CARBON DIOXIDE REMOVAL IN CALIFORNIA

Deployment Readiness, Market Access, and the Case for Public Procurement

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GOLDMAN SCHOOL OF PUBLIC POLICY

UNIVERSITY OF CALIFORNIA, BERKELEY

AUTHOR

Pamela Castell de Oro

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I. INTRODUCTION

California has set one of the most ambitious climate targets globally, through Assembly Bill 1279 (2022)[1], requiring carbon neutrality by 2045 and at least an 85 percent reduction in emissions below 1990 levels. This leaves roughly 65 MMT of residual emissions that cannot be eliminated through conventional mitigation and must be addressed through carbon dioxide removal (CDR). The California Air Resources Board's 2022 Scoping Plan translates this into an operational target of approximately 75 MMT of CDR annually by 2045[2]. While the role of CDR is now clearly embedded in state policy, the conditions required to support its deployment at scale are still emerging. The scale of this requirement is not only technical, but economic.

The economic scale of this obligation is substantial by any benchmark. At a future price point of around $100 per ton, often cited as a target for cost-competitive direct air capture (DAC)[3], delivering 75 MMT of removals would require roughly $7.5 billion per year. The price level has begun to appear in forward purchase agreements, such as Google's 2024 offtake deal with Holocene[4], though it reflects expected futures costs rather than current market prices.

At current voluntary market prices, the cost is significantly higher. Biochar and other biomass-based pathways can be around $180 per ton, while direct air capture ranges from $500 to $1000 per ton[5]. At those levels, the same 75 MMT would cost up to $34 billion annually.

For comparison, California's cap-and-invest program appropriated $3.1 billion from the Greenhouse Gas Reduction Fund (GGRF) to administering agencies for Fiscal Year 2024-2025[6]. Whichever price trajectory materializes, the annual cost of meeting California's 2045 removal obligation would exceed the entire Fiscal Year 2024-25 GGRF appropriation by a factor of two to eleven. Building procurement capacity at this scale is not a matter of reallocating existing climate finance structures; it requires institutional mechanisms that do not yet exist.

This scale raises a strategic question that state policy has not yet addressed explicitly: should the state meet its removal obligations by purchasing the lowest-cost credits available globally, or by deliberately building in-state CDR capacity?

In practice, procurement decisions will be driven by cost, pushing California to source removals from the lowest-cost global suppliers rather than building in-state capacity. CDR projects are already active across all four major pathways outside California. Direct air capture is under construction in Texas[7]

1 Assembly Bill 1279 (Muratsuchi), 2022, codified at Cal. Health & Safety Code §§ 38561.1–38562.4.

2 CARB, *2022 Scoping Plan*, App. I.

3 IEA, *Direct Air Capture: A Key Technology for Net Zero*, 2022.

4 CDR.fyi, "The Google–Holocene Deal," 2024.

5 IEA, "Driving Down the Cost of Carbon Removal," 2025.

6 California Climate Investments, "About California Climate Investments," 2026.

7 Occidental Petroleum, "Stratos Direct Air Capture and Storage Facility," 2026.

and Louisiana[8]; bioenergy with carbon capture and storage operates at the Blue Flint facility in North Dakota; enhanced rock weathering is being deployed across the U.S. Corn Belt[9], with multi-year field trials documenting carbon removal alongside agronomic co-benefits; and ocean alkalinity enhancement projects have secured permits in North Carolina.

Five U.S. states — Louisiana, North Dakota, West Virginia, Texas, and Wyoming — have secured EPA Class VI primacy for geologic CO_2 sequestration[10], substantially shortening the permitting timelines that constrain DACCS and BECCS deployment. California has not. In this context, a state that optimizes narrowly for near-term compliance cost would have clear options to procure removals from these jurisdictions rather than build in-state capacity. Any case for in-state procurement must therefore be grounded in considerations beyond cost alone.

The case for in-state procurement rests on three distinct but convergent grounds, briefly outlined below. These rationales are acknowledged in the CDR policy literature; this paper does not seek to develop each in detail but takes them as the starting point that motivates its central focus on procurement design. First, compliance alignment. California will need to purchase removals regardless, and CARB has direct regulatory authority over quality, durability, and monitoring standards only for projects within its jurisdiction. In-state projects operate under the state's compliance framework from day one; imported credits rely on third-party registries whose standards may not fully align with California's. Second, economic return. Spending in the range of $7.5 to $34 billion annually generates very different returns to the state economy, depending on where the money flows. Procurement directed at California-based projects supports in-state jobs, tax revenue, supply chain investment, and broader economic activity. Procurement directed at imported credits delivers the carbon ton, but little of this economic value. Third, sectoral integration. Several CDR pathways deliver carbon removal as a co-benefit of addressing sector-specific challenges California already manages, including wildfire risk reduction through forest biomass utilization, safer biosolids management in urban water systems, soil health improvement through biochar application, and reduced agricultural burning in air-impacted communities. In these cases, carbon removal is not the primary driver of action, but a measurable outcome of interventions the state already prioritizes and funds.

This distinction is central to policy design. Not all pathways function in the same way: some are embedded within existing sectoral systems, while others deliver removal as a primary output. Different pathways require different policy objectives, funding rationales, and procurement structures, a point this paper develops in detail.

Even accepting the case for in-state procurement, a substantial gap remains between California's policy ambition and its operational capacity to purchase CDR at scale. Current market mechanisms, such as the voluntary carbon market, the Low Carbon Fuel Standard, and the cap-and-invest program, are not individually or collectively sufficient to generate a durable demand signal that project developers need to make a final investment decision. The voluntary market is fragmented and contracting[11]; the LCFS covers only specific pathways with narrow accounting rules; and Cap-and-Invest has not yet created a compliance pathway for CDR. Although AB 1207 directs CARB to consider new compliance offset protocols, including carbon dioxide removal, the current proposed

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8 *Canary Media*, "World's Largest Direct Air Capture Plant Starts Sucking CO2," 2024.

9 Beerling et al., "Enhanced Weathering in the US Corn Belt," 2024.

10 WRI, "How US States Can Lead on Carbon Removal Policy," 2024.

11 ClearBlue Markets, *Q1 2026 Voluntary Carbon Market Review*.

amendments do not include any new CDR protocols, and CARB is not required to update existing offset protocols until 2029. CARB is, however, currently developing CDR protocols through the implementation of SB 905, which creates the Carbon Capture, Removal, Utilization, and Storage Program[12]. This creates a near-term implementation gap, roughly 2026 to 2030, in which California has set ambitious targets but lacks the procurement infrastructure to deliver them.

This paper proceeds in five parts. Section II reviews California's evolving CDR policy landscape, including current regulatory gaps and the allocation of Greenhouse Gas Reduction Fund (GGRF) appropriations. Section III assesses the four CDR pathways along technology, resource, MRV, and regulatory dimensions, identifying where California's structural advantages and disadvantages lie. Section IV evaluates current carbon market access and documents the structural nature of the cost coverage gap. Section V develops the case for public procurement and proposes a design framework for deploying SB 840 authority across the three horizons identified above: immediate procurement design, preparation for the integration of cap-and-invest compliance, and embedded sectoral policy reform. Section VI concludes.

[12] CARB, *Initial Statement of Reasons: Cap-and-Trade Regulation Amendments*, 2026.

II. CALIFORNIA CDR POLICY LANDSCAPE

Over the past three years, California has passed a set of laws that together began to form a policy framework for carbon dioxide removal. The laws enacted since AB 1279 have defined regulatory authority, created funding channels, and established targets, but the resulting landscape is uneven, and architecture is mature in some dimensions and visibly incomplete in others. What the landscape does not yet include is a dedicated in-state procurement mechanism, pathway-specific MRV methodologies, and a reliable demand signal, precisely what a large-scale deployment requires.

Figure 1 maps this architecture along four functional axes: binding climate targets, regulatory and MRV authority, funding and demand mechanisms, and pathway-specific instruments. Each axis contains enacted laws, vetoed bills, bills that died in the legislative process, and in one case, a complete policy gap. Reading the diagram horizontally reveals where California has acted and where it has not. The subsections below describe each axis briefly, identifying both the enacted elements and the gaps that still need to be addressed to enable in-state CDR deployment.

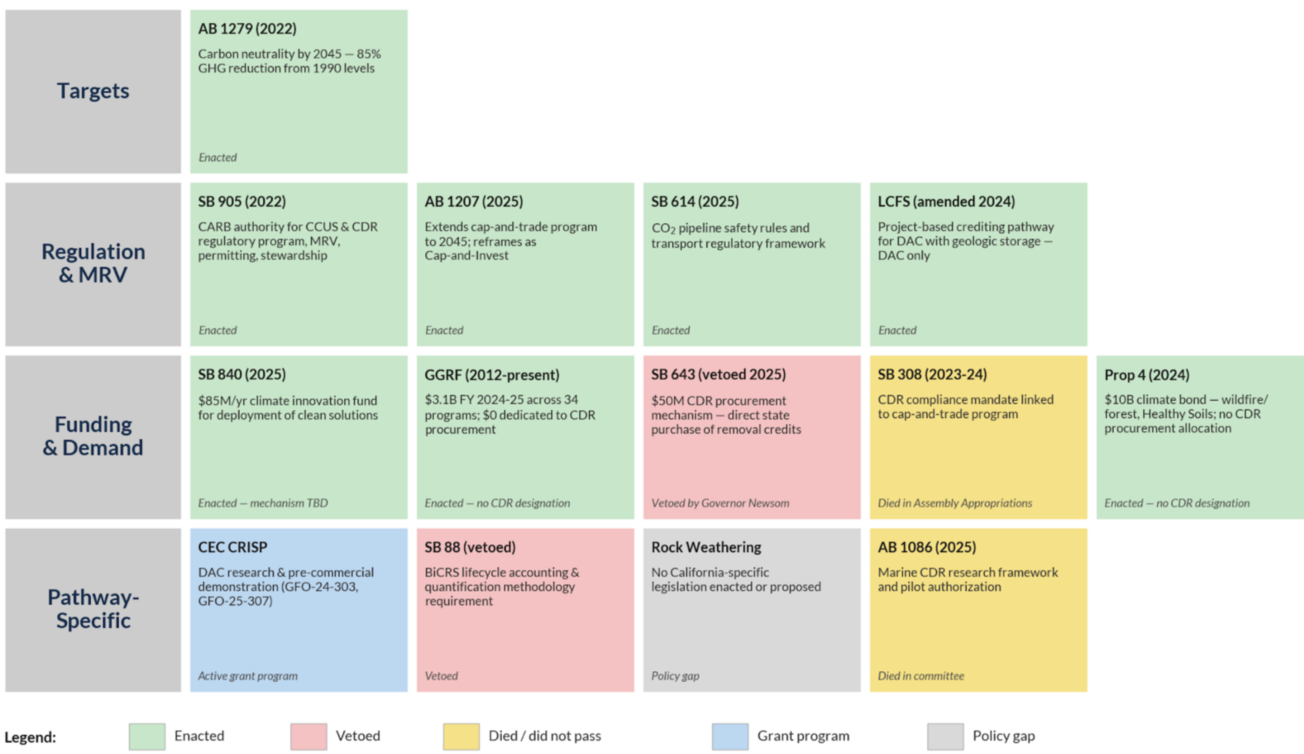

Figure 1. California CDR Policy Architecture (2022–2025). Author compilation

II.1 Targets

AB 1279 (2022) establishes carbon neutrality as a binding statutory target but contains no CDR-specific provisions of its own. The Scoping Plan trajectory, approximately 7 MMT CO_2e annually by 2030, scaling to 75 MMT by 2045, provides the quantitative anchors for everything that follows, but these figures are operational projections rather than legally binding interim targets. There are no pathway-specific targets or procurement milestones; the trajectory from zero in-state procurement today to 65–75 MMT by 2045 is not legally specified in binding terms.

II.2 Regulation and MRV

This axis is the most mature. However, a key gap remains. SB 905 (2022) grants the California Air Resources Board (CARB) authority to develop regulatory programs for carbon capture, utilization, and storage (CCUS) and carbon dioxide removal (CDR), including MRV, permitting, and long-term stewardship[13]. AB 1207 (2025) reauthorizes the cap-and-trade program through 2045 and reframes it as the Cap-and-Invest Program, while SB 614 (2025) establishes CO_2 pipeline safety rules. The Low Carbon Fuel Standard (LCFS), amended in 2024, provides project-based crediting for direct air capture with geologic storage, with no equivalent pathway from other CDR technologies[14].

