solution within the synthetic CDR (sCDR) category because it could offer high efficiency, full electrification, and cost-effectiveness in carbon removal. Since then, there has been significant growth of CDR

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ii   The three categories are biogenic CDR (bCDR), geochemical CDR (gCDR), and synthetic CDR (sCDR). Definitions are in the *Glossary* section.

iii   Some of these approaches required additional CO_2 storage.

Exhibit 1 — Advantages and Challenges/Risks to Synthetic CDR Deployment

Defining sCDR	Advantages	Challenges/risks	High level CDR approaches
Synthetic CDR (sCDR) approaches mainly rely on energy. They use engineered systems powered by low-carbon energy to directly separate carbon dioxide from the air and capture it, or to alter water chemistry to indirectly remove carbon dioxide from the air.	**High durability**, assuming associated storage **High scalability** For DAC, likely **lower environmental risks** than other CDR approaches **Controllable measurement**	**High costs*** **High energy use*** **High system complexity*** **Currently at low TRL** and/or low installed capacity	**Direct air capture (DAC)** approaches use machines to capture CO_2 from the atmosphere in a concentrated stream. **Indirect water capture (IWC)** approaches indirectly remove carbon from the air by altering water chemistry. **Hybrid (HYB)** approaches merge multiple CDR approaches, such as combining DAC with enhanced rock weathering.

*These challenges/risks of energy-intensive CDR approaches can be overcome through electrochemistry.

RMI Graphic. Source: RMI, *Creating a Diversified Solutions Portfolio to Meet the Scale of the Carbon Removal Challenge*, 2023

startups, expanding the application of electrochemical processes in CDR systems. Exhibit 1 defines sCDR, outlines the unique advantages and challenges of this CDR category,[7] and details the three high-level CDR approaches in which the application of electrochemistry is explored within the scope of this insight brief.

Integrating electrochemistry into CDR applications, particularly within sCDR, could significantly reduce energy requirements and improve economics in at least four different ways:

1. **Lower energy use** (reduces operating expenditures): Electrochemistry targets CO_2 bonds directly for CO_2 release, reducing energy use compared with temperature swing methods often used in DAC systems that heat the entire reactor.

2. **Simplified systems (**reduce capital and operating expenditures): By eliminating complex temperature and pressure swings, the system becomes simpler, thus reducing both capital and operating expenditures.

3. **Modular designs** (reduce capital and operating expenditures): Electrochemistry enables modular system designs that are adaptable across various environments, facilitating standardization and mass production. These systems can be integrated with the electricity grid or operate independently on intermittent electricity sources, enhancing their deployment flexibility.

4. **Valuable by-products:** The production of valuable by-products, such as hydrogen, not only supports the energy transition but can also improve overall economics.

Accordingly, there are compelling reasons to believe electrochemistry can transform the CDR industry. However, the technical readiness of electrochemistry-based solutions remains relatively low, and the overall investment to date in electrochemistry-based CDR startups lies between $300 million and $400

million. This amount is significantly less than the $2.5 billion to $7 billion RMI's *Applied Innovation Roadmap*[8] estimates will be needed to test and demonstrate the viability of known electrochemistry-based approaches at scale.

This brief aims to equip investors, entrepreneurs, and research funders with critical insights for making well-informed decisions on CDR technologies that employ electrochemistry. It seeks to fill the gap in independent evaluations of technologies' effectiveness and scalability. The brief provides an overview of state-of-the-art applications of electrochemistry in CDR, highlights the critical trade-offs in various electrochemistry-based CDR systems, and offers practical guidelines on avoiding biased or inaccurate assessments.

The brief exclusively covers CDR systems that use electrochemistry for capturing CO_2 from diluted sources, either directly from the air or indirectly from the ocean. As such, it omits electrochemical applications in bioenergy with carbon capture and storage (BECCS) or CO_2 utilization. Furthermore, it does not include the latest advancements in electrochemical and photoelectrochemical techniques for the capture and conversion of CO_2 into fuels or other high-value products. The scope was chosen to explore the application of electrochemistry in CDR. CO_2 utilization is unlikely to yield negative emissions in most cases.[iv] Including BECCS would necessitate a broader examination of the field of electrochemistry-based carbon capture, utilization, and storage (CCUS), which constitutes a climate mitigation but not a CDR solution.

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iv   Although CO_2 utilization may not lead to negative emissions, it can be critical for decarbonizing hard-to-abate industries such as aviation. See RMI's insight brief on e-fuels: **https://www.third-derivative.org/insights**.

Application of Electrochemistry in CDR: State of the Field

Electrochemistry, the study of relationships between electrical energy and chemical reactions, plays a critical role in the energy transition. It is fundamental in developing efficient energy storage and conversion technologies, including advanced batteries and fuel cells, which are vital for storing renewable energy and powering electric vehicles. Additionally, electrochemistry is instrumental in green hydrogen production, CCUS, and most recently in CDR.

From 2019 to 2024,[v] the number of electrochemistry-based startups increased from 3 to 24, with numerous promising pilot and demonstration projects underway, and startups successfully closing funding rounds. Exhibit 2 (previous page) illustrates all profiled electrochemistry-based CDR startups that fall within the scope of this work, categorized by the amount of funding raised and their deployment stage.

Exhibit 2 — Startup Landscape by Funding and Deployment Stage

**Cumulative funding to-date ($M, USD)**
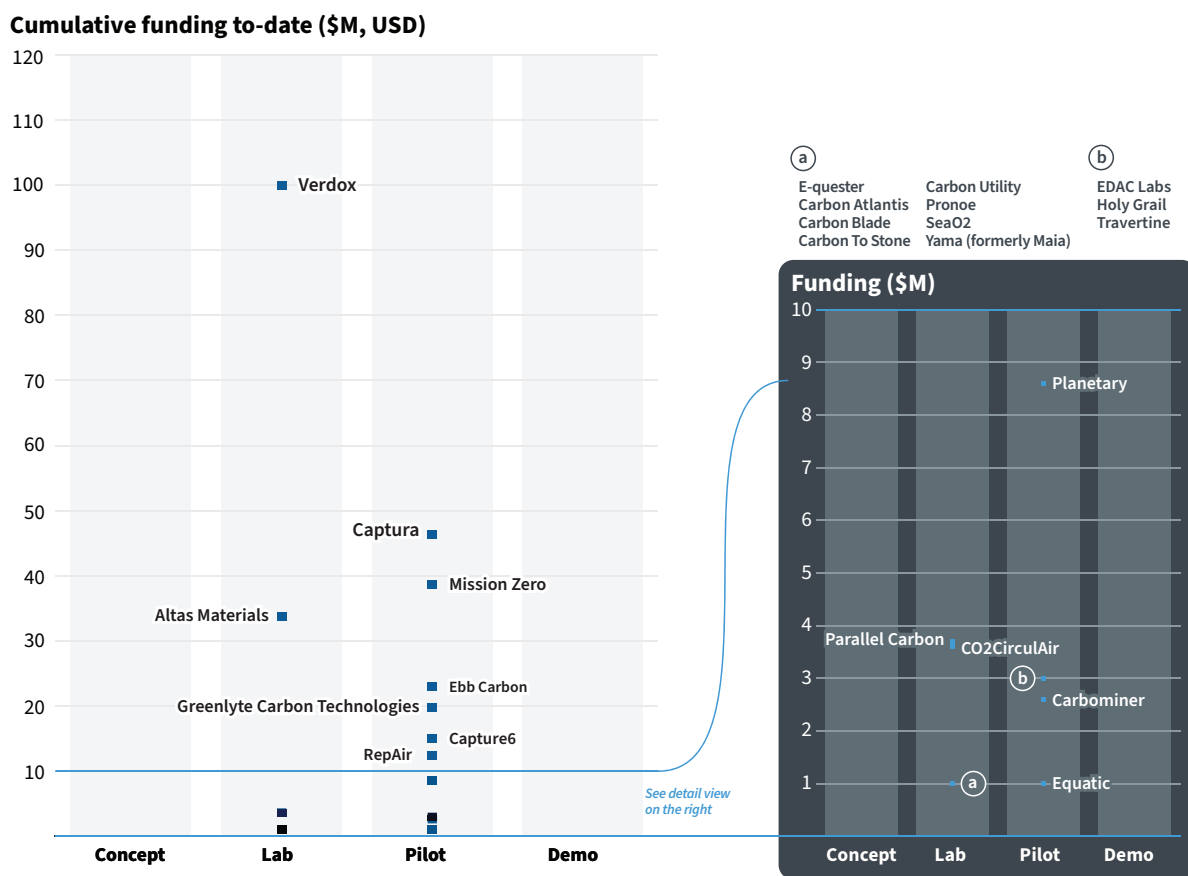
Note: Non-dilutive funding is not added to these values.

