



The CREO FOAK Framework

Case Study: Carbon Management Technologies



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1 Why is a first-of-a-kind (FOAK) framework important?

Achieving net zero emissions by 2050 requires a significant increase in financing and deployment of emerging climate hardware technologies.ⁱ According to the International Energy Agency (IEA), approximately 40% of necessary emissions reductions rely on technologies that have not been commercially deployed.¹ This presents a financing hurdle for scaling up climate solutions.

As an emerging climate technology moves from development to deployment, the **financial needs for projects shift from corporate equity to debt capital** (i.e., from venture capital to project finance) to limit ownership dilution and to attract funds appropriate for high capital expenditures. Debt financing, however, is challenging to secure because of expectations and requirements for projects, slowing the deployment of emerging climate technologies.

Debt financiers often avoid projects that are the first to deploy an emerging climate technology.ⁱⁱ Pioneering large-scale projects have higher levels of risk and financing requirements that can make financiers reluctant to lend capital. If developers of these projects cannot secure needed loans, the ability to scale the deployment of important technology and achieve decarbonization goals could be significantly compromised.

First-of-a-kind (FOAK) commercial projects are a pivotal milestone for technology scaling. Yet, they struggle to attract sufficient capital, and they carry a distinct set of risks. **The CREO FOAK framework identifies what makes a commercial climate project “first.” The framework also helps to demonstrate deployment precedent and allay financier FOAK concerns.** This paper illustrates the framework’s usefulness by applying it to carbon management technologies and analyzing data on the scalability of each project. Ultimately, the FOAK framework should help to remove obstacles to financing and achieving decarbonization objectives.

ⁱ Emerging climate hardware technologies include those in hydrogen, sustainable aviation fuel, cement, and steel, carbon dioxide removal, and select others.

ⁱⁱ Unlike equity investors who seek to deploy capital in climate companies with *innovative* and *industry-disruptive* technology, debt investors underwrite *proven* and *turnkey* projects. The reason for this difference in risk appetite is that, while venture investors allocate capital for an equity stake in a company with an expected 30%+ return, debt financiers fund a project for a 12%+ return. In other words, lenders accept lower returns in exchange for lower risk. ([AngelList](#))

2 What is a “first-of-a-kind” climate project?

The term “first-of-a-kind,” and its acronym “FOAK,” proliferate in the climate community as emerging climate technology companies seek to develop projects. **A first-of-a-kind (FOAK) climate project is generally known as the *first* commercial-scale deployment of an emerging emissions-reducing hardware technology or material.** “Commercial scale” projects, while relative for each technology and material, produce a set volume of a product with consistent quality to meet market demand and operate profitably.ⁱⁱⁱ Further refinement of the term “first-of-a-kind” and categorization of FOAK projects can help establish baselines of climate “firsts” and perhaps shift perceptions of climate projects from *innovative* to *proven* among debt financiers.

While challenging, building and financing a FOAK commercial facility for an emerging climate company proves the technology’s commercial performance and establishes a track record for profitable future projects. Costs usually decline after subsequent plant builds due to operational optimization, process design improvements, mass manufacturing, innovation, and cheaper cost of capital. Thus, production capacity and financing can help to evaluate whether emerging climate technology projects are rapidly scaling, predictability improving, or reaching a stable commercial-scale (e.g., when dollars invested per unit of output starts to flatline).^{iv}

Some frameworks help to assess the commercial viability of a technology. NASA’s Technology Readiness Level (TRL) framework, which is used to determine a technology’s preparedness for project deployment, shows that technologies with a TRL of 7 or 8 are ready for large-scale development.² Elemental Excelsior’s Commercial Inflection Point (CIP) scale, which is used to indicate a technology’s degree of commercial readiness among climate projects in particular, shows that technologies with a CIP of 5 are ready for an initial commercial deployment.³ While these frameworks are helpful for assessing technologies before they begin or complete a project, there is no framework for qualifying and documenting a climate project as a “first-of-a-kind.” Doing so helps to prove a technology’s repeatability, suitability, and momentum toward profitability to debt financiers.