Although CARB has broad regulatory authority, pathway-specific MRV methodologies are still under development. The Cap-and-Invest Program does not yet integrate CDR for compliance purposes; CARB's January 2026 Initial Statement of Reasons introduces a placeholder for future integration, but methodology development is deferred to subsequent rulemaking, with protocol updates not required until January 2029[15]. Legislative attempts to mandate pathway-specific MRV methodologies have not advanced, leaving operational methodology missing for most pathways beyond DAC.

In early 2026, CARB began the SB 905 implementation process by releasing a preliminary concepts document soliciting stakeholder feedback on potential regulations for the CCUS Program.[16] While not yet a formal rulemaking proposal, the document provides the most concrete signal to date of CARB's regulatory direction. It establishes applicability for six initial project types — carbon capture from large emissions sources, direct air capture, BECCS, and three geologic storage configurations (depleted oil and gas reservoirs, saline aquifers, and mafic and ultramafic reservoirs) — with requirements modeled on the EPA Class VI program but extended in several California-specific dimensions: including extending post-injection monitoring from 50 to 100 years; requiring enhanced seismic monitoring and mandating financial responsibility coverage throughout the full monitoring period. Beyond geologic storage, the framework explicitly identifies four additional pathway categories under evaluation for protocol development: marine CDR (including electrodialysis and coastal enhanced weathering), carbon mineralization (including terrestrial enhanced weathering and surficial mineralization), biomass and bio-oil storage (including pyrolysis to biochar and bio-oil), and carbon utilization (including cement,

13 Senate Bill 905 (Caballero), 2022.

14 CARB, *Low Carbon Fuel Standard Regulation*, 2024.

15 CARB, *Initial Statement of Reasons: Cap-and-Trade Regulation Amendments*, 2026.

16 CARB, *Preliminary Concepts of Potential Regulations: CCUS Program*, 2026.

biochar, and durable wood products). Together, these categories cover most of the pathways examined in Section III, indicating a regulatory pipeline considerably broader than the current LCFS CCS Protocol's DAC-only focus[17].

Several substantive questions remain open. Alternative definitions for key terms such as "area of review" and "storage complex" are presented for stakeholder input, with CARB asking whether to adopt EPA UIC definitions, LCFS CCS Protocol definitions, or a hybrid approach. Non-CO_2 geologic storage methods — bio-oil sequestration, storage in building materials, and similar mediums — are flagged as candidates for possible inclusion but not yet incorporated. Verification mechanisms for long-term financial responsibility, including the role of independent assurance providers, remain under consideration. CARB explicitly limits the initial focus to mechanical carbon removal approaches with high technology readiness, deferring nature-based strategies to AB 1757 implementation, and notes that all concepts remain subject to ongoing discussion and may change in eventual rulemaking. For the analysis developed in this paper, the implication is twofold: the regulatory architecture identified as "most mature" on the four-axis map is now visibly in motion, with concrete pathway coverage and timelines emerging; yet the operational methodologies that would enable compliance integration remain 12 to 24 months from completion at the earliest, leaving the 2026–2030 implementation gap on the demand side substantially in place.

II.3 Funding and Demand

This is the most fragile axis of the architecture. Funding exists, but no mechanism is explicitly designed to procure CDR. SB 840 (2025) allocates $85 million per year from the Greenhouse Gas Reduction Fund (GGRF) for climate innovation without establishing a procurement mechanism or specifying that funds must be used for CDR. Moreover, in the context of California's significant budget deficit and broader fiscal constraints, some policymakers question whether the $85 million will actually be available, and if so, whether it may be redirected to backfill programs that lost federal funding. The Greenhouse Gas Reduction Fund (GGRF) allocated approximately $3.1 billion across 34 programs in FY 2024–25, yet none of these programs are explicitly designed to procure CDR.[18]
Proposition 4 (2024) authorizes $10 billion in climate bonds, including allocations for wildfire resilience (approximately $1.5 billion), Healthy Soils ($65 million), and forest management ($181 million), none of which are designated for CDR procurement.[19]

At the same time, the proposals that would have created CDR-specific demand did not advance. SB 643 (2025) would have established a $50 million state procurement program with public-private matching but was vetoed by Governor Gavin Newsom in October 2025[20]. SB 308 (2023–24) would have created a compliance-side demand signal by requiring cap-and-trade participants to invest in CDR; after substantial revisions, it died in Assembly Appropriations in August 2024.

17 CARB, *Preliminary Concepts of Potential Regulations: CCUS Program*, 2026.

18 California Climate Investments, "About California Climate Investments," 2026.

19 California Natural Resources Agency, "Proposition 4 Climate Bond," 2026.

20 Carbon Direct, "California Governor Vetoes Carbon Removal Program (SB 643)," 2025.

Taken together, California funds climate action broadly through multiple vehicles of significant scale, but the proposals that would have created either direct procurement or compliance-side demand for CDR did not survive. The result is a system without a reliable demand signal for carbon removal.

II.4 Pathway-Specific

California's pathway-specific architecture is the most fragmented of the four axes, ranging from active grant programs to complete policy gaps. Direct air capture is the only pathway with a dedicated California instrument: the California Energy Commission's Carbon Removal Innovation Support Program (CRISP), which has advanced from early-stage research grants to a second phase (released May 2026) of pre-commercial demonstration funding, most recently a May 2026 solicitation requiring community engagement components. Biomass-based pathways lack an equivalent instrument; SB 88 (2023), which would have required CARB to develop BiCRS-specific lifecycle accounting and quantification methodologies, was vetoed by Governor Newsom.

Enhanced rock weathering represents a complete policy gap, with no California-specific legislation enacted or proposed. Marine CDR has been the subject of one recent effort, AB 1086 (2025), which would have authorized a research framework and pilot program but died in committee. This axis is therefore where California's policy architecture is most uneven; Section III examines each pathway in operational detail, including these policy conditions alongside resource, MRV, and stakeholder dimensions.

III. PATHWAY READINESS

Section II mapped California's CDR policy architecture across four functional axes: binding climate targets, regulatory and MRV authority, funding and demand mechanisms, and pathway-specific instruments. That mapping reveals where the state has acted and where structural gaps remain. This section moves from architecture to operations, from what authority exists on paper to what conditions each pathway actually faces when attempting to deploy in California.

The four pathways examined — direct air capture with carbon storage (DACCS), biomass-based carbon removal and storage (BiCRS), enhanced rock weathering (ERW), and ocean-based carbon dioxide removal — are not interchangeable. They differ in technological maturity, resource requirements, monitoring complexity, regulatory exposure, and community context. Treating them as a homogeneous category would yield policy recommendations that are too blunt to be effective and too broad to be actionable. The pathway-specific analysis that follows identifies where California's geography and infrastructure offer structural advantages, where operational barriers remain unresolved, and what targeted interventions could advance each pathway.

Each pathway is therefore assessed across five dimensions that reflect the actual conditions developers encounter in California. The first dimension, technology and storage pathways, characterizes how removal occurs and how carbon is ultimately stored, including the degree of reliance on geologic storage, biomass supply chains, mineral availability, or ocean processes. The second dimension, California resource base, examines the extent to which the state's geography, infrastructure, and resource endowment enable or constrain deployment. This includes access to suitable geologic formations, availability of biomass feedstocks or minerals, energy system conditions, and siting constraints specific to California. The third dimension, California project landscape, provides a snapshot of operational projects, in development, or publicly announced as of 2026. This dimension is descriptive rather than evaluative: it identifies where activity is occurring and which actors are involved, without assessing permitting timelines or regulatory feasibility, which are addressed separately.
The fourth dimension, MRV, regulatory, and permitting status, examines what developers concretely encounter when attempting to use existing frameworks: the availability (or absence) of methodologies, the structure and timelines of permitting processes, and unresolved regulatory gaps that directly affect project viability. The fifth dimension, stakeholder alignment, captures the political and social context of deployment. This includes environmental justice concerns, community responses, NGO positions, and broader perceptions of each pathway within California. In several cases, these factors represent binding constraints on deployment independent of technical feasibility.

Each pathway section closes with a summary of deployment gaps that synthesizes findings across these dimensions and identifies the primary constraint limiting scale in California.

3.1 Direct Air Capture and Storage (DACCS)

Technology and storage pathways

Direct air capture (DAC) is an industrial process that removes carbon dioxide directly from ambient air using chemical reactions. Atmospheric CO_2 is highly diluted, at approximately 420 parts per million, which makes DAC more energy-intensive than capturing emissions from a concentrated source such as a power plant or cement kiln[21].

Two technology families dominate current DAC development. Solid sorbent DAC (S-DAC) captures CO_2 by passing ambient air over solid materials, typically amine-based, that bind CO_2 at near-ambient temperatures. The captured CO_2 is then released using low-temperature heat (approximately 80–120°C), producing a concentrated stream for compression and storage.[22] [23] This lower heat requirement allows S-DAC systems to integrate with renewable or waste heat sources and supports modular, containerized designs that can be deployed incrementally.[24]

Liquid solvent DAC (L-DAC) captures CO_2 by passing air through alkaline liquid solutions. Releasing the captured CO_2 requires high-temperature calcination, typically up to about 900°C, which is usually powered by natural gas in current systems, although the resulting emissions are captured within the process. This higher energy demand makes decarbonizing L-DAC more technically challenging and generally favors larger, centralized facilities.[25]

DAC-derived CO_2 can be stored through three primary pathways. Geological storage involves compressing CO_2 and injecting it into deep underground formations such as saline aquifers or depleted oil and gas reservoirs. This pathway requires Class VI injection wells under EPA's Underground Injection Control program, which governs site characterization, well design, monitoring, and long-term liability. California has not obtained primacy for Class VI permitting, meaning projects must be approved by the federal EPA, a procedural constraint that has direct implications for permitting timelines.[26]

In-situ mineralization involves injecting CO_2 into reactive geological formations, such as basalt, where it converts into stable carbonate minerals underground. As of 2026, no DAC-linked in-situ mineralization projects have been identified in California.[27] Ex-situ mineralization involves incorporating captured CO_2 into materials such as concrete, where it reacts and is permanently stored as solid carbonate. This pathway does not require Class VI permits. In February 2023, Heirloom and

21 IEA, "Direct Air Capture" (web page), 2026.

22 WRI, "Direct Air Capture: Resource Considerations and Costs."

23 Project Drawdown, "Deploy Direct Air Capture," 2026.

24 IEA, *Direct Air Capture: A Key Technology for Net Zero*, 2022.

25 IEA, *Direct Air Capture: A Key Technology for Net Zero*, 2022.

26 EPA, "Underground Injection Control: Class VI Wells."

27 California Geological Survey, "Overview of Geologic Carbon Sequestration Potential in California," Special Report 183.

CarbonCure demonstrated the first use of DAC-derived CO_2 in concrete at a commercial facility in San Jose, with resulting materials used in Bay Area construction projects.[28] [29]

California resource base and project landscape

California's resource base for DACCS is organized around two empirically documented co-location zones, western Kern County and Imperial Valley, where renewable energy resources, existing infrastructure, and characterized geological storage converge. Both zones are currently the subject of active DOE-funded feasibility and engineering work.

In western Kern County, the California Direct Air Capture Hub (CalDAC), developed by Carbon TerraVault at California Resources Corporation's Kern Front and Elk Hills sites, is designed around a multi-source, low-carbon energy configuration. According to DOE/NETL Front-End Engineering and Design (FEED) documentation, the hub integrates solar PV electricity with battery storage, shallow and deep geothermal heat and power, and fuel cells with CO_2 capture to provide energy for DAC operations[30]. The hub design includes a pipeline connecting Kern Front to Elk Hills, with geological storage at the Elk Hills site in saline or hydrocarbon formations in western Kern County[31]. Separately, the Aera DAC Hub at the Belridge oil field, also in Kern County, is designed to store DAC-captured CO_2 at the Carbon Frontier sequestration site, which is permitted under CEQA for dedicated Class VI injection wells in the North Belridge field[32].

In Imperial Valley, DOE's FOA-2560 selections include a FEED study for Climeworks' direct air capture project at the Brawley Geothermal Plant in Brawley, Imperial County, designed to leverage geothermal thermal energy to drive DAC operations. The project is described as strategically located near a proposed geological storage site in California's Southern Central Valley, with the intent of minimizing CO_2 transport distances[33].