RMI Graphic. Source: RMI dataset, March 2024

At the core of applying electrochemistry to CDR is the electrochemical cell, a versatile device that uses electrical energy to drive chemical reactions. Exhibit 3 illustrates a simple schematic of an electrochemical cell. *Appendix A* supports more sophisticated readers who are conducting technical due diligence on electrochemistry-based CDR startups. It lists the key components, desired properties, and the most important trade-offs of electrolytic cells that apply to all electrochemical cells, regardless of their specific CDR application.

Exhibit 3   **A Basic Electrochemical Cell**

1 An electrochemical cell consists of two **electrodes** — an **anode** and a **cathode** — immersed in an **electrolyte** solution that enables ion movement between the electrodes.

2 Positively charged **cations (+e⁻)** move toward the negatively charged **cathode**, and negatively charged **anions (-e⁻)** move toward the positively charged **anode**.

3 At the anode, electron loss occurs, leading to **oxidation reactions**, whereas the cathode gains electrons, facilitating **reduction reactions**.

4 The electrodes are often separated by a permeable barrier **(cell separator)**, like a membrane, to prevent them from directly touching. They are also connected by an external **electrical conductor**, such as a wire, allowing electrons to flow from the anode to the cathode.
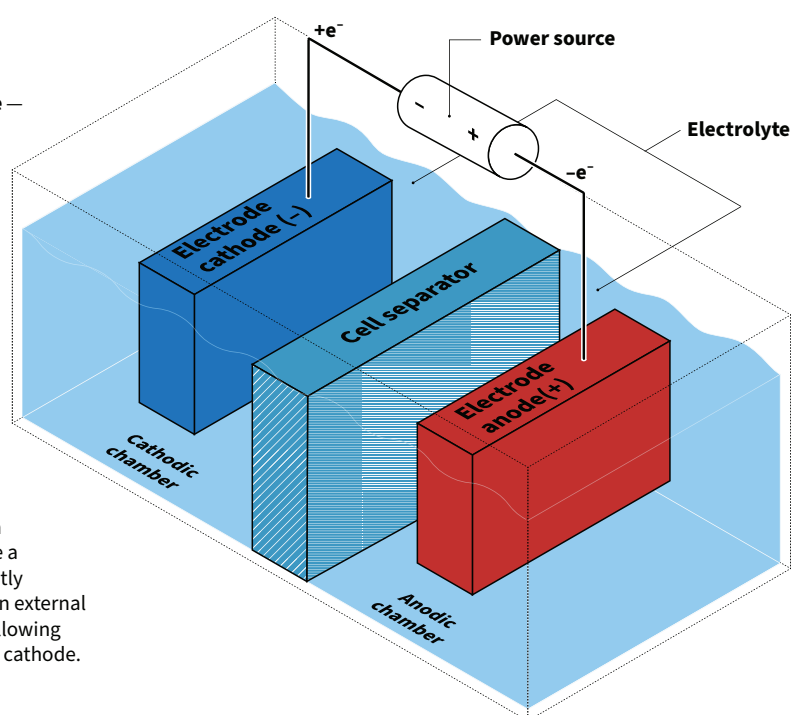
RMI Graphic. Source: Royal Society of Chemistry, *Electrochemical Carbon Dioxide Capture to Close the Carbon Cycle*, 2020

A common mistake when assessing electrochemistry-based CDR is assuming that two startups using the same CDR approach and core electrochemical process, such as electrolysis or bipolar membrane electrodialysis, employ similar CDR systems. It's important first to understand the specific role the electrochemical cell plays in each startup's CDR system before examining the detailed workings of their electrochemical processes.

Distinguishing electrochemical cells' role is crucial for an unbiased assessment of their potential scalability and viability, especially when comprehensive TEAs have not yet been developed. Depending on the specific CDR pathway, the electrochemical cell may not be the main component of the CDR system, and many other components may be required. Therefore, it is essential to compare data for similar subcomponents across different CDR systems to ensure accurate evaluations. Failing to properly understand the role of the electrochemical cell within the system can lead to misleading comparisons and unrealistic expectations about the potential return on investment for investors in these technologies.

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v   Cutoff date for this publication was the end of March 2024.

Among the CDR startups reviewed, this brief identifies three different roles electrochemical cells play in CDR systems:

- **Electrochemical CO_2 capture and release** (ECCR): The electrochemical cell is used to both capture and release CO_2. Release in this context refers to the process of separating the CO_2 from the material with which it has been captured.

- **Electrochemical CO_2 release** (ECR): The electrochemical cell is used to release the CO_2 and regenerate the solvent used to capture it. The capture of the CO_2 happens outside the electrochemical cell and/or in a different system component.

- **Electrochemical preprocessing of inputs** (EPOI): The electrochemical cell is used for preprocessing the input(s) needed in the CDR system, commonly for acid and base production. The base can potentially be used to capture CO_2 and the acid to release it,[vi] both in different system components outside the electrochemical cell.

> **Distinguishing electrochemical cells' role is crucial for an unbiased assessment of their potential scalability and viability, especially when comprehensive TEAs have not yet been developed. Depending on the specific CDR pathway, the electrochemical cell may not be the main component of the CDR system, and many other components may be required.**

Exhibit 4 (next page) maps the 24 electrochemistry-based CDR startups that were assessed for this insight brief, grouping them based on:

- The specific CDR approach (DAC, IWC, or HYB)

- The role of the electrochemical cell within their CDR systems (ECCR, ECR, or EPOI)
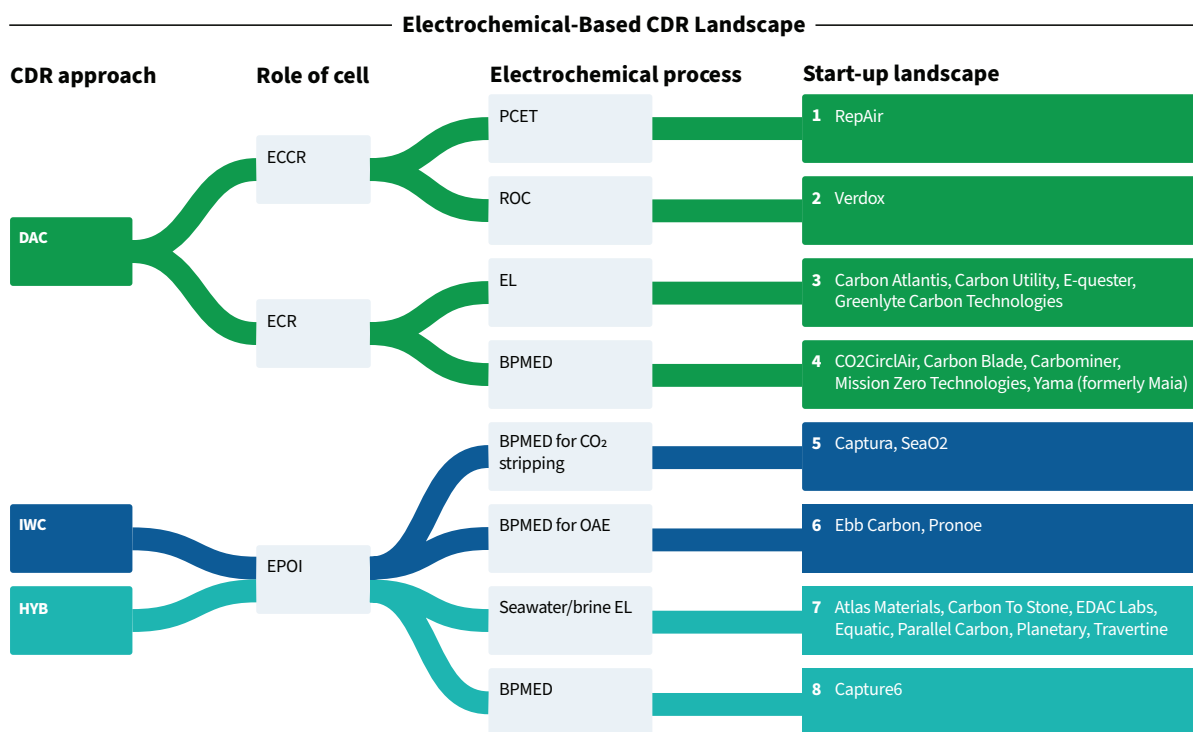
- The core electrochemical process being used

For the viability analysis in the following section, this brief will refer to the resulting eight different types of electrochemistry-based CDR systems as "CDR system archetypes." These archetypes include all essential components required for capturing CO_2 from air and ocean. However, they do not include infrastructure needed for the permanent storage of CO_2.