A first-of-a-kind climate project does not mean that an individual company commercially deploys a new technology or material for its first time. The first commercial-scale projects within an industry or region are true “firsts.” Therefore, it is important to identify what makes

ⁱⁱⁱ For emerging climate technologies and materials, because the number of deployed projects is low, it is difficult to establish a threshold at which a project is considered “commercial scale.” A climate hardware company might start with a bench-scale and pilot-scale project producing a small fraction of projected production capacity and costing hundreds of thousands to single-digit millions of dollars. These projects are proofs-of-concept to test that a technology or material *can* be delivered. Subsequent demonstration facilities prove that a technology or material works at scale and quell concerns about scale, yield, availability, cost predictability, serviceability, and customer satisfaction. As data on cost and production from initial projects are collected, the company can grow toward a commercial-scale, FOAK project that produces at maximum capacity and costs hundreds of millions or single-digit billions of dollars.

^{iv} Production capacity is the maximum possible output of a facility over a certain period. The upper-bound of production capacity for climate technologies continuously evolves due to optimizations in processes and new innovations; even wind turbines continue to grow in size and power. The average capacity of newly installed wind turbines grew 7% from 2021 to 2022, to 3.2 MW, while the hub height — distance from the ground to the middle of the turbine’s rotor — increased 4% from 2021 to 2022, to 98.1 meter. ([U.S. Department of Energy](#))

a project an industry or global first. Table 1 presents an ontological framework to categorize an emerging climate technology project as FOAK based on four factors: Deployment, Production, Integration, and Location.

Table 1: CREO FOAK framework.

FOAK ‘first’ factor	Definition	Categorical Examples	
		Technology	Material
Deployment	First installation of a technology or material at commercial scale.	Liquid solvent direct air capture facility	Skyscraper built with sustainable steel
Production	First production of a technology or material at commercial scale.	Molten-salt battery manufacturing plant	Green cement factory
Integration	First integrated installation of 2+ technologies or materials at commercial scale, which on their own might not be FOAK.	Green hydrogen facility with 100% renewables	Electric vehicle produced with green steel
Location	New country or regional location for Deployment or Production of a technology or material at commercial scale.	Geothermal energy pump in Tunisia	Green cement factory in Argentina

The FOAK factors are not mutually exclusive. Each demonstrates a different accomplishment or characteristic of what makes it a “first.” One project might therefore include several FOAK factors. For example, a battery recycling facility could qualify as both a Deployment and Production FOAK project. If the project were the first globally, nationally, or regionally, it would qualify as a Location FOAK project. For a given technology or material, Deployment and Production FOAK factor projects typically precede Integration and Location FOAK factors. The technology or material must have been deployed or produced before those activities can be combined with another technology or placed in a new location.

Each FOAK factor carries a slightly different set of risks associated with the project. First-of-a-kind projects present unique risks at every single stage of the project development cycle which extend beyond the core technological risks: siting, construction, supply chain, community engagement, credit, offtake, tax and compliance, and political risks. All are examples of large first-of-a-kind risks that must be overcome for the project’s success.^v By better defining how a project is determined to be the “first” of a kind, certain risks may more easily be underwritten.

^v Further research on large climate project risks can be explored more thoroughly through Prime Coalition’s [“Barriers to the Timely Deployment of Climate Infrastructure”](#) 2022 report. The research is extended and applied more specifically to FOAK projects in Trellis Climate’s [“Catalyzing Development of First-of-a-Kind Climate Projects”](#) 2023 report.

3 How does the FOAK framework apply to carbon management technologies?

Applying the framework to a climate-specific subsector like carbon management demonstrates its utility in classifying FOAK projects and understanding patterns in project maturation. Carbon management technologies capture, contain, and store or utilize carbon dioxide.^{vi} For this research, only technologies that capture carbon dioxide from point source or the atmosphere are evaluated. These technologies include point-source carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC). It is largely accepted that DAC and CCS are necessary technologies to achieve net zero goals and limit global warming to 1.5 degrees Celsius. Due to the relative nascency of these technologies, many of the commercial-scale projects within this sector are first-of-a-kind.

The source of CO₂ and process for carbon capture and storage varies among the three categories of carbon management technologies.