Both zones reflect a siting logic confirmed by national DAC siting analyses: proximity to characterized geologic storage is one of the most important siting factors for DAC facilities, as co-location with storage minimizes pipeline requirements and transport risk.[34] WRI's DAC siting guidance similarly emphasizes that while DAC has inherent location flexibility compared to point-source CCS, locating facilities near storage is recommended where possible.[35]

California's geological storage endowment is substantial at the basin scale. The CEC-sponsored WESTCARB assessment estimates that saline formations in the ten largest California basins have storage capacity on the order of 150 to 500 gigatons of CO_2, with the San Joaquin, Sacramento, Los Angeles, Ventura, and Central Coast basins identified as having the greatest opportunities.[36] The USGS

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28 CarbonCure Technologies, "Carbon Mineralization in Concrete."

29 Heirloom Carbon, CarbonCure Technologies, and Central Concrete, "First-Ever Storage of Atmospheric CO_2 Captured by DAC in Concrete," 2023.

30 DOE/NETL, "California Direct Air Capture Hub — FEED Presentation" (CalDAC, Carbon TerraVault).

31 DOE/NETL, "California Direct Air Capture Hub — FEED Presentation" (CalDAC, Carbon TerraVault).

32 CEQAnet, "CarbonFrontier Carbon Capture and Sequestration by Aera Energy LLC."

33 DOE, "FOA-2560 Selections: Climeworks Direct Air Capture at a California Geothermal Facility."

34 Lebling et al., *Direct Air Capture: Assessing Impacts to Enable Responsible Scaling*, 2022.

35 WRI, "Direct Air Capture: Resource Considerations and Costs."

36 CEC/WESTCARB, "Phase II Final Report: West Coast Regional Carbon Sequestration Partnership."

National Assessment of Geologic CO_2 Storage Resources has quantified technically accessible storage resources in storage assessment units across the Central California Coast, Los Angeles, Sacramento, San Joaquin, and Ventura basins.[37] These assessments are source-agnostic; they do not distinguish DAC-sourced CO_2 from industrial CCS streams, and none of the public technical work breaks out capacity specifically earmarked for DAC. The two active DAC hub concepts in California are both targeting storage sites within the San Joaquin Basin.

Three siting constraints are relevant for DACCS deployment in California. First, access to low-carbon electricity and heat is a binding requirement: both CalDAC and the Climeworks Brawley project have structured their siting decisions around existing energy infrastructure, the Elk Hills Power Plant, local substations, and operating geothermal facilities, specifically to reduce transmission build-out requirements.[38][39] Second, water availability is a core constraint, particularly for DAC configurations that rely on evaporative cooling or water-intensive solvent cycles; WRI's DAC siting analysis identifies water scarcity as a key constraint in arid regions, and California's San Joaquin and Imperial valleys face chronic water stress.[40] Third, community and environmental justice considerations add a procedural layer to siting in California. The CALDAC project, led by Berkeley's Center for Law, Energy and the Environment, explicitly incorporates community-centered DAC development and social feasibility as core components, recognizing that DAC hubs in Kern County and other fossil-intensive regions must navigate existing environmental justice concerns around industrial siting, local air quality, and employment.[41]

California Project Landscape

California's DACCS project landscape as of 2026 is characterized by two small operational facilities, one commercial-scale pilot in development with state funding, and a pipeline of hub-scale projects still in feasibility and engineering stages, several of which have recently lost federal funding.

The most significant currently operational DAC facility in California is Heirloom Carbon Technologies' plant in Tracy, San Joaquin County, which opened in November 2023 and is described as the first commercial-scale DAC facility in the United States.[42] The plant uses limestone-based DAC, powered entirely by renewable electricity supplied by Ava Community Energy, and has a reported capacity of up to 1,000 tonnes of CO_2 per year. Captured CO_2 is permanently stored via ex-situ mineralization in concrete through a partnership with CarbonCure Technologies.[43] Avnos operates a second, smaller operational pilot in Bakersfield, Kern County. Project Alpine launched in November 2023 in partnership with SoCalGas and with DOE funding. The facility uses Avnos' hybrid DAC system, which captures both CO_2 and water using a moisture-swing adsorbent, and has a capacity of approximately 30 tonnes of CO_2 per year.[44]

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37 USGS, "National Assessment of Geologic CO_2 Storage Resources."

38 DOE/NETL, "California Direct Air Capture Hub — FEED Presentation" (CalDAC, Carbon TerraVault).

39 DOE, "FOA-2560 Selections: Climeworks Direct Air Capture at a California Geothermal Facility."

40 WRI, "Direct Air Capture: Resource Considerations and Costs."

41 DOE, "CALDAC — Community-Centered DAC Feasibility Study," Berkeley CLEE.

42 Heirloom Carbon Technologies, "Heirloom Unveils America's First Commercial DAC Facility," 2023.

43 Heirloom Carbon Technologies, "Heirloom Unveils America's First Commercial DAC Facility," 2023.

44 Avnos, "Avnos Launches the World's First Hybrid DAC System," 2023.

A third California-based DAC developer, AirMyne, is preparing to deploy its first commercial-scale pilot in the state. In October 2025, the California Energy Commission approved a $4 million CRISP grant (Agreement CRI-25-001) for AirMyne's DeltaDAC project at the Port of Stockton, San Joaquin County, with a target capacity of 1,000 metric tonnes of CO_2 per year by the end of the agreement. The project uses AirMyne's liquid-sorbent DAC system with low-temperature thermal regeneration — compatible with geothermal and industrial waste heat — and explicitly requires community engagement, benefits planning, and community education components as part of the grant terms, embedding equity considerations into project design from the outset. AirMyne is headquartered in Berkeley, California.

At the hub scale, California has two projects under DOE's Regional Direct Air Capture Hubs program (FOA-2735), both in early-stage development in Kern County. The Aera DAC Hub Kern, developed by Aera Energy, is in the feasibility stage with a target storage capacity of at least 1 million tonnes of CO_2 per year if fully built, with storage planned at the Carbon Frontier sequestration site at the Belridge oil field.[45] The California DAC Hub Consortium, led by Carbon TerraVault, received approximately $12 million in DOE funding for Front-End Engineering and Design (FEED) work at California Resources Corporation's Kern Front and Elk Hills sites.[46] In October 2025, DOE cancelled the federal awards for both projects as part of a broader rescission of clean energy awards.[47](see Federal funding risk below). Neither hub had entered construction prior to the cancellations, and their path to commercial-scale deployment without federal funding is not established in public documentation as of 2026.[48]

Two additional projects are at earlier stages. The CALDAC feasibility study, led by Berkeley's Center for Law, Energy and the Environment, was also among the DOE-cancelled awards[49]. Climeworks is conducting a FEED study for a DAC system co-located with the Brawley Geothermal Plant in Imperial County, under DOE FOA-2560, the status of this award has not been publicly confirmed as cancelled as of the time of writing.[50]. Avnos operates a pilot-scale hybrid DAC facility in Bakersfield, Project Alpine, with DOE and SoCalGas funding.

No large-scale DACCS facility is operational in California beyond Heirloom's Tracy plant. 1PointFive, the operator of the United States' largest operational DAC plant, has no announced or permitted facility in California as of 2026; its projects are located in Texas.[51]

MRV, Regulatory, and Permitting Status

DACCS has a more developed MRV infrastructure than most other engineered CDR pathways, primarily because it produces a concentrated, directly measurable CO_2 stream rather than a diffuse

45 DOE/NETL, "DE-FE0032383 — Aera DAC Hub Kern Project."

46 DOE, "California DAC Hub Consortium — FEED Award," 2023.

47 *Carbon Herald*, "U.S. DOE Axes $7.6B Worth of Awards," 2025.

48 *Latitude Media*, "Can Domestic DAC Survive Without DOE?," 2025.

49 *Carbon Herald*, "U.S. DOE Axes $7.6B Worth of Awards," 2025.

50 DOE, "FOA-2560 Selections: Climeworks Direct Air Capture at a California Geothermal Facility."

51 CARB, "CCUS and CDR Project List."

change in a natural system. This methodological tractability is a structural advantage in the California regulatory context, where quantification uncertainty is a primary barrier for pathways such as OAE and ERW.

MRV framework

At the federal level, the 45Q tax credit provides the primary revenue driver for DACCS projects with geological storage, and requires measurement and verification of injected CO_2 volumes under IRS and EPA standards.[52] The 45Q credit has been preserved by Congress despite broader DOE award rescissions in 2025, sustaining the core federal financial incentive for DACCS[53].

At the state level, California's most relevant MRV instrument for DACCS is the LCFS Carbon Capture and Sequestration Protocol, adopted by CARB in 2020.[54] The protocol establishes detailed requirements for site characterization, injection monitoring, permanence verification, and leakage management for CO_2 stored in approved geological formations. However, the protocol was designed primarily for CO_2 captured from processes associated with LCFS-regulated fuel production such as refineries or hydrogen plants and does not provide a standalone crediting pathway for DAC removals disconnected from fuel production.[55] As of 2026, there is no LCFS methodology that awards compliance credits to DAC projects purely as atmospheric carbon removal, meaning that facilities like Heirloom's Tracy plant operate under voluntary carbon market standards rather than California's compliance framework.[56]

Under SB 905, CARB is mandated to develop a comprehensive CCUS Program that includes monitoring and reporting schedules for carbon capture, removal, and sequestration projects. As of 2026, CARB has published a pre-rulemaking information solicitation and submitted its 2025 report to the legislature, but has not yet published a DAC-specific MRV methodology or finalized the broader CCUS Program regulations.[57] DAC is not currently eligible to generate compliance offsets under California's Cap-and-Invest program.

Permitting

The single most consequential permitting requirement for DACCS projects with geological storage is the EPA Class VI Underground Injection Control permit, required under the Safe Drinking Water Act for all CO_2 injection wells.[58] California has not obtained primacy for Class VI permitting from EPA, meaning all applications are reviewed by EPA Region 9 — a procedural distinction that adds federal review timelines to any California project.[59]

52 Internal Revenue Service, "45Q Tax Credit for Carbon Oxide Sequestration."

53 Milkywire, "CDR Policy Entering a New Phase — Fall 2025," 2025.

54 CARB, "Carbon Capture and Sequestration Protocol under the LCFS."

55 CARB, "Carbon Capture and Sequestration Protocol under the LCFS."

56 CARB, *SB 905 2025 Report to Legislature*, 2025.

57 CARB, "SB 905 (Caballero, 2022) — Carbon Sequestration, CCUS Program."

58 EPA, "Underground Injection Control: Class VI Wells."

59 USEA, "US Class VI Permitting and State Primacy."

On December 30, 2024, EPA issued the first Class VI permits ever granted in California: four permits to Carbon TerraVault JV Storage Company, a subsidiary of California Resources Corporation, for injection wells at the Elk Hills oil field in Kern County.[60] These are also the first Class VI permits nationally for injection and storage of CO_2 in a depleted oil and gas field.[8] The permits authorize injection at a rate of up to 1.46 million metric tonnes per year into the 26R reservoir, with an estimated total storage capacity of 38 million metric tonnes.[61] The application was submitted in FY2022; draft permits were published in December 2023, and final permits issued in December 2024, a process of approximately three years from application to approval.[62] CRC has seven additional Class VI applications under EPA review, representing an estimated additional capacity of up to 287 million metric tonnes.[63]

For the Aera DAC Hub's planned storage site at Belridge, CEQA documentation confirms the project is designed around dedicated Class VI injection wells, but no final Class VI permit has been issued for that site as of 2026.[64] No air permits specifically for DAC facilities have been identified in consolidated public records, as these are issued at the district level by entities such as the San Joaquin Valley Air Pollution Control District and are not centrally tracked.[65]

Federal funding risk

In October 2025, DOE canceled approximately $7.56 billion in clean energy awards across 223 projects, including the DOE awards for both the Aera DAC Hub Kern and the California DAC Hub Consortium.[66] These cancellations directly affect the two hub-scale DACCS projects in California that had received DOE feasibility and FEED funding. Of the original 21 DAC Hub program awardees nationally, 19 are now on DOE cancellation lists; the two projects that retain their federal funding are both commercial-scale hubs located outside California.[67] The 45Q tax credit, which provides a per-tonne federal incentive for permanently stored CO_2, remains intact.

Stakeholder Alignment

Stakeholder alignment around DACCS in California is fragmented and context-dependent, shaped primarily by the pathway's association with fossil fuel infrastructure in Kern County and the absence, to date, of a large hub-scale project that could crystallize organized positions. The most documented

[60] EPA, "EPA Issues First-Ever Underground Injection Permits in California," 2024.