Initially, most companies in this field pursued business models that revolved around a single CDR approach, either capturing CO_2 directly from the air or indirectly from the ocean. More recently, there has been an increase in startups that specialize in specific segments of the supply chain — particularly in improving electrosynthesizers to cost effectively produce inputs for various CDR approaches. For example, some startups use brine to generate acid and base streams. The base can be used in air contactors to extract CO_2

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vi   Not all startups make use of the acid stream.

Exhibit 4 **Visualization of Current Applications of Electrochemistry in CDR**

— **Electrochemical-Based CDR Landscape** —

CDR approach	Role of cell	Electrochemical process	Start-up landscape
DAC	ECCR	PCET	1 RepAir
		ROC	2 Verdox
	ECR	EL	3 Carbon Atlantis, Carbon Utility, E-quester, Greenlyte Carbon Technologies
		BPMED	4 CO2CirclAir, Carbon Blade, Carbominer, Mission Zero Technologies, Yama (formerly Maia)
IWC	EPOI	BPMED for CO_2 stripping	5 Captura, SeaO2
		BPMED for OAE	6 Ebb Carbon, Pronoe
HYB		Seawater/brine EL	7 Atlas Materials, Carbon To Stone, EDAC Labs, Equatic, Parallel Carbon, Planetary, Travertine
		BPMED	8 Capture6

Notes: CDR methods that leverage electrochemistry include DAC, IWC, and HYB approaches. This results in eight electrochemistry-based CDR archetypes: (1) DAC–ECCR–PCET; (2) DAC–ECCR–ROC; (3) DAC–ECR–EL; (4) DAC–ECR–BPMED; (5) IWC–EPOI–BPMED (CO_2 stripping); (6) IWC–EPOI–BPMED (OAE); (7) HYB–EPOI–EL; and (8) HYB–EPOI–BPMED. Holy Grail is also using an electrochemistry-based technology; however, it could not be categorized with certainty.

RMI Graphic. Source: RMI dataset, March 2024

from the air or for IWC by adding it (alkalinity) to the ocean, while acids can be used to treat mine tailings to produce valuable ores and release the captured CO_2.

This focus on a particular component of the supply chain provides startups with the flexibility to partner and collocate with industries outside of CDR, enabling them to leverage existing infrastructure. In the example above, this opportunity primarily arises from the use of brine (waste from desalination plants, effluent treatment facilities, or reverse osmosis plants) and waste rock and mine tailings (waste from mining activities).[vii]

Among the 24 startups assessed for this insight brief, four main electrochemical processes are used predominantly, with three being variations of pH swings. In the context of carbon capture, pH swing refers to the use of an electrochemical cell to alter the acidity (pH) of a solution, enabling CO_2 capture and release. Specifically, increasing the alkalinity (raising the pH) of a solution allows for more CO_2 to be captured, while reducing the pH of the solution releases the CO_2.

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vii Examples of these companies are Capture6 and Travertine. Capture6 removes CO_2 from the atmosphere with a solvent created from saltwater, which can be sourced from water treatment facilities. The technology synthesizes conventional water treatment processes and air contactors to operate seamlessly within the water treatment plant. At the end of their process, CO_2 and fresh water are produced from the salty brine waste. Travertine upcycles sulfate byproducts into carbon-negative sulfuric acid and green hydrogen, while simultaneously and permanently sequestering CO_2 from the air into carbonate minerals. The produced carbon-negative sulfuric acid is then used for the extraction of lithium, nickel, and cobalt.

Exhibit 5 lists these four main electrochemical processes and outlines the different separation mechanisms, key components, potential outputs (depending on the specific cell configuration), and current industry applications beyond carbon capture. Note that these four processes require a distinct electrochemical cell design and present unique trade-offs in energy requirements, costs, resource requirements, and manufacturability. While Exhibit 5 describes the core processes in general terms, Exhibit 6 (next page) visualizes and describes these processes in greater detail in the context of CDR.

Exhibit 5   Core Electrochemical Processes in CDR

Electrochemical process	Separation mechanism	Key material inputs	Potential outputs	Key applications
EL (water or seawater brine) `pH swing`	A process that directly splits water molecules to facilitate a pH swing near the two electrodes, often by generating H_2 and O_2 gases at the cathode and anode, respectively	Electrolyte solution Ion-selective membranes (optional)	Gaseous CO_2 Carbonate minerals Green H_2 O_2 (non-ideal for carbon use or storage) Metal extraction Acid production	Water splitting for hydrogen production Metal extraction and refining (e.g., aluminum, nickel, magnesium, and copper) from ores Wastewater treatment for removing contaminants Synthesis of chemicals (e.g., chlorine and sodium hydroxide) from electrolysis of brine or water pretreatment (demineralization)
BPMED `pH swing`	Use of bipolar membranes, composed of laminated anion and cation exchange layers that selectively transfer ions to the anode and cathode, effectively controlling the pH	Ion-selective and bipolar membranes (most costly components) Electrolyte solution	Gaseous CO_2 Carbonate minerals Acid production	Acid and base production from their respective salts Water desalination and purification processes Dairy industry for demineralization of whey and milk
PCET, with redox metal oxides (inorganic) `pH swing`	Metal-based electrodes release or consume ions (H^+ or OH^-) through redox (reduction and oxidation) reactions, altering the pH around the electrodes	Redox-active molecules or ions Ion-selective membranes (optional)	Gaseous CO_2	Solar energy conversion (solar-to-fuel) Catalysis, including water splitting, oxygen reduction, and CO_2 reduction
ROC	ROCs are chemical substances that bind to or release target species through reduction and oxidation reactions, respectively	Redox-active molecules or ions	Gaseous CO_2	Batteries for energy storage Electrochemical sensors for detecting various substances Organic synthesis Drug delivery/medical applications

RMI Graphic. Source: Royal Society of Chemistry, *Electrochemical Carbon Dioxide Capture to Close the Carbon Cycle*, 2020; Applied Sciences, **Analysis of Technologies for Carbon Dioxide Capture from the Air**, 2022; American Chemical Society, *Electrochemical Approaches toward CO2 Capture and Concentration*, 2020

While the *Introduction* and this section of this insight brief have focused on demystifying the complex landscape of electrochemistry-based CDR by identifying the key defining features of different systems and grouping similar CDR systems into archetypes, the next two sections will provide investors and funders with practical knowledge and guiding principles to make well-informed decisions on startups and projects falling into these archetypes.