- **Point-source carbon capture and storage (CCS)** technologies remove high concentrations of CO₂ directly from facility point-source emissions, such as from factories and power plants. Technologies capturing carbon with this method are more developed and significantly cheaper than DAC.^{vii} The lower cost of CCS has allowed for a proliferation of new projects applying the technology to a range of emitting industries, including steel and cement manufacturing as well as ammonia, ethanol, hydrogen, and pulp and paper production.
- **Bioenergy with carbon capture and storage (BECCS)** technologies capture and store CO₂ from biomass energy generation (bioenergy).⁴ When paired with carbon capture and storage, bioenergy generation can be sustainable and a source of net negative emissions because CO₂ is permanently removed from the carbon cycle. BECCS technologies use solvents to isolate CO₂ from flue gases produced from the combusted biomass.^{viii}
- **Direct air capture (DAC)** technologies remove CO₂ directly from ambient air. Captured CO₂ can be stored or treated and used in various products such as building materials or synthetic fuels. Since CO₂ in the atmosphere is more dilute than in point source emissions, DAC plants require more energy, as well as more complex and expensive technology. Key DAC technologies for separating CO₂ from the ambient air are described in further detail in Table 4 in the appendix.

^{vi} Once CO₂ is captured by a carbon management technology, it is compressed, chilled, and transformed into a fluid before being transported through pipelines for utilization or storage. Storage sites are deep, underground geological formations and can include former oil and gas reservoirs, deep saline formations, and coal beds. CO₂ can remain safely and permanently stored in these locations.

^{vii} There are three primary point-source capture technologies: (1) post-combustion carbon capture, which is the primary method used in existing power plants, (2) pre-combustion carbon capture, which is primarily used in industrial processes, and (3) oxy-fuel combustion systems.

^{viii} While the carbon capture and storage technology for BECCS is no different than the other point-source capture technologies, select novel BECCS projects have been included in the analysis because of their distinct classification as a carbon removal technology.

All three categories of carbon management technologies need to be deployed at scale quickly to meaningfully contribute to decarbonization.⁵ Point-source capture technologies, despite being the oldest and cheapest to deploy, currently make up just 4% of the carbon capture needed by 2030.⁶ Only 1% of the projected 190Mt CO₂ removal necessary by 2030 is currently being captured from BECCS.⁷ DAC technologies must capture 100,000 times their current capacity to achieve the 1 billion metric ton annual removal capacity to reach net zero by 2050.^{ix,8}

It is important to take stock and understand what has been accomplished with existing and scheduled FOAK carbon removal projects. Fifteen FOAK projects within the carbon management space have been identified and classified according to the FOAK framework.^{x,xi} Table 2 explains how select projects are categorized using the FOAK framework.

^{ix} While this seems impossible, it would in fact be comparable to the growth rate of solar between 2011 to 2021, where the megawatt capacity from solar energy generation jumped 12x. See the Global Solar Market Overview section of ISA's [World Solar Report 2023](#).

^x These have been sourced from multiple datasets, including [Rhodium's Clean Investment Monitor](#), the [IEA's CCUS Projects Database](#), the [Clean Air Task Force \(CATF\)'s Carbon Capture Activity and Project Table](#), the [Direct Air Capture Coalition](#), as well as from various public sources, company announcements, news articles, and securities filings.

^{xi} FOAK framework analysis of carbon management technologies relies on publicly available datasets and announcements. These resources contain limited project-level data on production capacity and financing.

Table 2: Select FOAK projects and FOAK factor categorization rationale.

Project	Technology	Primary FOAK Factor	Categorization rationale
Utility-scale power plant (NET Power, Texas)	Point-source Capture (Allam-Fetvedt cycle)	Deployment	NET Power will build a utility-scale natural gas-fired power plant with near-zero emissions by deploying 8 Rivers' Allam-Fetvedt cycle power plant technology. ⁹ By combusting natural gas with pure oxygen, recirculating supercritical CO ₂ to spin a turbine, and sequestering leftover CO ₂ , the Allam-Fetvedt cycle produces energy from natural gas. ¹⁰ This power plant will produce 300 MW of clean power and will capture over 850,000 metric tons of CO ₂ . ¹¹ While the Allam-Fetvedt technology is being deployed in other projects in the US and the UK, this project in Texas will be the first and largest global utility-scale deployment of the Allam-Fetvedt cycle technology. ^{12,13}
Project Octopus in South Korea (Capture6)	DAC with desalination	Integration	Project Octopus in South Korea will deploy Capture6's DAC technology to build the world's first integrated water management facility with CO ₂ removal. ¹⁴ The DAC technology uses the desalination facility's high salt concentration to capture carbon, creating more potable water, reducing the amount of waste brine, and producing green chemicals (e.g., hydrochloric acid and calcium carbonate). ¹⁵ The project aims to capture 500,000 metric tons of CO ₂ per year when operational. ¹⁶
US Steel Corporation, CarbonFree Chemicals Holdings	Point-source capture with steel manufacturing	Deployment	US Steel Corporation and CarbonFree Chemicals Holdings are building the first large-scale point-source capture project applied to a steel production plant in North America. ^{17, xii} CarbonFree's SkyCycle technology captures and mineralizes up to 50,000 metric tons of CO ₂ per year from US Steel Corporation's Gary Works Blast Furnaces, making it one of the first green steel plants.
Occidental; ADNOC	DAC	Location	Occidental is using its DAC technology in the Middle East for a megaton capacity project in the UAE. Occidental will use the same DAC technology as its STRATOS project in the US. ¹⁸