[61] EPA, "EPA Issues First-Ever Underground Injection Permits in California," 2024.

[62] EPA, "Class VI UIC Permits for Carbon TerraVault, Elk Hills, CA," docket EPA-R09-OW-2023-0623.

[63] California Resources Corporation, "Carbon TerraVault Provides 2024 Update," 2025.

[64] CEQAnet, "CarbonFrontier Carbon Capture and Sequestration by Aera Energy LLC."

[65] CARB, *SB 905 2025 Report to Legislature*, 2025.

[66] *Carbon Herald*, "U.S. DOE Axes $7.6B Worth of Awards," 2025.

[67] *Latitude Media*, "Can Domestic DAC Survive Without DOE?," 2025.

engagement comes from environmental justice communities, while labor, tribal, and local government positions remain largely implicit or underdeveloped with respect to DAC specifically.

Environmental justice communities

EJ communities in California's San Joaquin Valley, the geographic center of the state's DACCS activity, approach DAC with conditional skepticism rooted in Kern County's history of disproportionate industrial siting. Research conducted through community workshops in Bakersfield documented concerns about cumulative impacts, the potential for DAC-related waste streams or co-pollutants to burden already-overburdened neighborhoods, and the risk that DAC's large energy demand could raise electricity costs in energy-stressed communities.[68] At the same time, the same research found that community opposition is not categorical: when asked whether they would support a DAC hub conditioned on equity safeguards, local benefits, and community governance, approximately 75 percent of workshop participants indicated strong or conditional support, with only a small share expressing outright opposition.[69] This conditionality, support contingent on genuine community control rather than consultation, is the defining feature of EJ engagement on DAC in California.
The CALDAC initiative, co-led by Berkeley's Center for Law, Energy, and the Environment with EJ partners, explicitly operationalizes this framing. Its Letter of Intent describes the proposed hub as "community-centered and community-informed," spanning Madera, Fresno, and Kern counties, and emphasizes governance structures that embed community benefits, transparency, and public authority to prevent capture by incumbent industries.[70]

Environmental NGOs

Major environmental NGOs in California address DAC as part of a broader orientation toward environmental justice in energy and climate policy, though DAC-specific formal positions are limited in publicly available documentation. A coalition of sixteen organizations, including the Center for Biological Diversity, Sierra Club California, the Center on Race, Poverty and the Environment, 350 Bay Area, The Climate Center, and the California Environmental Justice Alliance, has been actively engaged in California energy planning processes, consistently arguing that resource decisions must integrate non-energy benefits and social costs, including local air quality, water quality, public health, and community economic impacts.[71] While this coalition has not published a document specifically opposing DAC, its broader posture in California energy policy, which prioritizes direct emission reductions, renewable deployment, and frontline community protection, signals significant caution toward any carbon management technology perceived as extending fossil fuel operations or diverting resources from proven solutions. National organizations such as NRDC have not published detailed DAC-specific positions for California; their general posture endorses limited, well-regulated CDR as a supplement to emissions reductions for genuinely hard-to-abate sectors, under stringent EJ and MRV conditions.

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68 Scott-Buechler et al., "Communities Conditionally Support Deployment of DAC in the United States," 2024.

69 Scott-Buechler et al., "Communities Conditionally Support Deployment of DAC in the United States," 2024.

70 CALDAC / Berkeley CLEE, "CALDAC Letter of Intent."

71 Center for Biological Diversity et al., *Petition to California Energy Commission*, 2024.

Tribal and Indigenous communities

No California tribal nation has published a formal, DAC-specific position as of 2026. The state context is nonetheless relevant: California adopted AB 1284 in 2024 to enable co-management agreements between tribal nations and the state for natural resource stewardship, establishing a policy expectation that tribes should be co-designers of climate and land-use projects.[72] Any DAC or geological storage project involving new injection wells, pipelines, or surface infrastructure near tribal lands would be expected to require formal consultation under existing state and federal law, though this process has not been publicly documented for any California DAC project to date. Tribal perspectives on DACCS in California remain an under-documented dimension that warrants proactive engagement rather than assumption.

Labor

No DAC-specific platform from California building trades unions or labor organizations has been publicly identified. The general pattern of California's construction and energy labor politics, in which the State Building and Construction Trades Council and affiliated unions expect project labor agreements, prevailing wages, and local hiring commitments on major infrastructure projects, would apply to any hub-scale DAC facility. The CALDAC Letter of Intent explicitly identifies labor as a stakeholder in its community benefits governance model.[73] This creates a potential alignment opportunity in Kern County, where the transition away from oil and gas employment creates demand for high-quality industrial jobs, but also a cost and permitting consideration for developers.

Figure 2. DACCS deployment in California by dimension

Dimension	Status	What's there / what's missing
Technology & storage pathway	Mature	S-DAC and L-DAC well understood; ex-situ mineralization operational in California. Geological storage framework established via LCFS CCS Protocol and Class VI permitting. No unresolved technical barriers to deployment.
California resource base	Partial	Kern County and Imperial Valley identified as co-location zones; WESTCARB and USGS basin assessments complete; CTV I Class VI permits issued at Elk Hills. No confirmed energy supply agreements for hub-scale operations; co-location with storage is structurally favored given SB 905's moratorium on new CO_2 pipeline construction pending federal PHMSA rulemaking.
California project landscape	Pilot only	One commercial-scale operational facility (Heirloom Tracy, ~1,000 tCO_2/yr) and one pilot-scale operational facility (Avnos Bakersfield, ~30 tCO_2/yr); AirMyne DeltaDAC commercial pilot (1,000 tCO_2/yr target) in pre-construction with $4M CRISP grant (October 2025). Hub-scale

[72] Pew Charitable Trusts, "New California Law Means Clearer Path for Tribes to Co-Manage Natural Resources," 2024.

[73] CALDAC / Berkeley CLEE, "CALDAC Letter of Intent."

Dimension	Status	What's there / what's missing
		awards (Aera, CalDAC, CALDAC) cancelled by DOE in October 2025. No hub-scale facility under construction.
MRV, regulatory & permitting	**Developing**	LCFS CCS Protocol exists but no standalone DAC crediting pathway. SB 905 CCUS Program under development; no DAC-specific CARB MRV methodology published. First California Class VI permits issued (CTV I, December 2024) but none for DAC hub storage sites. Multi-year permitting timelines remain a structural bottleneck.
Stakeholder alignment	**Fragmented**	EJ communities show conditional support contingent on community governance and local benefits. Major NGO coalition skeptical of fossil-linked DAC. Labor and tribal positions undocumented. AirMyne's CRISP grant requirements (community engagement, benefits planning) model embedded EJ design.

3.2 Biomass-based Carbon Removal and Storage (BiCRS)

Technology and Storage Pathways

Biomass carbon removal and storage (BiCRS) encompasses a family of pathways that share a common logic, capturing carbon already sequestered by photosynthesis and preventing its return to the atmosphere, but differ substantially in their conversion processes, storage mechanisms, durability profiles, and regulatory treatment. For the purposes of this analysis, four sub-pathways are relevant: bioenergy with carbon capture and storage (BECCS), biochar, bio-oil geological storage, and biomass burial. These are treated separately throughout this section because their operational implications and California-specific feasibility differ in ways that make aggregation analytically misleading.

BECCS

BECCS combusts or gasifies biomass to generate energy, captures the resulting CO_2-rich flue gas, and injects it into deep geological formations for permanent storage. The captured CO_2 is compressed to a supercritical state and injected into porous rock, typically deep saline aquifers or depleted hydrocarbon reservoirs overlain by low-permeability caprock, using Class VI injection wells under EPA's Underground Injection Control program.[74] The storage mechanism and durability profile of BECCS are directly analogous to industrial CCS: properly sited and operated storage sites are expected to retain more than 99 percent of injected CO_2 over 1,000 years, with leakage risk managed through structural, residual, solubility, and mineral trapping mechanisms codified in the Class VI regulatory framework.[75]

[74] EPA, "Underground Injection Control: Class VI Wells."

[75] EPA, "Underground Injection Control: Class VI Wells."

BECCS is the only BiCRS sub-pathway that produces a concentrated CO_2 gas stream suited directly for Class VI geological injection. California's 2022 Climate Change Scoping Plan currently includes a specific form of BECCS gasification of biomass to produce hydrogen with CCS as a CDR pathway, projected to contribute approximately 9 million metric tonnes of CO_2e per year by 2045.[76] This represents a narrow configuration of BECCS focused on a single feedstock-technology-product combination. A 2025 analysis by the Clean Air Task Force found that broadening California's BiCRS portfolio beyond hydrogen-BECCS to include combustion-to-electricity with CCS, gasification, and other configurations could substantially expand the pathway's contribution to the state's CDR target.[77]

Biochar

Biochar is produced by heating biomass in low-oxygen conditions, creating a stable, carbon-rich solid that can be applied to soils. Unlike other carbon removal pathways, biochar stores carbon in solid form, without requiring injection wells or subsurface infrastructure.

The durability of biochar depends on how it is produced. Higher-temperature processes generally result in more stable carbon, with a substantial share expected to persist in soils for centuries to millennia.[78] At the same time, a portion of the carbon remains less stable and decomposes over time, meaning biochar provides a durable but not permanent carbon sink.[79]

While some frameworks use chemical indicators, such as hydrogen-to-carbon ratios, to estimate permanence, recent research highlights uncertainty in applying these metrics universally, as results can vary depending on production conditions and environmental context.[80] From a regulatory perspective, biochar differs fundamentally from pathways such as BECCS or bio-oil injection. It does not require Class VI wells or subsurface permitting, and instead raises questions related to soil application standards, product quality, and land management.

Bio-oil Geological Storage

Bio-oil geological storage converts biomass into a carbon-rich liquid through fast pyrolysis and injects it into deep geological formations via EPA-regulated injection wells, where the oil's negative buoyancy causes it to sink and solidify in place.[81] The pathway is led commercially by Charm Industrial, which has sequestered more than 6,000 net tonnes of CO_2e using this method and partnered with Isometric to publish the first independent MRV protocol for bio-oil geological storage in 2024.[82] The storage mechanism differs from BECCS: rather than a gaseous CO_2 stream, the injected material is a viscous liquid hydrocarbon mixture with approximately 40–50 percent carbon content, stored as a non-aqueous liquid phase rather than as supercritical CO_2.[83]

76 CATF, *Exploring BiCRS Scenarios for California*, 2025.

77 CATF, *Exploring BiCRS Scenarios for California*, 2025.

78 Schmidt et al., "Permanence of Soil Applied Biochar," 2022.

79 Schmidt et al., "Permanence of Soil Applied Biochar," 2022.

80 Petersen et al., "The H/C Molar Ratio and Its Potential Pitfalls for Biochar's Permanence," 2025.

81 Charm Industrial, "A New Negative Emissions Method and Our First Customer."

82 Charm Industrial, "A New Negative Emissions Method and Our First Customer."

83 Charm Industrial, "A New Negative Emissions Method and Our First Customer."

Bio-oil does not fit cleanly within the Class VI regulatory framework, which EPA designed specifically for CO_2 injection for geological sequestration.[84] Charm describes its wells as "EPA-regulated injection wells" under the UIC program, but does not specify which UIC class applies in its public materials.[85] The regulatory classification of bio-oil injection and, by extension, its eligibility pathway for California's LCFS CCS Protocol, which is written for CO_2 storage, remains unsettled as of 2026. Permanence claims for bio-oil storage are based on analogy to fossil hydrocarbon storage and early operational experience rather than long-term empirical validation, and independent assessors have flagged uncertainties around long-term chemical alteration and potential well integrity risks.[86]

Biomass Burial

Biomass burial storing relatively unprocessed biomass in anoxic environments such as engineered vaults, mine voids, or deep marine sediments is excluded from this analysis. The pathway has no operational projects in California, carries high permanence uncertainty driven by site-specific moisture, temperature, and disturbance conditions, and is not included in California's 2022 Scoping Plan, which relies on DAC and hydrogen-BECCS as its primary CDR pathways.[87]

California Resource Base

California's resource base for BiCRS is defined by a substantial and geographically distributed biomass supply, an existing but limited bioenergy infrastructure, and a structural mismatch between where biomass is concentrated and where geological storage is best characterized.