Exhibit 6

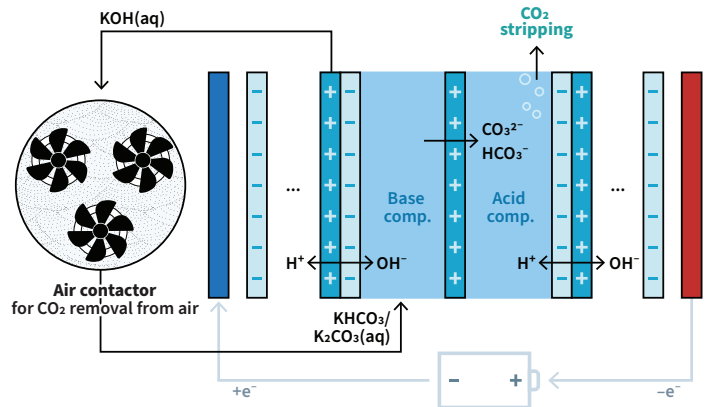# Examples of Core Electrochemical Processes in CDR Systems

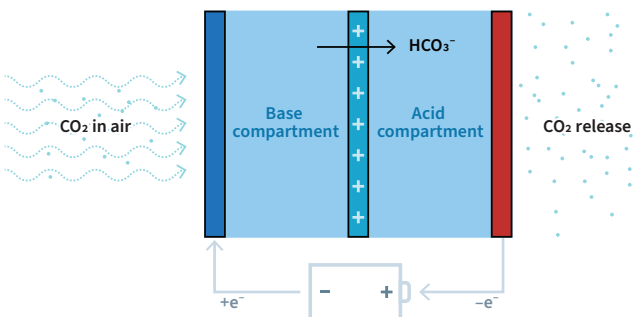## Electrolysis (EL)
Electrochemical CO_2 Release (ECR)
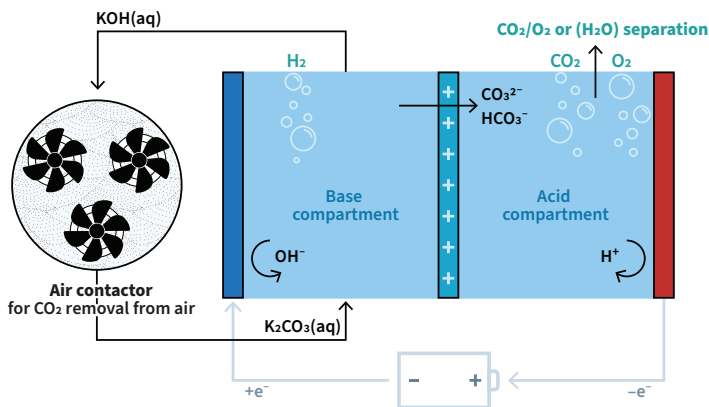
Bipolar Membrane Electrodialysis (BPMED)
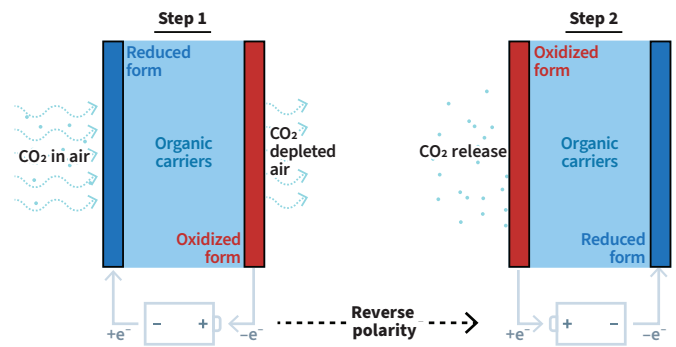Electrochemical CO_2 Release (ECR)

PCET: Redox Metal Oxides (Inorganic)
Electrochemical CO_2 Capture & Release (ECCR)

Redox Organic Carriers (ROC)
Electrochemical CO_2 Capture & Release (ECCR)

Legend: Cathode (−) · Anode (+) · Anion exchange membrane (AEM) · Cation exchange membrane (CEM) · Bipolar membrane (BPM) · $-/+e^-$ Electron loss/gain

Notes:
i. CO_2 is captured from the air using a potassium hydroxide (KOH) liquid solvent. The resulting CO_2-rich solution (i.e., K_2CO_3) is then fed into the electrochemical cell for alkaline regeneration, where CO_2 is recovered (released through CO_2 stripping) and hydrogen (H_2) is produced. The resulting CO_2-lean solvent (i.e., KOH) is recirculated back into the air contactor to capture CO_2 again. Note that a separate vessel might be used for CO_2 release.

ii. This system facilitates ion transfer and water dissociation into OH^- and H^+ ions. When a sufficient electric field is applied, the bipolar membrane (BPM) dissociates water, creating a controllable pH difference across the BPM. The pH difference happens because OH^- ions accumulate in the base compartment and H^+ ions in the acid compartment. This process enables both solvent recovery and CO_2 release. Like EL, the CO_2-lean solvent is then recirculated back into the air contactor for further CO_2 capture.

iii. When electrical current is applied to the cathode, the metal-based electrode is activated, generating OH^- ions that facilitate the capture of CO_2, forming HCO_3^-. These bicarbonate (HCO_3^-) ions then cross a membrane to the anode side, where CO_2 release occurs, with the carrier being oxidized as it consumes OH^-. Every few hours, the electrode polarities and inlet airflow are swapped to enable continuous DAC.

iv. During the binding step, the carrier, activated at the cathode, binds with the targeted species (i.e., CO_2 molecules) in its reduced state. In the release step, the captured CO_2 is released through the oxidation of the carrier at the anode, where reversed polarity is applied, simultaneously regenerating the carrier.

This schematic excludes examples of electrochemical processes for the preprocessing of inputs, like EL and electrodialysis. This simplification is made because these processes are already illustrated in the context of electrochemical CO_2 release pathways.

Abbreviations: AEM: anion exchange membrane; CEM: cation exchange membrane; BPM: bipolar membrane.

RMI Graphic. Source: Royal Society of Chemistry, *Electrochemical Carbon Dioxide Capture to Close the Carbon Cycle*, 2020; Applied Sciences, **Analysis of Technologies for Carbon Dioxide Capture from the Air**, 2022

Assessing Viability at Scale

Assessing the viability at scale of electrochemistry-based CDR is challenging, primarily due to:

- The complexity of electrochemistry's core concepts

- The low TRL of electrochemistry-based CDR solutions and associated supply chains (e.g., for membranes)

- The lack of independent, third-party data on the performance of these solutions, making it harder to contextualize the system performance reported by startups.

To confidently evaluate electrochemistry-based CDR methods in light of these complexities and uncertainties, it is essential to understand the key trade-offs among various systems that directly affect removal costs. In the analysis below, we will outline the most critical parameters and the principal trade-offs involved when comparing these systems.

Energy Requirements and Cell Design

Energy efficiency is a key factor in evaluating electrochemistry-based CDR systems because reduced energy use is their primary advantage compared with alternative sCDR approaches. Given the uncertainties and data gaps mentioned above, we do not attempt to identify the most promising systems from an energy perspective at present. Instead, we outline the most important energy-related metrics and practical choices that startups face when designing an effective electrochemical cell. Exhibit 7 (next page) provides an overview on these energy-related metrics. Exhibit 8 (page 20) outlines the six most important choices startups face when designing an electrochemical cell and flags their specific trade-offs.

Exhibit 7 **Important Metrics Underlying Energy Requirements**

ENERGY USE measured in joules or watt-hours, is the most important metric for evaluating required energy consumption. High energy requirements for an sCDR solution generally lead to higher operational expenditures, making this metric essential for quantitative comparisons across sCDR approaches.[*] However, caution is advised when such analyses include approaches that leverage different forms of energy, such as thermal versus electrical, because these cannot be summed up simply. The key metrics underpinning energy requirements in electrochemical cells include **1) current density, 2) faradaic efficiency, 3) voltage efficiency, and 4) overpotential.**[†] Techno-economic studies for CCUS indicate that for industrial viability, current densities >200 milliamperes per square centimeter (mA/cm^2) alongside faradaic efficiencies >90% for a specific product at cell potentials < 3V are required.[‡]

1 **CURRENT DENSITY** is the electric current per unit area of electrode or membrane and is a metric that influences the rate of CO_2 capture or release by affecting the amount of electrical current flowing through the electrodes/system. High current densities reduce the size of the electrolyzer, which reduces capex, and improve capture rates; however, they may also lead to increased overpotential and cell voltage (e.g., due to resistive losses), which increase opex.