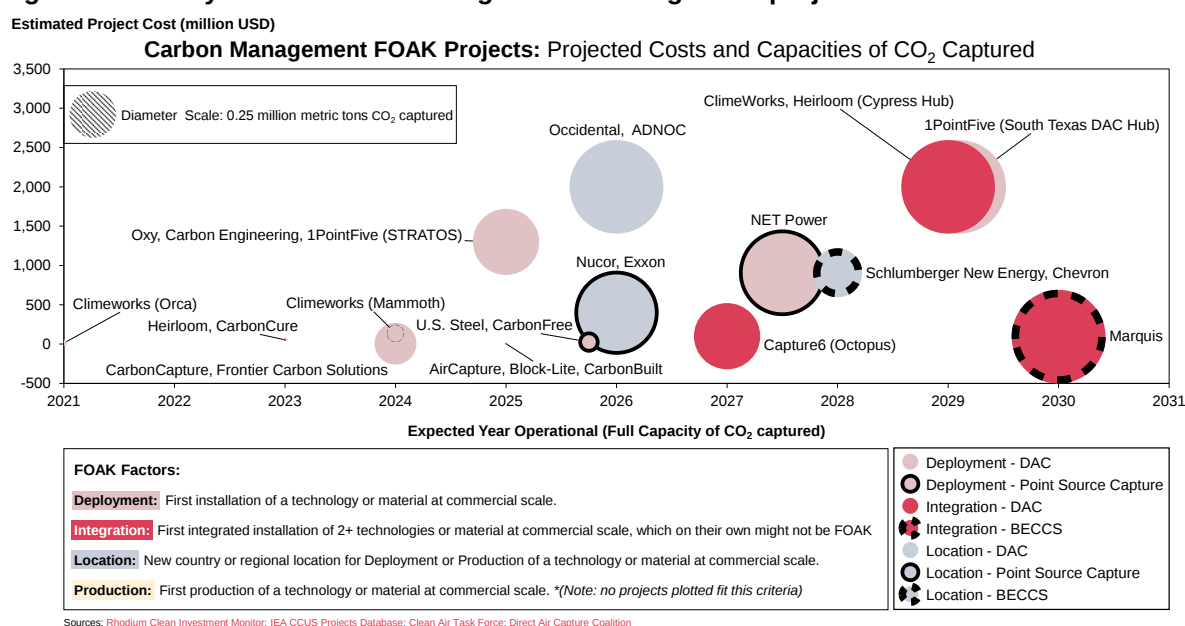
^{xii} There are existing carbon capture and utilization projects in Europe, such as [Arcelor Mittal's Steelanol plant](#) in Belgium.

Figure 1 below shows the distribution of projects identified as FOAK within the carbon management space.^{xiii}

Table 3: The variables of the plot.

X Axis	Y Axis	Size (Diameter)	Color	Outline
Expected year when facility is operating at full capacity	Estimated cost to finance and build the facility ^{xiv}	Capacity for CO ₂ captured, in million metric tons (MMT)	FOAK factor (see plot legend)	The type of carbon management technology (see plot legend)

Figure 1: Primary FOAK factors among carbon management projects.



^{xiii} While projects can be categorized with multiple FOAK factors, only the primary FOAK factor was plotted. Projects have a primary Location factor if they are not a Deployment or Production FOAK.

^{xiv} Rhodium Group's [Clean Investment Monitor](#) database was used for the estimated project cost values. The database employs a cost model based on the different types of capture source, plant scale, and estimates provided under NDA by developers and financiers of the projects themselves. Where missing, the cost estimates were derived based on the projected capacity of the plant, location, and the average costs of the technologies.