Feedstock base and Wildfire Context

California's biomass supply draws on three feedstock categories: agricultural residues, including orchard removals and pruning, nut shells, and rice hulls; forest biomass, including thinning, slash, and mill residues; and urban wood waste, including construction and demolition wood and tree trimmings. According to the California Biomass Energy Alliance, the state's biomass industry currently processes approximately 7.3 million tons of solid wastes and residues annually, diverting approximately 4.3 million tons of wood residue from landfill disposal each year.[88]

California's wildfire management agenda is generating a growing and documented stream of forest residues directly relevant to BiCRS. The California Wildfire and Forest Resilience Task Force has committed to treating one million acres of forest annually, and in 2023 recorded more than one million activity acres of treatment, including thinning and chipping, in its Interagency Treatment

84 EPA, "Underground Injection Control: Class VI Wells."

85 Charm Industrial, "A New Negative Emissions Method and Our First Customer."

86 Isometric, "New Protocol for Bio-Oil Geological Storage."

87 CATF, *Exploring BiCRS Scenarios for California*, 2025.

88 CBEA, "Biomass: Essential for California."

Dashboard.[89][90] Much of this biomass is currently disposed of through pile burning, a practice California has actively moved to reduce — most notably through the near-complete phase-out of agricultural open burning in the San Joaquin Valley under SB 705 and successive CARB concurrence actions[91]; it represents an underutilized feedstock that is compatible with BECCS, biochar, and bio-oil sub-pathways, though only BECCS has existing California infrastructure to receive it at scale.[92]

BECCS Infrastructure and Spatial Constraint

California's existing biomass power sector provides the most developed infrastructure relevant to any BiCRS sub-pathway. There are currently 23 operating solid-fuel biomass power plants in 17 counties across the state, generating around 532 megawatts of electricity from agricultural, forest, and urban wood feedstocks.[93] These plants are concentrated in the Central Valley and Sierra Nevada foothills, near feedstock supply zones, and have established feedstock supply chains and grid interconnections, infrastructure that any BECCS deployment in California would need to either retrofit or replicate. However, a structural geographic constraint applies: the best-characterized geological storage basins for CO_2 in California are in the San Joaquin and Sacramento basins, and connecting capture sites in the foothills to deep storage formations would require CO_2 pipeline infrastructure.
The pipeline regulatory landscape in California is in transition. SB 905 (2022) established a moratorium on the use of pipelines to transport CO_2 pending completion of federal PHMSA safety rulemaking.[94] SB 614 (2025) subsequently modified this framework: intrastate CO_2 pipelines may now be used once the California State Fire Marshal adopts implementing regulations, with a deadline of July 1, 2026.[95] However, the federal PHMSA rulemaking on interstate CO_2 pipeline standards, which the Trump administration withdrew from publication in January 2025 and categorized as a "long-term action" with an undetermined timeline, remains incomplete, leaving interstate pipeline transport of CO_2 effectively prohibited.[96] The practical effect for BECCS hub development is that intrastate pipeline connections between capture and storage sites within California may become available in 2026, while interstate pipeline options remain blocked indefinitely pending federal action.

Biochar

California does not have a documented commercial-scale biochar production and soil application infrastructure as of 2026; the pathway is at the demonstration and pilot stage.[97] The CATF analysis identifies pyrolysis-based pathways, including biochar as higher-social-acceptance scenarios for California, in part because they can be deployed at smaller scales closer to feedstock sources and avoid the air quality concerns associated with combustion.[98] The primary resource constraints for biochar are feedstock logistics, transporting low-density residues from dispersed forest thinning sites

89 California Wildfire & Forest Resilience Task Force, "The Plan."

90 California Wildfire & Forest Resilience Task Force, "Interagency Treatment Dashboard Shows Progress Toward Resilience," 2024.

91 CARB, "San Joaquin Valley Agricultural Open Burning," 2026.

92 Net Zero California, "Addressing California's Wood Waste Crisis."

93 CBEA, "Biomass: Essential for California."

94 Senate Bill 905 (Caballero), 2022.

95 *Global Environmental Law Review*, "New Law Bolsters CCUS Projects in California," 2025.

96 *Global Environmental Law Review*, "New Law Bolsters CCUS Projects in California," 2025.

97 CATF, *Exploring BiCRS Scenarios for California*, 2025.

98 CATF, *Exploring BiCRS Scenarios for California*, 2025.

to pyrolysis facilities, which is costly, and the absence of a California compliance market incentive that would reward long-term soil carbon storage. Neither the LCFS nor Cap-and-Trade currently provides a crediting pathway for biochar soil carbon.[99]

Bio-oil Geological Storage

California has no operational bio-oil pyrolysis or injection facilities as of 2026. The pathway faces the same spatial mismatch and pipeline constraints described for BECCS, with the added regulatory uncertainty about how bio-oil injection fits within California's UIC and LCFS frameworks. These constraints compound an already significant infrastructure gap.

Structural Constraint Across Sub-Pathways

Across all sub-pathways, however, a common structural constraint applies. The CATF 2025 analysis identifies a "chicken and egg" barrier common to all BiCRS sub-pathways in California: absent guaranteed biomass supply chains, bioconversion facilities will not be built, and absent operating facilities, supply chains will not form.100 This coordination failure is distinct from the technology readiness or regulatory gaps that constrain individual sub-pathways and requires active policy intervention, including long-term feedstock supply contracts and pilot funding to resolve.

California Project Landscape

California's BiCRS project landscape as of 2026 is nascent. No BECCS project with geological CO_2 storage is operational or permitted in the state, despite the existence of 23 operating biomass power plants that could serve as retrofit candidates.[101] [102] The only identified BECCS concept with documented federal recognition is Clean Energy Systems' California Carbon Negative Energy project — a planned oxy-combustion facility using agricultural wood waste — which was selected as a Phase 1 semifinalist in DOE's CDR Purchase Pilot Prize under the BiCRS pathway, though it remains at the concept stage.[103] Pacific Biochar operates a biochar production site at the Humboldt Sawmill in Scotia, California, using sawmill residues and applying biochar to regional agricultural land; Isometric issued the project's first 3,042 verified carbon removal credits in December 2025, with an annual removal capacity of approximately 10,600 tonnes of CO_2e.[104] [105] Vaulted Deep, in partnership with Advantek Waste Management Services, operates slurry injection wells at the Terminal Island Renewable Energy (TIRE) site within the City of Los Angeles's Terminal Island Water Recovery Plant. The site has injected biosolids since 2008 under federal EPA permits, currently handling approximately 20 percent of the city's biosolids (~65,000 tons annually), with more than 500,000 tons injected to date; in July 2025

[99] CARB, *SB 905 2025 Report to Legislature*, 2025.

[100] CATF, *Exploring BiCRS Scenarios for California*, 2025.

[101] CBEA, "Biomass: Essential for California."

[102] CATF, *Exploring BiCRS Scenarios for California*, 2025.

[103] Clean Energy Systems, "DOE CDR Purchase Pilot Prize Phase 1 Semifinalist."

[104] *Carbon Herald*, "Isometric Issues First Verified Credits for Pacific Biochar," 2025.

[105] Isometric Registry, "Pacific Biochar — Humboldt Sawmill."

the company signed a 12-year offtake agreement with Microsoft for up to 4.9 million tonnes.[106] [107] No bio-oil geological storage or biomass burial projects have been identified in California.

MRV, Regulatory, and Permitting Status

California's regulatory framework for BiCRS is incomplete across all sub-pathways and differs materially between them.

BECCS is the only BiCRS sub-pathway with a potential pathway into California's compliance carbon market. Under the LCFS Carbon Capture and Sequestration Protocol, a BECCS project can generate compliance credits only if the facility produces a transportation fuel such as hydrogen or sustainable aviation fuel sold in California markets; standalone biomass power generation with CCS does not qualify for LCFS crediting.[108] Where that fuel linkage exists, LCFS provides a well-developed MRV framework including site characterization, injection monitoring, 100-year permanence verification, and quarterly CARB reporting.[109] An additional and California-specific constraint for BECCS is air quality permitting. Any new or modified biomass combustion facility in the San Joaquin Valley — where most of California's biomass power plants operate — must obtain permits from the San Joaquin Valley Air Pollution Control District under Title V of the Clean Air Act, in a region that remains in non-attainment for PM2.5 and ozone.[110] This imposes stringent Best Available Control Technology requirements and significant permitting timelines on any BECCS retrofit or new build.[111] The CATF 2025 analysis explicitly identifies combustion-based BiCRS pathways as lower social acceptance scenarios in California, in part due to these air quality concerns.[112]

Biochar and bio-slurry injection have no pathway into California's compliance carbon markets. CARB has not published a BiCRS-specific MRV methodology under SB 905 for any sub-pathway, and credits from both Pacific Biochar and Vaulted Deep are issued under voluntary market protocols rather than California compliance instruments.[113] The CATF analysis recommends full implementation of SB 905 as a prerequisite for enabling the infrastructure and permitting frameworks needed for BiCRS projects involving geologic storage, noting that a unified permit application, pore space unitization framework, and identification of suitable storage sites all remain unfinished.

Stakeholder Alignment

Stakeholder alignment around BiCRS in California is sharply divided by sub-pathway, with combustion-based BECCS facing organized opposition and biochar enjoying more favorable terrain.

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106 Vaulted Deep, "Technology."

107 *ESG Today*, "Microsoft Signs One of Largest-Ever Carbon Removal Deals with Vaulted Deep," 2025.

108 CARB, "Carbon Capture and Sequestration Project Eligibility FAQ."

109 CARB, "Carbon Capture and Sequestration Project Eligibility FAQ."

110 San Joaquin Valley Air Pollution Control District, "About."

111 San Joaquin Valley Air Pollution Control District, "About."

112 CATF, *Exploring BiCRS Scenarios for California*, 2025.

113 CARB, *SB 905 2025 Report to Legislature*, 2025.

Environmental Justice — BECCS and CCS

Opposition to BECCS with geological CO_2 storage is organized and documented. In June 2022, more than 80 environmental justice and conservation groups urged EPA to reject carbon capture project applications in California's Central Valley, citing threats to public health and inadequate environmental review of Class VI injection well applications.[114] In April 2025, Earthjustice filed a lawsuit challenging Kern County's CEQA approval of the Carbon TerraVault I project, the storage site designated for BECCS and DAC hubs in the region, on behalf of affected communities.[115] Communities for a Better Environment has separately filed litigation challenging CARB's LCFS amendments for failing to analyze air quality impacts on communities near biomass combustion and biofuel facilities, with CBE specifically citing harms to San Joaquin Valley residents from the expansion of biomass-based fuels.[116]

Environmental Justice — Biochar

EJ concerns regarding biochar focus on facility siting and production risks rather than soil application. A 2023 analysis on biochar siting and environmental justice identified concerns about locating pyrolysis facilities in communities already burdened by industrial infrastructure, including public health risks from combustion byproducts and facility management.[117] No documented EJ opposition to biochar soil application as a carbon removal strategy has been identified, a meaningful distinction from combustion-based pathways.

Agriculture and Forestry Sector

The agricultural and forestry sectors represent the most affirmatively supportive stakeholder constituency for BiCRS in California. California's agricultural community has shown documented interest in biochar for soil health, with the California Department of Food and Agriculture funding research evaluating biochar from locally available biomass for on-farm soil management, with almond growers in the Central Valley among the stakeholders engaged in that work.[118] The forestry sector broadly supports biomass residue utilization pathways that create economic value from thinning operations while reducing wildfire risk. The framing of the CATF 2025 analysis identifies as central to higher-social-acceptance BiCRS scenarios.[119]

Tribal and Labor

No California tribal nation has published a formal position on any BiCRS sub-pathway as of 2026. Tribal nations are actively engaged in forest management policy through cultural burn agreements under SB 310, and any BiCRS project involving forest biomass on or near tribal lands would require

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114 Center for Biological Diversity et al., "EPA Urged to Reject Carbon Capture Projects in Central California," 2022.

115 Earthjustice, "Lawsuit Challenges Faulty Environmental Analysis for California's First Carbon Capture and Storage Project," 2025.