2 **FARADAIC EFFICIENCY** refers to the efficiency with which electrons are used during the electrochemical process. A 100% faradaic efficiency means that each electron transferred in the system results in the capture or release of one mole of CO_2. Higher faradaic efficiencies indicate that less input energy and area of electrolyzer are required to produce a ton of CO_2, which reduce opex and capex, respectively.[§]

3 **VOLTAGE EFFICIENCY** refers to the ratio between the thermodynamic (reversible) potential and the operating potential of an electrochemical cell. It indicates how much the actual voltage deviates from the theoretical minimum required for a given reaction. A 100% voltage efficiency means that the cell operates at the theoretical minimum voltage, while any deviation from this value reflects energy losses due to overpotential, resistance, or other inefficiencies.

4 **OVERPOTENTIAL** refers to the extra voltage required beyond the thermodynamic potential voltage to operate the cell (drive the electrochemical reaction). In other words, the thermodynamic potential voltage of a system may be 1.0 volts, meaning that in ideal conditions, the reaction should occur when 1.0 volts are applied to the system. Yet, when operating the system in real-world conditions, a voltage of 1.2 volts may be required before the reaction occurs. This difference between 1.2 volts and 1.0 volts is the overpotential. It occurs because of factors such as kinetic limitations, concentration gradients, and resistance. It is known by various names, such as polarization, irreversibility, voltage drop, and losses.[**]

Notes:

[*]To calculate the relative energy use per ton of CO_2, one first needs to determine the absolute energy requirement of the system and the CO_2 removal (or capture) capacity. The CO_2 removal capacity refers to the net amount of CO_2 that the CDR system can remove.

[†]Other metrics that are not directly related to energy and cell design characteristics are the CO_2 separation capacity and CO_2 capture efficiency. The CO_2 separation capacity is somehow captured in the energy requirements if energy is not reported in terms of absolute values, but per amount of CO_2 removed. The higher the CO_2 removed, the lower the energy and cost. CO_2 capture efficiency refers to the percentage of carbon dioxide removed by the CDR system, calculated by comparing the CO_2 concentrations before and after the process.

[‡]Depending on the electrochemical process, a higher voltage might be needed. For example, in BPMED, as the number of membrane pairs increases, the voltage increases because of voltage drop over the membranes.

[§]This metric might be normalized to the theoretical moles of CO_2 separated per moles of electrons transferred (based on stoichiometry), allowing it to scale from 0 to 1. Deviations from stoichiometric values can result from factors such as weak binding affinities or side reactions. Monitoring this metric over relevant time scales is critical.

[**] The causes of overpotential include slow charge transfer (i.e., the movement of charge from electrons to ions, referring to the portion of cell voltage lost to maintain the required reaction rate on the electrodes), resistance losses (i.e., losses due to electronic and ionic conduction), and mass transport losses (i.e., losses evident at high current densities because of limitations in mass transport).

RMI Graphic. Sources: iScience, *Perspective and Challenges in Electrochemical Approaches for Reactive CO_2 Separations*, 2021; Royal Society of Chemistry, *Electrochemical Carbon Dioxide Capture to Close the Carbon Cycle*, 2020; National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, 2022

Exhibit 8

Key Energy-Related Parameters and Trade-Offs in Cell Design

	Relevance	Process agnostics trade-off	Rationale
Cell voltage	Influences the actual energy requirements under a certain set of conditions.	Process efficiency vs. material stability and cost	Higher cell voltage can improve the reaction efficiency, but it may require more expensive or less stable electrode materials, membranes, and electrolytes to withstand the higher potential differences without degrading.
Current density	Affects the rate of CO_2 capture/release by influencing how much charge passes through the cell.	Opex vs. capex	Higher current densities can enhance capture rates and thus reduce capex costs but may lead to increased energy losses and heat generation (e.g., resistive losses), requiring additional energy for cooling and potentially decreasing the overall system efficiency.
Electrode material	Electrodes and electrocatalysts affect the current density and durability.	Material cost and stability vs. performance	Materials with high catalytic activity and large surface area can improve reaction rates and selectivity but may be more expensive or less durable (especially in oxygen revolution reaction catalysts).
Electrolyte concentration	Influences the conductivity of the solution, the CO_2 solubility and kinetics (which depends on process), and Faradaic efficiency.	Resistive overpotential vs. limiting current	Electrolyte concentration should be optimized to minimize resistive overpotential and voltage drop (because of improved ionic conductivity) while supporting a sufficiently high limiting current to maintain optimal reaction rates.
Choice of membrane (where applicable)	Affects the selective transport of ions, cell potential, and possibly overpotential.	Durability vs. performance	There must be a balance between the need for long-lasting materials with the requirement for high-efficiency separation or transport (selectivity and permeability) and low environmental impacts.
		Faradaic efficiency vs. voltage	Generally, thicker membranes are better at preventing unwanted back diffusion of ions, but they also have a higher resistance and so have a higher cell voltage across them for a given current density.
Mass transport	Refers to the movement of reactants toward the electrode and products away from them.	Concentration polarization vs. flow rates and energy use for pumping	Optimizing flow rates and the design of mass transport systems to avoid polarization (the depletion or accumulation of reactants or products near the electrode surface) should minimize energy needs while maintaining adequate mass transport.

RMI Graphic. Sources: Royal Society of Chemistry, *Electrochemical Carbon Dioxide Capture to Close the Carbon Cycle*, 2020; National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, 2022

Due to the complexity and possible permutations resulting from the six choices and their associated trade-offs outlined in Exhibit 8, we recommend that investors concentrate on the primary choices and trade-offs related to cell design:

- **Cell voltage:** The ideal cell voltage should be low enough to minimize energy consumption but high enough to trigger the necessary chemical reactions without causing excessive overpotentials. However, looking at cell voltage in isolation isn't very informative. Investors should examine the relationship between cell voltage and current density, which is depicted in a curve. This curve is essential because it shows how the cell performs under varying operational loads and is crucial for designing and optimizing the system that uses the cell.

- **Current density:** Higher current densities increase the rate of the reaction, but they also increase the energy requirements. Operating at high current densities increases overpotentials and overall cell voltage, resulting in higher energy consumption. However, higher current densities reduce the size of the electrolyzer, resulting in lower capital expenditures. Although there is no one-size-fits-all number for current densities, industrial electrochemical processes often operate with current densities in the range of tens to thousands of mA/cm^2. Project developers should consider tailoring current density based on local availability and cost of energy, and determining what that implies for the trade-off between capital expenditures and operating expenditures.

- **Material selection:** The choice of electrodes and electrolytes affects operating and capital expenditures. Operational costs are influenced by factors such as cell voltage, CO_2 capture, selectivity of the reaction, stability of these materials, and electronic and ionic conductivity.[viii] Capital costs are affected by the cost of the materials, which are also crucial. Membranes, which are expensive (e.g., costs of Nafion membranes are estimated at $2,000/m^2$),[9] are used in most electrochemistry-based CDR systems. Because of their high cost, it is crucial to reduce the required surface area and increase the stability of the membranes while maintaining high performance.

System-Level Trade-offs

Without detailed and independent TEAs and LCAs to facilitate a confident cost comparison of electrochemistry-based CDR systems, we recommend evaluating their scalability by focusing on key system-level characteristics and trade-offs. Among these, energy requirements are particularly critical. If interpreted with sufficient caution and the necessary energy-related knowledge,[ix] startups and academic literature form an essential component of the system-level analysis.

Exhibit 9 (page 23) compares the most important system-level characteristics that influence the cost and scalability of electrochemistry-based CDR systems, focusing on the eight electrochemical CDR system archetypes identified in Exhibit 4 (page 15). For more detailed information on the technical challenges of the eight archetypes, refer to *Appendix B*.

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viii   Further research and development of machine learning techniques will be crucial in unraveling the complex relationships between electrode, electrolyte, and membrane material properties and electrochemical performance. This knowledge will facilitate the design of highly efficient electrochemical processes.

ix   Note, energy is used for more than operation of the electrochemical cell (discussed in the previous section).