3.1 The plot prompts several observations:

- 1. The carbon management sector does not currently include Production FOAKs because each project is bespoke.** Each project is a tailored implementation and not yet streamlined to be sold as a technology, meaning all are Deployment FOAKs. While some projects output a material (e.g., Aircapture, Block-Lite, and CarbonBuilt leveraging their DAC technologies to store carbon in concrete to produce sustainable concrete), the primary novelty factor is the actual deployment of a DAC and mineralization facility. The production of carbon-to-value materials is still aspirational because these products are not being sold at meaningful volumes. Until carbon management technologies are manufactured at scale like wind turbines and solar panels are today, there will not be Production FOAK projects.
- 2. Integration and Location carbon removal projects sequence behind Production and Deployment FOAK projects.** This matches expectations because Integration projects typically are a combination of Production and Deployment projects, and a Location project requires a global first of a Production or Deployment project.
- 3. Deployment FOAK projects are more expensive than Location or Integration FOAK projects.** Per million metric tons of CO₂ captured, Deployment factor projects in this sample set are 85% more expensive than Integration projects and 40% more expensive than Location projects. DAC Integration projects are particularly less expensive than Deployment or Location projects. Because Integration projects tend to follow Deployment projects, they likely benefit from cost and risk reductions from prior Deployment projects. For example, Capture6's Project Octopus DAC Integration project is significantly cheaper than similar-size DAC projects. This could be attributed to Capture6's innovative technology stack leveraging existing infrastructure (i.e., desalination and water recovery systems) to reduce the cost of carbon removal. Many other factors might also influence the estimated cost of the projects, including the price of the carbon dioxide or carbon credits purchased, project siting and permitting, the location of the project, and the fate of the carbon (i.e., storage vs. utilization). Market-rate investors will likely be more interested in later-stage projects, such as Integration or Location FOAK projects, because they are more capital-efficient. Government and catalytic capital for early Deployment DAC projects is therefore paramount.
- 4. Capacity for CO₂ capture or removal from carbon management technology projects increases exponentially.** The only operational DAC projects today, Climeworks' Orca in Hellisheidi, Iceland and Heirloom's facility in Tracy, California, are barely visible dots on the plot compared to the megaton projects scheduled to be operational in the next few years.^{xv} Climeworks' second DAC plant, Mammoth, is set to be operational in late 2024 with an expected capacity of 36,000 metric tons of CO₂ annually. It took three years for the company to scale its DAC technology capacity ninefold. To reach its projected megaton capacity by 2030, Climeworks will have to increase the capacity scale-up exponentially (28 times the current capacity).¹⁹ Other players in the DAC ecosystem, such as Carbon Engineering, CarbonCapture and 1PointFive, have planned to build plants with a starting capacity of around 500,000 metric tons of CO₂ annually. However, expected technological cost reductions do not

^{xv} Climeworks' Orca project began operations in 2021 and has capacity to capture 4,000 metric tons of CO₂ annually, and Heirloom's project began operations in 2023 and has capacity to capture 1,000 metric tons of CO₂ annually. ([Climeworks](#))

mirror this exponential increase in capacity.²⁰ Achieving profitability will require substantial additional funding to further deploy and mature the technology. Point-source capture and BECCS facilities plotted also show non-linear increases in capacity. The outcomes of the next few years' projects will radically shape projections for longer-term capture capacity and costs.

- 5. Larger carbon management projects are enabled by government funding.** The projects plotted with the greatest capture capacities are largely enabled by government support, particularly in the US. Two megaton-capacity DAC hubs, the South Texas and Cypress hubs, are expected to receive a combined \$1.2 billion of the \$3.5 billion total funding for all the future Regional DAC Hubs through the US Bipartisan Infrastructure Law.²¹ This represents the world's largest investment in engineered carbon removal in history, and is roughly equal to the total funding amount received by all the major DAC companies globally.^{22,23} Climeworks' Mammoth was funded entirely by their own balance sheet, but the 30x scale Cypress Hub Integration project between Climeworks and Heirloom is largely government-funded. Other legislation, like the Inflation Reduction Act and its carbon capture tax credit, helps companies like NET Power and Marquis Inc. finance their projects.^{24,25} The first megaton-capacity DAC facility built outside of the US, in a partnership between Occidental and ADNOC, directly benefits from the Biden Administration's US-UAE Partnership to Accelerate Transition to Clean Energy (PACE).^{xvi}