116 Communities for a Better Environment, "Environmental Justice Group Sues California Agency Over Flawed LCFS Changes."

117 Carbon Neutral Cities Alliance, "Biochar Siting for Environmental Justice," 2023.

118 CDFA, "Evaluation of Biochar for On-Farm Soil Management in California."

119 CATF, *Exploring BiCRS Scenarios for California*, 2025.

formal consultation under existing state and federal law.[120] No labor union has published a BiCRS-specific platform, though the California Forestry Sector Jobs Initiative funded by CAL FIRE represents an active workforce development effort in the forest sector that intersects with the feedstock supply chains BiCRS would require.[121]

Figure 3. BiCRS deployment in California by dimension

Dimension	Status	What's there / what's missing
Technology & storage pathway	Partial	BECCS and biochar well understood; storage mechanisms and durability profiles established in peer-reviewed literature. Bio-oil geological storage operational at small scale globally but regulatory classification under UIC program unsettled. Biomass burial excluded as near-term pathway due to high permanence uncertainty. Sub-pathways differ fundamentally in storage mechanism, MRV tractability, and regulatory treatment aggregation is analytically misleading.
California resource base	Partial	Large feedstock base: 7.3M tons of biomass residues processed annually; 1M+ acres of forest thinning treatments in 2023 generating underutilized woody biomass. 23 existing biomass power plants provide BECCS retrofit candidates. Key gaps: spatial mismatch between biomass plants and storage basins requires CO_2 pipeline infrastructure; SB 614 intrastate pipeline framework pending July 2026; no commercial-scale biochar or bio-oil infrastructure in state; "chicken and egg" supply chain barrier across all sub-pathways.
California project landscape	Nascent	No BECCS project with geological CO_2 storage is operational or permitted; Clean Energy Systems' California Carbon Negative Energy project (oxy-combustion BECCS) is at concept stage, recognized as DOE CDR Purchase Pilot Prize semifinalist. Pacific Biochar operates a biochar pilot at Humboldt Sawmill, Scotia CA (~10,600 tCO_2e/yr; first Isometric-verified credits issued December 2025). Vaulted Deep operates bio-slurry injection at LA's Terminal Island Water Recovery Plant since 2008 (~65,000 tons biosolids/yr; Microsoft offtake through 2037). No bio-oil geological storage or biomass burial projects identified in California.
MRV, regulatory & permitting	Fragmented	BECCS: LCFS CCS Protocol provides a compliance pathway only if linked to fuel production (hydrogen, SAF) sold in California; standalone power-with-CCS does not qualify. SJVUAPCD Title V permitting adds stringent BACT requirements for any biomass combustion in the non-attainment San Joaquin Valley. Biochar and bio-slurry: no LCFS or Cap-and-Invest compliance pathway; credits issued under voluntary market protocols only. CARB has not published BiCRS-specific MRV methodology under SB 905 for any sub-pathway. SB 905 CCUS Program remains incomplete: no unified permit application, no pore space unitization framework, no designated storage sites.

120 Senate Bill 310, 2021, tribal cultural burn agreements.

121 California Forestry Sector Jobs Initiative.

Dimension	Status	What's there / what's missing
Stakeholder alignment	Divided	BECCS faces organized EJ opposition: 80+ groups urged EPA to reject CCUS permits in Central Valley (2022); Earthjustice filed CEQA lawsuit challenging Carbon TerraVault I approval (2025); Communities for a Better Environment suing CARB over LCFS air quality impacts. Biochar enjoys more favorable terrain: agricultural sector is affirmatively supportive (CDFA-funded soil research; almond grower engagement); EJ concerns focus on pyrolysis facility siting, not soil application. Tribal and labor positions on BiCRS specifically are undocumented as of 2026.

3.3 Enhanced Rock Weathering (ERW)

Technology and Storage Pathways

Enhanced rock weathering (ERW) accelerates the natural chemical weathering of silicate rocks by applying finely ground minerals such as basalt to land surfaces, typically croplands; rainwater absorbs atmospheric CO_2 to form carbonic acid, which reacts with calcium- and magnesium-bearing silicates and converts CO_2 into dissolved bicarbonate that ultimately moves through soils and rivers to the ocean.[122]In the ocean, dissolved bicarbonate is stored on geological timescales and may eventually be incorporated into marine carbonates and sediments, which is why general assessments treat ERW as a high-durability carbon dioxide removal pathway.[123]

Monitoring, reporting, and verification (MRV) is the central technical challenge for ERW because field deployments occur in heterogeneous open environments where weathering rates depend on climate, soil chemistry, and hydrology.[124] Credible quantification requires combining direct field measurements with conservative geochemical and life-cycle accounting, and durability and net-removal claims hinge on the quality of that MRV.[125]

California-specific empirical work has begun under local conditions. UC Davis and collaborators have applied crushed volcanic rock to California farmland and report measurable CO_2 removal in dryland agricultural settings.[126]A DOE-supported research program has examined three Central Valley field trials in which crushed basalt was applied to croplands and changes in soil organic carbon pools were tracked, providing California-specific data on how basalt amendments interact with soil carbon

122 Project Drawdown, "Deploy Enhanced Rock Weathering"; Carbon180, "Enhanced Rock Weathering."

123 Project Drawdown, "Deploy Enhanced Rock Weathering"; Carbon180, "Enhanced Rock Weathering."

124 IRCR, "Enhanced Weathering / MRV Barriers"; Sylvera, "Enhanced Rock Weathering."

125 Sylvera, "Enhanced Rock Weathering."

126 UC Davis, "Adding Crushed Rock to Farmland Pulls Carbon out of the Air."

cycling.[127] However, operational MRV systems for ERW in California remain at an early research stage and are not yet codified in state-specific regulatory guidance.[128]

California Resource Base

California has the rock and the institutional interest, but the basic resource and logistics work needed to plan ERW deployment at scale has not been done. California's geology supports ERW in principle. The California Geological Survey (CGS) identifies mafic and ultramafic rocks, including basalt, as one of three categories of CO_2-reactive geologic resources under evaluation, with deposits identified in many parts of the state.[129]CARB's ultramafic rock map shows widespread surface exposures across the Klamath Mountains, the northern and central Coast Ranges, parts of the Sierra Nevada foothills, and smaller areas in southern California.[130]

There is an important caveat. The most chemically reactive rocks for ERW are ultramafic rocks (dunite, peridotite, serpentinite), and these are precisely the rocks CARB has mapped because they carry naturally occurring asbestos, primarily chrysotile.[131] Mafic basalt is less reactive but generally lower-risk; CARB notes that asbestos is much less likely to occur with non-ultramafic rocks like gabbro and diabase.[132]In practice, this means California's "ERW resource base" is two different resources with very different deployment profiles, and the cited evidence does not break out how much of the state's reactive rock is asbestos-free basalt versus higher-risk ultramafic material.

California has institutional infrastructure for carbon mineralization, but it is pointed elsewhere. SB 905 (2022) directed CGS to establish a Geologic Carbon Sequestration Group and provide technical support to CARB, and CGS has built a public Data Portal mapping sequestration potential statewide.[133]However, that framework targets subsurface injection at depths below 3,000 feet not surface rock spreading on cropland.[134]The state, therefore, has the agency, the mandate, and the geologic mapping capacity to support ERW, but no mandate to do so.

UC Davis has conducted California field trials with basalt amendments and recently launched a center focused on the scalability of rock dust and soil performance[135]. The data layers needed to plan deployment exist in USDA's Cropland Data Layer maps, California cropland at 30-meter resolution, which, combined with CGS and CARB rock maps, could support a co-location analysis of rock supply and demand[136]. That analysis is not cited in the evidence.

127 DOE Genomic Science Program, "Interactions Between Enhanced Rock Weathering and Soil Organic Carbon Cycling in California Croplands."
128 Sylvera, "Enhanced Rock Weathering."
129 California Geological Survey, "Geologic Carbon Sequestration in California."
130 CARB / California Division of Mines and Geology, *Ultramafic Rocks in California*, Open-File Report 2000-19, 2000.
131 CARB / California Division of Mines and Geology, *Ultramafic Rocks in California*, Open-File Report 2000-19, 2000.
132 CARB / California Division of Mines and Geology, *Ultramafic Rocks in California*, Open-File Report 2000-19, 2000.
133 California Geological Survey, "Geologic Carbon Sequestration in California."
134 California Geological Survey, "Geologic Carbon Sequestration in California."
135 UC Davis, "Adding Crushed Rock to Farmland"; UC Davis, "New UC Davis Center Paves the Way for Rock Dust Research."
136 USDA NASS, *Cropland Data Layer* (California, 2019).

The cited evidence does not include: a state estimate of accessible ERW-suitable rock volumes; a published inventory separating asbestos-free basalt from higher-risk ultramafic feedstock; a quarry-to-cropland supply-chain or transport analysis; or an environmental and public-health screen identifying which feedstocks can deploy at scale. These gaps are decision-relevant: without them, the state cannot size an ERW procurement program or set safety guardrails.

California Project Landscape

California's ERW activity is exclusively research, not commerce. University of California work is the entire visible portfolio. UC Davis has run field trials applying crushed volcanic rock to California farmland;[137] a DOE/Genomic Science program is running three Central Valley basalt-amendment trials;[138] and UC Davis has launched a rock dust research center.[139]
California's compliance-relevant carbon-mineralization activity is in the subsurface track through SB 905 and the CGS Geologic Carbon Sequestration Group, not in surface ERW.[140] The cited evidence does not document any commercial ERW developer operating at scale in California, nor any pathway by which surface ERW is creditable under California's compliance carbon programs. By contrast, voluntary global markets are moving faster, with companies selling ERW credits under voluntary protocols.[141]

MRV, Regulatory, and Permitting Status

Surface ERW has no California regulatory home. A project would have to assemble a permitting path from existing soil-amendment, mining, and air-quality regimes, and rely on voluntary-market MRV protocols rather than state-recognized methodologies.

On MRV, voluntary carbon markets have published ERW-specific protocols defining eligible rock types, monitoring approaches, and conservative default factors[142]. Their applicability to a future California compliance pathway remains unresolved, with credibility depending on conservative weathering rate and life-cycle accounting.

On the regulatory side, two California contact points are worth flagging:

- **Soil amendments.** CDFA regulates fertilizing materials and soil amendments through labeling and registration; rock-dust products would fall under this regime[143]. The cited materials do not address how a CDFA-registered amendment would be evaluated for carbon removal claims.
- **Mining and air toxics.** Any feedstock supply involving ultramafic rock would intersect with California's existing naturally occurring asbestos regulatory framework. The cited evidence

137 UC Davis, "Adding Crushed Rock to Farmland Pulls Carbon out of the Air."

138 DOE Genomic Science Program, "Interactions Between Enhanced Rock Weathering and Soil Organic Carbon Cycling in California Croplands."

139 UC Davis, "New UC Davis Center Paves the Way for Rock Dust Research."

140 California Geological Survey, "Geologic Carbon Sequestration in California."

141 Isometric, "New Protocol for Enhanced Weathering"; Rainbow Standard, "Enhanced Rock Weathering" methodology.

142 Isometric, "New Protocol for Enhanced Weathering"; Rainbow Standard, "Enhanced Rock Weathering" methodology.

143 CDFA, *Fertilizing Materials Inspection Program Guide*.

does not document how ERW-specific operations, grinding, transport, and field application, would be evaluated under that framework.

General ERW literature also flags potential heavy-metal leaching and dust emissions from finely ground rock as recurring environmental concerns, particularly with ultramafic sources[144]. California-specific guidance for evaluating these issues in an ERW context is not documented in the cited evidence.

Stakeholder Alignment

Stakeholder positions on surface ERW in California are largely undeveloped. The state has the conditions for both buy-in and pushback, depending on how projects are designed.

Documented California stakeholder positions on ERW are limited. UC Davis is partnering with growers on field trials, which suggests that at least some California growers are willing to participate in research deployments.[145] General ERW literature notes potential agronomic co-benefits, pH adjustment in acidic soils, nutrient supply, and possible yield effects, though these are context-dependent and not demonstrated for California settings in the cited materials.[146] If demonstrated under California field conditions, these co-benefits would represent the sectoral integration logic applied to ERW — carbon removal as a measurable outcome of soil management interventions California growers may already have reason to pursue, rather than as a standalone CDR activity.

The clearest California-specific point of friction is asbestos. CARB has mapped the state's ultramafic rocks precisely because disturbing them poses public-health risks, making asbestos a foreseeable focus for regulators and health advocates if ERW scaled with ultramafic feedstock[147]. General ERW literature flags additional concerns, including heavy-metal leaching and dust from finely ground rock, which would intersect with California air- and water-quality oversight in any large deployment[148].

The cited evidence does not document organized positions, supportive or oppositional, from California environmental justice organizations, water-quality regulators, NGOs, or industry stakeholders specifically on ERW. Stakeholder alignment will likely emerge around specific project proposals and depend heavily on whether deployments deliver on agronomic co-benefits while limiting mining intensity, dust, asbestos, and water-quality impacts in already-burdened communities.