> **"Without detailed and independent TEAs and LCAs to facilitate a confident cost comparison of electrochemistry-based CDR systems, we recommend evaluating their scalability by focusing on key system-level characteristics and trade-offs. Among these, energy requirements are particularly critical."**

The analysis in Exhibit 9 (next page) includes the following parameters and metrics:

- **Technology maturity:** Technology maturity of electrochemistry-based CDR methods is evaluated based on their TRLs on a scale from 1 to 9 with 9 being the most mature.[x] TRLs of electrochemistry-based CDR systems range from 3 to 6,[xi] indicating development stages from lab to pilot scale.

- **Low-cost material availability:** For electrochemical processes to be economically viable, using low-cost materials is essential. Across all systems, opportunities exist to reduce the costs of electrolytes and electrocatalysts. However, membranes will continue to represent a significant cost component.[xii,10]

- **Energy requirements:** Some electrochemical processes have a higher minimum energy requirement than others, which varies depending on the chemical reactions involved. Although this metric is significant, it should not be considered in isolation, given most industrial processes use more than double the energy compared with theoretical minimums.[xiii] Furthermore, evaluating total system-level energy requirements (e.g., energy for air processing, water pumping, seawater or brine pretreatment, and CO_2 purification and compression) is essential, as the electrochemical cell may not be the sole core component of the system.

- **System complexity:** This metric evaluates the complexity of various electrochemistry-based CDR systems, categorizing them into three main levels: simple, design-intensive, or complex. Although some systems primarily rely on the electrochemical cell as their core component, they may still exhibit operational complexity because of their design and operation. For example, ROC operates in sequential steps of CO_2 capture and release, and thus, for a continuous operation, at least one additional cell is required to operate in parallel.

- **Products:** Some processes can produce additional products besides CO_2, which can be marketed and improve overall economics. However, CO_2 production is often intertwined with by-product generation, posing extra challenges in designing the electrochemical cell and necessitating further post-processing and storage or utilization solutions for by-products.

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x   We assigned TRLs to the different electrochemical-based CDR systems based on *DOE's Technology Readiness Assessment Guide*.

xi   This range suggests that electrochemical-based CDR systems have yet to undergo the extensive testing necessary to identify and mitigate initial faults and inherent challenges at larger scales.

xii   In our previous insight brief, we set a development target for membrane costs at below $10 per ton of CO_2 removed to ensure the economic viability of these systems, such as DAC. Another key strategy to minimize capital expenditures, applicable across all systems and therefore not detailed in Exhibit 9, involves adopting Earth-abundant electrocatalysts to circumvent the use of expensive metals like iridium or platinum.

xiii   Given that most chemical processes, if not all, operate above thermodynamic minimums, it is crucial not only to minimize the energy requirements for driving the necessary chemical reactions but also to reduce energy losses.

Exhibit 9

System-Level Characteristics for Electrochemistry-Based CDR

Archetype			Technology maturity — Defined by TRLs of existing startups*	Low-cost material availability? — Lists key materials and their low-cost availability	Products — Lists products of each archetype	Energy requirements — Provides estimates of energy requirements for the electrochemical process (excludes remaining system processes)	System complexity — Defines the level of complexity among system components and their operation.
DAC	ECCR	PCET	6	Lithium hydroxide: yes Manganese dioxide: yes Membranes: no	CO_2	Low energy, <650 kWh/tCO_2, based on startup reported values	**Design-intensive system:** although the electrochemical cell is the main component, continuous flow processes are only achievable if the polarity of electrodes and flows are reversed periodically with respect to the sides of the cell.
DAC	ECCR	ROC	5	Organics: possible	CO_2	Low energy, reported at 250–570 kWh/CO_2 for 0.6 to 10% CO_2 concentration	**Design-intensive system:** although the cell is the main component, it operates in sequence; for a continuous operation, at least one additional cell is required.
DAC	ECR	EL	3–5	Electrode/catalyst: possible Membranes (optional): no	CO_2, possible H_2, O_2	Single stack: 750–1,500 kWh/tCO_2	**Complex system:** it requires multiple independent steps of chemical processing because the electrochemical cell is only one of several components.
DAC	ECR	BPMED	4–5	Membranes: no	CO_2	Multi-stacks: 500–1,000 kWh/tCO_2	**Complex system** *(same as DAC EL above)*.
IWC	EPOI	BPMED for CO_2 stripping †	5–6	Membranes: no	CO_2	0.65–0.81 kWh/kg NaOH Additional energy is needed for seawater pumping‡	**Design-intensive system:** although the cell is the main component, multiple steps of preprocessing of seawater are required.
IWC	EPOI	BPMED for OAE	5–6	Membranes: no	CO_2, hydrogen chloride (HCl)	0.65–0.81 kWh/kg NaOH Additional energy is needed for seawater pumping	**Design-intensive system:** although the cell is the main component, multiple steps of preprocessing of seawater and design considerations for HCl disposal are required.
HYB	EPOI	EL	4–6	Electrode/catalyst: possible Membranes (optional): no	CO_2, possible H_2, O_2, Cl_2, carbonate minerals, metal extraction	1.56–1.64 kWh/kg NaOH	**Complex system** *(same as DAC EL above)*.
HYB	EPOI	BPMED	6	Membranes: no	CO_2, possible carbonate minerals, HCl	0.65–0.81 kWh/kg NaOH	**Complex system** *(same as DAC EL above)*.

Notes:

*We assigned TRLs to the different electrochemistry-based CDR systems based on CDR startups following *DOE's Technology Readiness Assessment Guide*.

†CO_2 stripping is possible when the acid, produced during the preprocessing of inputs, is used for CO_2 release. If the base, also produced during the preprocessing of inputs, is further processed/used, then carbonate precipitation is enabled. This is a different pathway, which is not currently pursued by any startup and, therefore, excluded from this table.

‡Still, approximately 100-fold energy greater than that required for OAE, due to higher pumping duties required. However, startups are considering ways to reduce the energy required for seawater pumping, e.g., by using tidal flows.

RMI Graphic. Sources: Renfrew et al., *Electrochemical Approaches toward CO_2 Capture and Concentration*, ACS Catalysis, 2020, 10(21), 13058–13074; TKumar et al., *Integrated Valorization of Desalination Brine through NaOH Recovery: Opportunities and Challenges*, Angewandte Chemie, 2019, 131(20), 6570–6579.

Based on the analysis, we identified the following major trade-offs for the eight electrochemistry-based system archetypes:

1. **DAC–ECCR–PCET**

   a. **System complexity versus operational complexity:** Although the electrochemical cell is the main system component, coupling CO_2 capture and release steps in a single unit presents challenges. These challenges exist because of the extreme difference in CO_2 concentrations between the capture (very low) and release (high) steps and the need for maintaining a continuous process operation.

   b. **Energy requirements versus material stability and cyclability:** Although this process might be characterized by relatively low energy consumption, the long-term stability and cyclability of the materials are critical factors. These factors could make operational costs more unpredictable and volatile if not thoroughly assessed over extended periods.

2. **DAC–ECCR–ROC**

   System complexity versus operational complexity: As we observed with archetype 1, coupling CO_2 capture and release steps presents challenges for designing a cell that operates optimally between a very low CO_2 concentration–capture step and a very high CO_2 purity–release step, while also maintaining continuous operation. Moreover, although a solid-based system offers a simpler system design by eliminating the need for a flowing electrolyte, this simplicity leads to slower kinetics and transport compared with liquid-based systems, such as those using quinones in solution.

3. **DAC–ECR–EL**

   Rate of CO_2 release versus rate of H_2 and O_2 generation: The critical trade-off involves balancing the rate of CO_2 release against the rate of H_2 and O_2 generation. Although electrolysis is technologically mature and widely deployed across various industries, it faces a limitation in CDR: the voltage for CO_2 release in the electrochemical cell is intrinsically tied to the voltage for H_2 and O_2 production. This interdependence is crucial, having a direct impact on the system's efficiency and operational dynamics.

4. **DAC–ECR–BPMED**

   Energy requirements versus membrane cost and durability: Electrodialysis, which is widely used in various industries and is considered technologically advanced, generally uses less energy than EL. However, this process requires multiple membranes to replace the electrode active areas when switching from EL to electrodialysis. These membranes must support high operating current densities, ensure high efficiency in ion transport, and maintain prolonged life span. Membrane requirements are significant factors influencing the system's operational efficiency and cost-effectiveness.