Given uncertainty about cost reduction and volatility in the voluntary carbon markets, policy support helps build the market for carbon dioxide removal technologies. Receiving significant government funding signals that the project has undergone significant diligence and removes certain risks around community engagement, location-related risk, or obtaining site permitting — making subsequent projects more attractive to private capital financing. While demand and support for carbon dioxide removal technologies in private markets is growing because of increasing net zero commitments, funding for these projects is small compared to what is required.^{26,27} Out of the \$1.3 billion raised by leading DAC companies, the vast majority has been equity financing, with high leverage of non-dilutive government grants.²⁸ The low debt-to-equity ratio in these projects suggests a gap in non-dilutive private debt funding. Finance therefore may be the limiting factor for the scale-up of these technologies. Government funding, through loans, grants, or credit, can bolster supply and demand required for full-scale, commercial projects.²⁹

^{xvi} PACE is set to catalyze \$100 billion in financing, investing, and supporting the global deployment of 100GW of clean energy by 2035: [“FACT SHEET: U.S.-UAE Partnership to Accelerate Transition to Clean Energy \(PACE\)” \(The White House\)](#)

4 Conclusion and opportunities for further research

Defining what makes a project “first” could help debt financiers deploy more capital toward key emerging climate technology projects. The CREO FOAK framework distinguishes the specific characteristics that qualify a project as being a “first-of-a-kind.” Rather than starting from scratch, developers of emerging climate technologies can build on the work of their predecessors and successful projects in the same field. **By categorizing and cataloguing FOAK projects, developers can quell debt financiers’ concerns and prove they are not “first” to allocate capital to these specific kinds of projects.**

The FOAK framework also helps to build the project development ecosystem beyond debt financiers. As project characteristics are defined, banks, insurers, EPCs, offtakers, and other actors important for reaching project bankability can refine their project scope. They can prioritize or specialize in particular characteristics that make a project a first-of-a-kind, thereby learning from a narrower set of projects and allocating capital more efficiently. As demonstrated through its application to carbon management technologies, the CREO FOAK framework organizes FOAK projects and facilitates pattern discovery in deployment capacities, timelines, estimated costs, and risks. Each FOAK factor implies a different development risk and can help uncover specific project barriers. Applying the framework to other emerging climate technologies and outlining risks associated with each FOAK factor can demonstrate the projected maturation of technologies to both equity and debt investors.

Consolidating this dataset of carbon management projects was challenging. We hope it helps to further others’ research and demonstrate areas for collaboration. There is ample opportunity to build more knowledge and capacity for FOAK projects. CREO is actively working on collecting project-level data and investment opportunities across the climate and sustainability sectors. If you would like to discuss any aspect of this research, collaborate on FOAK framework analysis for other climate technologies, or hold expertise on these topics as they relate to climate project development, please contact Sophie Thorel (sthorel@creosyndicate.org) and Kobi Weinberg (kweinberg@creosyndicate.org).

Appendix

Table 4: Selected DAC technologies.

DAC Technology	Description	Requirements and complexity
Solid sorbent adsorption	Solid sorbents are used to capture CO ₂ from the air. This utilizes cyclic adsorption-desorption processes in CO ₂ collectors. Typically, materials used for the sorbents are porous, such as activated carbon or metal-organic frameworks (MOFs), which bind with CO ₂ molecules. Once saturated, the captured CO ₂ is released through a combination of heat and vacuum, and the adsorbent can be regenerated.	Low pressure and medium temperatures (100 degrees Celsius). ³⁰
Liquid solvent absorption	Chemical absorption requires passing the air through a liquid solution that reacts with carbon dioxide to capture it. This utilizes continuous absorption and regeneration stages. Typically, amine-based compounds are used for the solvent to form a soluble CO ₂ compound. The CO ₂ can be released through a separate process which requires high temperatures.	High temperatures (900 degrees Celsius); more complex than solid sorbent technology. ³¹
Mineralization (or CaO ambient weathering)	The CO ₂ is converted to stable carbonates, mimicking natural weathering processes but accelerated for optimal carbon capture. The CO ₂ is bound to CaO in a carbonation phase and regenerated in a calcination phase.	High temperatures and pressures for calcination process of ex-situ (surface) mineralization. ³²

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