144 Sylvera, "Enhanced Rock Weathering"; Project Drawdown, "Deploy Enhanced Rock Weathering."

145 UC Davis, "Adding Crushed Rock to Farmland"; UC Davis, "New UC Davis Center Paves the Way for Rock Dust Research."

146 Project Drawdown, "Deploy Enhanced Rock Weathering."

147 CARB / California Division of Mines and Geology, *Ultramafic Rocks in California*, Open-File Report 2000-19, 2000.

148 Sylvera, "Enhanced Rock Weathering"; Project Drawdown, "Deploy Enhanced Rock Weathering."

Figure 4. ERW deployment in California by dimension

Dimension	Status	What's there / what's missing
Technology & storage pathway	Partial	Pathway well understood; treated as high-durability removal. MRV remains the standing technical challenge.
California resource base	Partial	Reactive rock identified statewide via CGS/CARB maps; institutional capacity exists through SB 905 and the CGS Geologic Carbon Sequestration Group but pointed at subsurface injection, not surface ERW. Key gaps: no inventory separating asbestos-free basalt from ultramafic feedstock; no quarry-to-cropland logistics study.
California project landscape	Early	Only UC-led research and DOE-funded trials; no commercial developers identified at scale in California.
MRV, regulatory & permitting	No state home	No CARB compliance protocol; SB 905 covers subsurface injection, not surface ERW. Voluntary protocols exist but California fit is uncertain.
Stakeholder alignment	Undeveloped	No organized positions documented. Asbestos hazard is the foreseeable friction point with regulators and public-health advocates.

3.4 Ocean-based Carbon Dioxide Removal

Ocean-based carbon dioxide removal (oCDR) encompasses a range of approaches that leverage ocean processes to increase carbon uptake or storage. These include ocean alkalinity enhancement (OAE), direct ocean removal (DOR), seaweed cultivation and sinking, and ocean fertilization. However, these approaches differ substantially in their level of technical maturity, environmental risk, and relevance to California's coastal context. For the purposes of this analysis, the focus is placed on OAE and DOC, which represent the most actively explored pathways in California and the only approaches currently advancing beyond early-stage research toward pilot deployment.

3.4.1 Direct Ocean Capture

Technology and Storage Pathways

Direct ocean capture (DOC) removes CO_2 directly from seawater rather than from ambient air, exploiting the ocean's natural role as a carbon sink. The mechanism operates through a chemical equilibrium principle: when dissolved CO_2 is extracted from seawater, a concentration gradient forms that draws additional CO_2 from the atmosphere into the ocean. The leading commercial approach in California uses electrodialysis to process seawater, liberating dissolved CO_2 as a concentrated, measurable gas stream. This process requires only ocean water and renewable electricity, without chemical sorbents, and produces no materials requiring disposal[149]. The resulting decarbonized water is returned to the ocean, which then absorbs an equivalent volume of CO_2 from the atmosphere; the extracted CO_2 stream can subsequently be permanently sequestered or utilized in products.[150]

From a storage standpoint, DOC occupies a distinct position relative to other oCDR approaches. Unlike OAE, which stores carbon as dissolved bicarbonate within the ocean column, DOC produces a concentrated CO_2 stream amenable to geological sequestration using established CCS infrastructure. DOC does not sequester carbon in the ocean but instead extracts it and produces a measurable gas stream, which simplifies permitting and makes carbon accounting more transparent and verifiable.[151] The technology's permanence and durability profile is therefore closer to DACCS than to open-system oCDR approaches.[152] The California Ocean Protection Council's March 2025 assessment of electrochemical mCDR approaches estimated deployment costs in the range of $150 to $2,500 per tonne of CO_2 removed, and identified key siting criteria, including ocean access, energy availability, and synergies with existing infrastructure such as desalination plants or CO_2 transport and sequestration infrastructure.[153]

California Resource Base

California's coastal geography and energy infrastructure offer a structurally favorable environment for DOC deployment. The state's extensive coastline provides abundant access to seawater, and its offshore oil and gas platforms nearing the end of their lives represent potential co-location sites that combine existing marine infrastructure with proximity to subsurface geological storage.[154]

California's renewable energy surplus also represents a structural asset: Captura designs its plants to maximize use of curtailed electricity not otherwise in demand, aligning DOC operations with the state's surplus solar and wind generation.[155] This represents another form of sectoral integration:

149 Frank, "This California Startup Helps the Ocean Absorb More Carbon Dioxide," 2025.

150 SoCalGas and Captura, "SoCalGas and Captura Begin Testing Direct Ocean Carbon Removal Technology," 2022.

151 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

152 Frank, "This California Startup Helps the Ocean Absorb More Carbon Dioxide," 2025.

153 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

154 SoCalGas and Captura, "SoCalGas and Captura Begin Testing Direct Ocean Carbon Removal Technology," 2022.

155 Frank, "This California Startup Helps the Ocean Absorb More Carbon Dioxide," 2025.

leveraging an energy resource the state is already producing and increasingly curtailing as renewable penetration grows, rather than dedicating new generation capacity to CDR.

California Project Landscape

The leading DOC developer in California as of 2026 is Captura, a Pasadena-based company founded at Caltech, which has pursued a staged piloting strategy across three successive systems. The first pilot began operating in 2022 at Caltech's Kerckhoff Marine Laboratory in Newport Beach, supported by SoCalGas[156]. A second system, rated at 100 tons of CO_2 per year, was subsequently installed at AltaSea at the Port of Los Angeles.[157] A third system, with a capacity of 1,000 tons per year, was deployed at the Hawai'i Ocean Science and Technology Park in Kona in partnership with Equinor, with the goal of completing kiloton-scale validation before commercial deployment.[158]

Captura has raised $12 million in Series A funding, led by Equinor Ventures, with participation from Aramco Ventures, Caltech, Future Planet Capital, Hitachi Ventures, and mTerra Ventures.[159] The company has stated it is ready to advance to its first commercial-scale facility, but that doing so requires either supportive policy, additional capital, or both.[160]

A second DOC-adjacent marine CDR pilot also operated at the Port of Los Angeles: an electrolysis-based system run by Equatic, a UCLA spinout, with a capacity of approximately 100 kilograms of CO_2 per day, which began operations in April 2023.[161] That pilot was time-limited; Equatic has since shifted its primary scale-up focus to the Equatic-1 demonstration plant in Singapore. With Equatic's LA pilot closed, Captura is currently the most visible DOC developer with an active pilot in California as of 2026.

MRV, Regulatory, and Permitting Status

DOC's MRV profile is more tractable than that of open-system oCDR approaches, primarily because its CO_2 output is a directly measurable stream rather than a diffuse change in ocean chemistry. However, full accounting of net atmospheric removal still depends on modeling ocean-atmosphere equilibration processes, which remain an area of active methodological development. Captura has developed an internal MRV protocol in collaboration with the Southern California Coastal Water

156 SoCalGas and Captura, "SoCalGas and Captura Begin Testing Direct Ocean Carbon Removal Technology," 2022.

157 Captura, "Captura's 100-Ton Carbon Removal System to Be Installed at AltaSea," 2023.

158 Captura, "Captura Advances Direct Ocean Capture Commercialization Efforts," 2024.

159 Captura, "Deployment Updates."

160 Frank, "This California Startup Helps the Ocean Absorb More Carbon Dioxide," 2025.

161 Equatic, "The Equatic Difference"; UCLA Samueli, "UCLA Institute and Equatic to Build the World's Largest Ocean-Based Carbon Removal Plant in Singapore," 2024.

Research Project (SCCWRP) and commits to independent third-party verification with publicly accessible reporting.[162]

Despite this methodological clarity at the project level, DOC lacks a recognized protocol under CARB's existing carbon market frameworks. No SB 905 compliance pathway or LCFS methodology has been finalized for DOC, and the technology is not eligible to generate credits under Cap-and-Invest. At the federal level, the United States currently lacks a national-level CDR MRV oversight mechanism.[163]

On the permitting side, DOC's marine deployment footprint engages multiple overlapping jurisdictions: the Army Corps of Engineers, the State Lands Commission, the Coastal Commission, and potentially NOAA and EPA, depending on discharge characteristics. No standardized permitting pathway for DOC systems has been established by any California agency, meaning each project proceeds through case-by-case review. High-quality DOC projects are expected to consult with local permitting agencies and develop plans to halt operations if ecosystem harm thresholds are exceeded,[164] a standard that currently has no formal regulatory definition in California. As of March 2025, OPC had convened initial interagency engagement with eight state agencies spanning carbon, lands, wildlife, coastal, water quality, and conservation jurisdictions,[165] but this interagency process had not yet produced permitting guidance or defined protocols specific to DOC projects.

Stakeholder Alignment

DOC benefits from a more favorable stakeholder environment than most oCDR approaches, in part because it avoids the introduction of any substances into the ocean. Captura's approach physically removes CO_2 from seawater and reports that its process helps mitigate ocean acidification rather than contributing to it,[166] a position Captura supported through its ongoing environmental monitoring program.

AltaSea at the Port of Los Angeles, where Captura operates its 100-ton pilot, provides an institutionalized platform for community engagement and industry collaboration within the blue economy ecosystem.[167] This institutional setting facilitates interaction between developers, researchers, and local stakeholders, representing a structural advantage relative to more spatially distributed or less visible CDR pathways.[168] However, this example does not fully capture the broader stakeholder landscape for DOC in California. Deployment at scale would extend beyond controlled pilot environments into a wider set of coastal jurisdictions, each with distinct regulatory authorities, community dynamics, and environmental sensitivities.

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162 Captura, "Carbon Dioxide Removal Pathway: Ocean Health and MRV," 2023.

163 Columbia Law School Sabin Center, *Marine Carbon Dioxide Removal MRV 101*, 2025.

164 Carbon Direct, "Abiotic Marine CDR: 2025 Criteria for High-Quality CDR," 2025.

165 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

166 Frank, "This California Startup Helps the Ocean Absorb More Carbon Dioxide," 2025.

167 Captura, "Captura's 100-Ton Carbon Removal System to Be Installed at AltaSea," 2023.

168 USC Sea Grant, "AltaSea," 2026.

More broadly, DOC operates within a high-scrutiny coastal governance context. Ocean-based interventions are subject to overlapping state and federal jurisdiction, and uncertainty around localized ecological impacts remains a central concern for regulators and stakeholders. While California's CDR targets and ongoing interagency coordination processes signal growing institutional attention,[169] [170] these efforts have not yet translated into clear deployment pathways or broad stakeholder alignment.

The primary stakeholder risk for DOC in California remains tied to siting and community context. AltaSea's location within the Port of Los Angeles highlights this dynamic: the surrounding communities of Wilmington and San Pedro have historically experienced disproportionate environmental and public health burdens. Although DOC operations do not themselves generate criteria pollutants, the association with existing industrial infrastructure and the novelty of ocean-based CDR warrant proactive and sustained community engagement, particularly as projects scale beyond pilot phases. The OPC has noted that marine CDR approaches may impact coastal communities both positively and negatively, and has emphasized the need for engagement and coordination with those communities in the design and execution of future research.[171]

Taken together, stakeholder alignment does not currently represent a binding constraint for DOC in California, but it remains a necessary condition for scale. Deployment will depend on demonstrating environmental safety, navigating fragmented coastal governance, and securing community acceptance beyond pilot contexts.

3.4.2 Ocean Alkalinity Enhancement

Technology and Storage Pathways

Ocean alkalinity enhancement (OAE) increases the ocean's capacity to absorb CO_2 by adding alkaline materials to seawater. This process changes ocean chemistry in a way that reduces the concentration of dissolved CO_2, allowing the ocean to take up additional CO_2 from the atmosphere until a new equilibrium is reached. In practice, OAE works by introducing alkaline substances that react with dissolved CO_2, effectively enabling further atmospheric CO_2 uptake.[172]

Two primary delivery mechanisms are currently under development. Mineral-based OAE spreads ground alkaline materials, such as olivine or crushed limestone, into coastal or open ocean waters. Electrochemical OAE uses electricity to generate alkaline solutions from seawater, which are then returned to the ocean.[173] In both cases, the goal is to increase seawater alkalinity and enable additional CO_2 uptake from the atmosphere.