5. **IWC–EPOI–BPMED**

   (CO_2 stripping): System complexity versus operational complexity: Although this system has lower complexity than other systems, operational costs are a major concern because of the large amount of energy needed to pump ocean water and pretreat seawater. This design should optimize the electrochemical cell to achieve optimal current densities and address challenges such as corrosion of electrocatalysts and membrane stability and life span. From a system perspective, high energy requirements for water pumping could be reduced if the system benefits from integrated solutions

or natural occurrences like tidal flows. These systems also face some challenges with monitoring, reporting, and verification (MRV).

6. **IWC–EPOI–BPMED (OAE)**

   System complexity versus operational complexity: Trade-offs in this system lie between system complexity and operational costs. The latter is influenced by the energy required for ocean water pumping and by the challenges of MRV in open systems and acid disposal. As with CO_2 stripping, pretreatment of seawater is required, and corrosion of the main equipment and material could lead to increased operating expenditures or higher capital expenditures to lengthen equipment life span.

7. **HYB–EPOI–EL**

   a. **Rate of acid/based generation versus CO_2 release versus rate of H_2 and O_2 generation:** The central trade-offs of this system involve the rate of acid/base generation, which is directly linked to the production rates of CO_2, H_2, and O_2. The generated base can be used for CO_2 capture in a DAC unit, while the acid can be used for CO_2 outgassing. Understanding this connection is crucial, as it determines the system's efficiency in balancing CO_2 capture and release. This directly affects its overall effectiveness in carbon management.

   b. **Co-located system benefits versus system complexity:** These systems could take advantage of several co-benefits if integrated optimally with other industries, however, this integration might impose additional system complexities.

8. **HYB–EPOI–BPMED**

   a. **Energy requirements versus membrane cost and durability:** Like other BPMED processes, although these systems can benefit from a lower energy requirement, the high cost and low durability of membranes can increase their operational expenditure.

   b. **Co-located system benefits versus system complexity:** Like the HYB–EPOI–EL systems, industrial integration is possible and could provide co-benefits to these systems, but it imposes additional system complexity requirements that must be considered.

Actionable Guidance for Investors, Entrepreneurs, and Research Funders

Based on our analysis of the current landscape of electrochemistry-based CDR companies, we recommend the following best-practice principles for investors, entrepreneurs, and research funders during their due-diligence process. These guidelines presume that stakeholders have significant technical expertise in-house. If this expertise is lacking, we suggest seeking the help of technical experts for additional support.

1. **Review the latest literature for up-to-date benchmarks on electrochemical technologies and costs:** Regularly check industry literature, as well as academic literature,[xiv] for comprehensive independent performance assessment and TEAs for technologies of interest. Currently, there is limited publicly available data on system performance and TEA of various electrochemistry-based CDR systems.[xv] However, the space is moving quickly, and sources from just a few years ago could already be outdated.

2. **Ask startups for data that enables unbiased comparisons across systems:**

   a. Startups should clearly define system boundaries for any TEA or LCA data they provide. Ideally, the system boundaries encompass the entire CDR system throughout its entire lifetime (cradle-to-grave) to accurately compare the net cost of carbon removal per ton.[xvi] Key process steps to include within the system boundaries for our system archetypes are:

      i. **DAC–ECCR–PCET/ROC:** includes the electrochemical cell that handles both capture and release of CO_2, with potential additional steps like CO_2 purification, compression, transportation, and storage, depending on the end-use of CO_2.

      ii. **DAC–ECR–EL/BPMED:** encompasses the air contactor for CO_2 capture and the electrochemical cell for CO_2 release, along with similar downstream steps, as above.

      iii. **IWC–EPOI–BPMED (CO_2 stripping/OAE):** covers the electrochemical cell and all equipment needed for the pretreatment of ocean water (i.e., demineralization steps) before acid and base generation in the electrochemical cell. Additionally, downstream pumping equipment must be included. For CO_2 stripping and storage, post-processing steps such as CO_2 extraction, purification, compression, transportation, and storage must also be included. For OAE, complex MRV processes are required.[xvii,11]

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xiv   For example, *Nature, Nature Energy, Science, and Energy and Environmental Science*.

xv   Publicly available data can be found in: Sabatino et al., Industrial & Engineering Chemistry Research, 2020, 59(15), 7007–7020; and Eisaman et al., International Journal of Greenhouse Gas Control, 2018, 70, 254–261.

xvi   If not explicitly stated within the LCA, ask startups for their assumed energy sources to confirm the carbon footprint of the CDR system.

xvii   These processes often rely on the alkalinization of seawater directly or by the dissolution of minerals within it (e.g., brucite, silicate rock, etc.) to enhance its CO_2 storage capacity. The enhancement of the CO_2 storage capacity results in the additional dissolution of atmospheric CO_2 in or its absorption into seawater, which in turn results in CDR. If mineral dissolution may occur within the system boundary, the temporal dynamics and the amount of atmospheric CO_2 removal that will occur can be readily established. But if mineral dissolution may occur slowly, and beyond the process boundaries (e.g., following discharge of the effluent into the ocean), it will be necessary to rely on an indirect basis of quantifying the CDR benefit.

iv. **HYB–EPOI–EL/BPMED:** includes the electrochemical cell for input preprocessing and the full CDR system where these inputs are used, with additional downstream steps as needed.

b. Startups should provide the detailed energy metrics underlying their reported energy requirements. Specifically, ask for:

    i. **Operational current density:** Typical requirements are between 50 and 200 mA/cm^2, which can vary based on factors like electrode materials and cell design.

    ii. **Faradaic efficiency:** Measures the efficiency of the electrochemical reactions, ideally close to 100% to indicate minimal energy loss.[xviii,12]

    iii. **Voltage efficiency:** Shows how closely an electrochemical cell operates relative to its theoretical energy requirements. High-voltage efficiency means that the cell is using the energy more efficiently.

c. Startups should also provide a detailed comparison between their proposed electrochemical process/system and an established conventional/non-electrochemical process/system. This comparison is essential for assessing the potential of the electrochemical solution and ensuring its effective contribution to climate goals. The comparison should be within the established boundaries of the process/system to effectively benchmark the evaluated technology against the state of the art. For example, compare an electrochemistry-based DAC approach to a solid sorbent temperature swing DAC approach.

d. Startups should deliver data relevant to the scalability of their systems (if not already included in shared TEAs and LCAs):

    i. A comprehensive list of all major system components

    ii. Current and projected costs of primary materials used in their electrochemical cells

    iii. Production rates of any by-products or valuable input materials (if applicable, check if the by-product has actual value or is a waste product with potential disposal costs)

    iv. The current cost of the primary materials used in their electrochemical cells and expected cost trajectory

    v. Any patents they hold for their technology

    vi. Targeted sites/infrastructure for integration

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xviii   In our previous work, we identified faradaic efficiency >50% to be a development target for electrochemical cells.

3. **Compare between similar system contexts: Only compare cost and energy data for systems using the same system boundaries.**

   a. Aim to compare entire systems rather than focusing excessively on the electrochemical cell. The most energy-efficient electrochemical cell does not always result in an energy-efficient and cost-effective CDR system.

   b. If data on complete systems is unavailable, restrict comparisons to electrochemical cells that perform identical functions in the same type of CDR approach.[xix]

   c. Standardize the data you are comparing to net carbon removal per ton values and avoid comparisons using absolute energy and cost values, as systems will most likely differ in size.

4. **Contextualize startup performance data: Given all electrochemistry-based CDR systems are at an early stage of technology readiness, do not overly rely on the nominal values of TEAs.**

   a. Consider resource constraints and system complexity as more accurate indicators of a technology's practical viability at scale.

   b. Validate assumptions on supply chains and material availability:

      i. Are offtake markets for co-products big enough? Will startups produce large enough quantities to successfully enter existing markets?

      ii. How realistic are the cost trajectories for critical materials? Have similar cost reductions for primary materials been achieved in other industries?

      iii. How easily can technology be integrated into existing infrastructure and manufacturing supply chains? In addition to having a component list for new equipment, startups need to assess and communicate if and when factories can assemble the equipment at scale.

   c. Validate the defensibility of the technology, considering the patents the startups hold.

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xix   For instance, if the electrochemical cell is used exclusively for CO_2 release or preprocessing of inputs, it necessitates additional system components, thereby incurring extra costs and energy requirements. Furthermore, energy needs can vary significantly even for similar roles within different CDR approaches. For example, blowing air through fans for DAC is generally less energy-intensive than pumping a liquid using IWC methods.

Conclusion

Previous RMI work has identified the current decade as the decisive one for DAC based on the necessary progress in research, development, and demonstration for gigaton-level DAC to be feasible by 2050.[13] Although this is true for DAC, it is even more critical for electrochemistry-based DAC and CDR, which have lower technological maturity than conventional DAC technologies. Electrochemistry-based approaches have the potential to transform the CDR industry by providing low-cost, verifiable, and durable solutions. However, these technologies can only contribute significantly to the broader climate solution portfolio if they mature rapidly enough to achieve gigaton-scale CDR by the 2050s. Achieving this will require billion-dollar-level investments in electrochemistry-based CDR this decade.

The pace and scale of investment into electrochemistry-based CDR are crucial over the next decade, ensuring that funds are directed to the most promising solutions is paramount. RMI urges investors and research funders to monitor how companies within these eight system archetypes address known challenges for electrochemistry-based CDR. Key developments to watch include improvements in membrane performance and longevity, and system resiliency under real-life conditions. Investors should also consider companies with promising characteristics that do not fit within the eight system archetypes outlined in this work; there are promising concepts in academic literature that could constitute new system archetypes if pursued by a startup. Innovations that improve and expand upon the archetypes described in this report may likely hold the key to unlocking gigatons of affordable, durable carbon removal.

Appendix A: Desired Characteristics of Electrolytic Cells

Exhibit A1   **Desired Characteristics**

Key Component	Role	Desirable characteristic	Rationale	Trade-off
Electrolyte *(usually a liquid solution, but it can also be a solid, a molten substance, or a polymer)*	A substance containing free ions that carry electric current between electrodes or a reactant in the chemical processes	**High ionic conductivity**	Reduces resistive losses due to faster reactions with less voltage drop.	Resistive overpotential vs. limiting current (opex)
		Low electronic conductivity	Prevents the formation of electrical short circuits.	
		High limiting current	Allows the device to operate at high currents without causing mass transport limitations.	
		Low resistive overpotential	Improves overall energy efficiency of system; can be achieved at high ionic conductivity and low current density.	
Electrode material *(conducting and semi-conducting elements)*	For providing the physical interface between the electrical circuit and the electrolyte — might be active in the redox reactions	**High electronic conductivity**	Allows for an efficient charge transport; can be affected by the type of electrode material.	Ideal material properties and high active surface area vs. low material cost (capex vs. opex)
		High active surface area	Promotes faster reaction kinetics that reduce material cost and system footprint.	
		Low activation overpotential	Increases for slow charge transfer reactions (depends on material properties and nature of the reaction).	
		High material stability	Accepts that some electrode materials will degrade more quickly in certain conditions (e.g., in seawater).	
		Type of material	Acknowledges some electrode materials are made of expensive or rare metals which are a barrier to scalability.	
Cell separator *(a diaphragm or an ion-permeable membrane)*	For promoting increased selectivity, limiting unwanted reactions, and increased product purity	**High ionic permeability**	Promotes faster ionic transfer that reduces resistive losses.	High ionic permeability vs. low material cost (capex vs. opex)
		High material stability	Is important for material longevity (related to material costs over time).	
		Type of material	Acknowledges that membrane costs are currently high; possible concerns over use of fluorinated membranes (e.g., Nafion), as polyfluoroalkyl substances (PFAS) are beginning to be restricted.	
Cell design	An important factor to minimize the cell resistance and therefore energy requirements	**Low distance between electrodes**	Reduces losses due to activation (charge transfer), resistance, and mass transfer.	Optimal operational efficiency vs. low cost (capex vs. opex)
		Low design complexity	Reduces cost of fabrication and material.	
		High active surface area	Increases current density; an important characteristic for scalability.	

Appendix B: Fundamental Technical Challenges by System Archetype

Here, we outline fundamental technical challenges associated with the materials, process design, and operation of electrochemical processes. This includes:

- Ongoing efforts to optimize cell performance

- The lack of long-term material testing for assessing durability, stability, and in some instances, reversibility

- Challenges related to the preprocessing of inputs and post-processing of outputs

- The challenge of measuring, monitoring, reporting, and verifying the net carbon removal by some systems

Fundamental Technical Challenges

Archetype			Fundamental technical challenges (material and process design & operations)
DAC	ECCR	PCET	**The rate** of electron and proton transfer can be slow, and synchronizing transfers to minimize energy losses is a challenge. **Long-term** reversibility studies (long testing of capture/release cycles) are needed. **Continuous** improvements in electrode architecture, including surface area and electrocatalysts, are required to enhance uptake rates and mass transfer efficiencies.
DAC	ECCR	ROC	**Better understanding of** kinetics and mass transport limitations of redox reactions are needed. **Long-term** reversibility studies are needed. (Redox organic carriers must withstand repeated cycles of oxidation and reduction without degrading.)* **The interaction** of redox organic carriers with other system components, such as electrodes and electrolyte solutions, can pose challenges.
DAC	ECR	EL	**The combination** of acid/base and hydrogen products complicates the optimal current density. **Developing** highly efficient, selective, and durable catalysts is crucial. **Large overpotentials** are required at high pH gradients.
DAC	ECR	BPMED	**To offset** high membrane costs, systems need high operating current density, high efficiency, and prolonged membrane life span. **Operating** at high current densities can cause high ohmic resistances within the stack as well as additional resistances due to gas evolution. **Regular maintenance** is required to address fouling and scaling on membranes, which can significantly hinder performance by increasing resistance and reducing ion transport efficiency.
IWC	EPOI	BPMED for CO_2 stripping	**Pumping water** requires significant energy, though using tidal flows could potentially reduce this energy requirement. **There is** increased risk of biofouling because of organisms and organic matter in the seawater. **Seawater's** highly corrosive nature poses a significant challenge, leading to corrosion and material degradation.‡
IWC	EPOI	BPMED for OAE	**Ensuring accurate** MRV in open systems is challenging, although closed or hybrid MRV options might be possible. **There is** increased risk of biofouling due to organisms and organic matter in the seawater. **The generation** of hydrogen chloride (HCl) poses disposal challenges because of its highly corrosive nature.
HYB	EPOI	EL	**Managing optimal** current density is complicated by the interactions between acid/base and hydrogen products. **Chlorine gas** (Cl_2) or HCl avoidance or disposal is needed. (Cl_2 and HCl are highly corrosive.)† **Developing** highly efficient, selective, and durable catalysts is crucial.
HYB	EPOI	BPMED	**To offset** high membrane costs, systems need high operating current density, high efficiency, and prolonged membrane life span. **Water from** seas, lakes, rivers, and treatment plants can contain harmful elements that complicate processing.‡ **Safely disposing** of HCl, which is very corrosive, is necessary.

Notes:

*Long-term testing is not only associated with reversibility studies, but also with the ability of the reduced organic carrier to maintain CO_2 capture capacity. Specifically, the presence of protons can neutralize the reduced organic carrier, which will then lower the CO_2 capture capacity.

†Oxygen-selective electrodes can reduce challenges associated with Cl gas, although oxygen evolution could accelerate electrode degradation.

‡Seawater is highly corrosive and contains Cl^- (3.5% average global salinity) and microorganisms that can affect metal corrosion and pose major challenges for electrodes and membranes.

RMI Graphic. Sources: Liu et al., Challenges and Opportunities in Continuous Flow Processes for Electrochemically Mediated Carbon Capture, iScience, 2022, 25; Gurkan et al., Perspective and Challenges in Electrochemical Approaches for Reactive CO_2 Separations, iScience, 2021, 24; Alexander P. Muroyama and Lorenz Gubler, Carbonate Regeneration Using a Membrane Electrochemical Cell for Efficient CO_2 Capture, ACS Sustainable Chemistry and Engineering, 2022, 10(49), 16113–16117.

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