In both approaches, carbon is stored as dissolved inorganic carbon in the ocean. This form of storage is generally considered durable on timescales of centuries to millennia under stable ocean conditions, although uncertainties remain around efficiency, permanence, and system-wide impacts.

169 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

170 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

171 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

172 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

173 IRCR, "Engaging Communities on Ocean Alkalinity Enhancement: Insights from Two Workshops in Sequim, Washington," 2024.

A key distinction from direct ocean capture is that OAE does not produce a concentrated or directly measurable carbon stream. Instead, carbon removal occurs gradually through air–sea gas exchange, which creates fundamental challenges for monitoring, reporting, and verification (MRV). Rather than measuring captured CO_2 at a facility, MRV relies on a combination of in situ measurements and modeling to estimate net carbon uptake against a highly variable ocean background. Additional monitoring of ecological and chemical impacts is also required to meet permitting standards.[174]

California Resource Base

California's coastal infrastructure presents specific opportunities for electrochemical OAE deployment, primarily through integration with existing water processing facilities. Ebb Carbon's deployment strategy centers on partnering with desalination plants, intercepting the brine discharge stream before it returns to the ocean, and processing it through an electrochemical system to produce an alkaline solution, additional freshwater yield, and valuable chemical co-products.[175] California operates significant desalination capacity, which could, in principle, serve as an integration partner, though no California desalination-based OAE deployment has been announced as of 2026.

Modeling work by researchers at UCLA and the Southern California Coastal Water Research Project has examined the potential for ocean alkalinity enhancement (OAE) in the San Francisco Bay estuary[176]. The results show that natural water mixing in the estuary can transport added alkalinity toward the open ocean, increasing the rate at which CO_2 is absorbed from the atmosphere. In particular, the San Francisco Bay plume appears to play a significant role in this process.
These findings suggest that California's major estuaries could provide favorable conditions for OAE deployment, including through existing wastewater outfalls, although this work remains at an early research stage.

California Project Landscape

As of 2026, there are no active OAE field pilots in California. Research and development activity is occurring at the modeling and experimental design stage. The most relevant commercial actor is Ebb Carbon, a company headquartered in South San Francisco that has raised $40 million to date and has a track record spanning multiple U.S. projects, including multi-year demonstrations with the Department of Energy's Pacific Northwest National Laboratory and Project Macoma in Port Angeles, Washington[177]. Ebb Carbon's active deployments are in Washington state, not California. Project Macoma, which aims to remove 1,000 tons of CO_2 during its two-year operation, received what Ebb Carbon describes as the first-of-its-kind NPDES permit for an OAE project, setting a precedent for how such projects can advance within existing regulatory frameworks[178].

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174 Carbon to Sea Initiative, "OAE Monitoring, Reporting, and Verification (MRV)."

175 Ebb Carbon, company homepage.

176 Long et al., "Ocean Alkalinity Enhancement in an Estuary," 2026.

177 Ebb Carbon, "Ebb Signs Initial Carbon Removal Offtake Agreement with Google," 2025.

178 Ebb Carbon, "Ebb Carbon's Project Macoma Begins Operations in Port Angeles," 2025.

On the commercial side, Ebb Carbon has signed an agreement with Microsoft to remove up to 350,000 tonnes of CO_2 over ten years using electrochemical OAE[179]. The company has also signed agreements with Google. These voluntary market commitments represent the primary demand signal driving OAE development globally, as no compliance market methodology for OAE yet exists.

MRV, Regulatory, and Permitting Status

OAE faces significantly greater MRV challenges than direct ocean capture. Because carbon removal occurs through changes in ocean chemistry rather than a measurable gas stream, quantification relies on a combination of field measurements and modeling approaches that remain under active development and carry higher uncertainty. Early protocols, such as those developed by Isometric, have begun to establish verification approaches, but the gap between contracted and independently verified removals remains substantial, indicating that market activity is outpacing methodological certainty.[180]

In California, no CARB-recognized methodology exists for OAE, and the pathway is not eligible for compliance markets. The regulatory landscape is also more complex than for other CDR approaches. Because OAE involves returning chemically altered water to the ocean, projects must comply with water quality standards under the Clean Water Act's NPDES permitting framework. While early permits have been issued in other states, California has not yet established a clear regulatory pathway or guidance specific to OAE deployment.[181]

Stakeholder Alignment

OAE faces more contested stakeholder terrain than DOC. The technology's potential co-benefits, particularly local mitigation of ocean acidification, are genuinely appealing to fishing communities, shellfish growers, and coastal habitat advocates. At the same time, the addition of materials to the ocean, even naturally occurring alkaline compounds, raises concerns among environmental groups about unintended ecological consequences. Public concerns about OAE have already led to at least one pilot project cancellation outside the United States, highlighting the importance of public perception for OAE feasibility[182]. The California Ocean Protection Council's March 2025 assessment noted that OAE carries risks, including changes in biogeochemistry and food systems, changes in phytoplankton species composition, the introduction of trace minerals, increased mining demand, and the risk of secondary precipitation of calcium carbonate minerals that could reduce rather than increase atmospheric CO_2 uptake.[183]

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179 Ebb Carbon, "Ebb Signs Initial Carbon Removal Offtake Agreement with Google," 2025.

180 Senken, "Understanding Ocean Alkalinity Enhancement Carbon Removal," 2026.

181 Senken, "Understanding Ocean Alkalinity Enhancement Carbon Removal," 2026.

182 Project Drawdown, "Deploy Ocean Alkalinity Enhancement."

183 California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

The OPC's March 2025 informational item reflects California's current posture toward mCDR: active tracking and research engagement without regulatory endorsement. OPC noted that although mCDR has been at the center of recent local, national, and international interest and investment, it is still considered an emerging area of research and development with many unknowns and is committed to working with stakeholders to track and assess individual mCDR technologies and their potential environmental impacts specific to California.[184]

Figure 5. Ocean-Based CDR deployment in California by dimension

Dimension	Status	What's there / what's missing
Technology & storage pathway	Mature (DOC) / Partial (OAE)	Direct ocean capture (DOC) is the most operationally advanced ocean-based pathway in the California context. Electrodialysis systems are already functioning at pilot scale, and carbon removal can be directly measured through a concentrated CO_2 stream, with a storage profile similar to DACCS. Ocean alkalinity enhancement (OAE), by contrast, relies on well-established chemistry but remains earlier in development. While both mineral-based and electrochemical approaches are under active research, OAE's core limitation is measurement: carbon removal occurs through diffuse air–sea exchange rather than a directly measurable stream, making MRV substantially more complex and uncertain.
California resource base	Partial	California offers favorable conditions for both pathways, though in different ways. For DOC, the state's extensive coastline, access to curtailed renewable electricity, and potential use of decommissioned offshore infrastructure create strong co-location opportunities. For OAE, existing desalination and wastewater infrastructure could provide integration points, and modeling work suggests that estuarine conditions in San Francisco Bay may support effective deployment. However, for both pathways, no confirmed co-location agreements or operational infrastructure exist as of 2026.
California project landscape	Active (DOC) / Research-only (OAE)	DOC has a clear lead in project development. Captura is operating a pilot facility at the Port of Los Angeles and has tested larger-scale systems outside California. However, no commercial-scale DOC facility is yet operational. OAE remains at an earlier stage. As of 2026, no field pilots are active in California, and leading developers have focused deployments in other states. Activity within California is limited to modeling and experimental design.
MRV, regulatory & permitting	Developing (DOC) / No state home (OAE)	DOC benefits from a more tractable MRV profile, with project-level protocols under development and measurable outputs, but it still lacks a recognized pathway within California's compliance markets. Permitting remains complex, requiring case-by-case approval across multiple marine and environmental agencies. OAE faces deeper uncertainty. No CARB-recognized methodology exists, and no permitting framework has been established in California.

[184] California Ocean Protection Council, "Marine Carbon Dioxide Removal (mCDR) Considerations for California," 2025.

Dimension	Status	What's there / what's missing
		Because OAE involves modifying ocean chemistry, it must comply with water quality standards under federal and state permitting regimes, which have not yet been adapted for this pathway.
Stakeholder alignment	Mixed	DOC operates in a relatively favorable stakeholder environment, in part because it does not introduce substances into the ocean and can be framed as mitigating ocean acidification. However, siting in industrial coastal areas raises environmental justice considerations that will need to be addressed. OAE is more contested. While it may offer co-benefits for marine ecosystems, it also raises concerns about ecological risks and ocean chemistry, and has faced public opposition in some contexts. In California, stakeholder positions remain largely undefined, but regulatory agencies are monitoring developments without formal endorsement.

IV. CARBON MARKET ACCESS AND COST COVERAGE BY PATHWAY

4.1 The Voluntary Carbon Market as a Starting Point

The voluntary carbon market has played a critical role in enabling the initial deployment of CDR. Early offtake agreements from a relatively small set of corporate buyers, led by initiatives such as Frontier, began around 2020 and provided the first demand signal for high-durability removals, allowing developers to test technologies, generate initial revenue, and advance measurement, reporting, and verification (MRV) approaches. In that sense, it did what early-stage markets are supposed to do: it helped create activity where none existed before.

However, the VCM is not designed to support deployment at the scale required to meet California's long-term climate targets. Four structural features of the VCM constrain its ability to provide the durable demand signal that capital-intensive CDR infrastructure requires:

1. Voluntary participation: buyers can enter or exit the market at will, with no enforcement mechanism for sustained commitment.
2. Heterogeneous standards: quality, MRV rigor, and durability vary widely across registries, making credits difficult to compare and price.
3. Non-binding demand: most commitments are intent-based or short-dated rather than contractually enforceable obligations on the scale that infrastructure financing requires.
4. Highly concentrated buyer base: as of 2025, CDR credits account for only about 5% of total VCM retirements, and overall market volumes have not grown meaningfully for 5 consecutive years,[185] and Microsoft alone accounts for roughly 58 percent of forward-offtake volumes among the eighty buyers tracked by Sylvera,[186] leaving the market exposed to a single firm's procurement decisions.

The market has responded to these constraints with instruments — long-term forward offtake agreements, multi-buyer coalitions such as Frontier, and pre-purchase commitments — that aggregate fragmented demand into stronger signals for developers. These tools have enabled early-stage CDR developers to reach commercial pilot scale, but they cannot, on their own, generate the volume of durable demand California's targets require.

185 Carbon Direct, "Key Trends in the 2026 Voluntary Carbon Market," 2026.

186 Sylvera, "Carbon Credit Demand: What Drives It," 2026.

The VCM's role, therefore, is best understood as complementary rather than terminal. It performs a function that compliance markets and public investment cannot easily replicate at the early stage of a technology's development: it provides the demand, evidence base, and operational learning that allow novel removal pathways to mature toward broader institutional adoption. But it cannot, on its own, provide the financial foundation needed to scale CDR to the levels implied by California's climate targets. The state's 2022 Scoping Plan, which operationalizes the carbon neutrality mandate established in AB 1279, estimates approximately 75 million metric tonnes of CDR per year by 2045 to balance residual emissions.[187] Moving beyond the VCM's near-term function will require integrating CDR into compliance frameworks such as the state's cap-and-invest program under AB 398. Assessing what is required to make that transition possible requires examining how cost structures and market access differ across pathways.

4.2 Market Access and Cost Coverage by Pathway

Market access and cost coverage conditions differ substantially across CDR pathways. While all pathways face a gap between current costs and available revenue, the nature of that gap varies: in some cases, it is driven by insufficient demand, in others by the absence of eligible markets, and in others by unresolved MRV or regulatory constraints. These differences ultimately determine whether a project can reach a final investment decision (FID).[188]

Table 1. Market access and cost coverage by pathway

Pathway	Est. Cost Today ($/t)	Revenue Today ($/t)	Market Access today	Indicative Gap
DACCS (geologic)	400–1,000	~100-250	LCFS (conditional), 45Q, VCM	Large
BiCRS (biochar/ waste biomass)	150–300	~100-200	VCM	Small-moderate
BiCRS (geologic: BECCS/ bio-oil)	80-250	<150	45Q (conditional), limited LCFS	Moderate-large
ERW	150-300	~200-500 (early-stage)	Early VCM	Moderate (uncertain)

187 CARB, *2022 Scoping Plan*.

188 *Final Investment Decision (FID) refers to the point at which a project developer commits to construction and capital expenditure, typically requiring secured financing, revenue certainty, and resolution of key regulatory and technical risks.*

Ocean CDR	200-600	~200-300 (early-stage)	Very limited	Large and highly uncertain

Cost estimates presented in this table reflect global ranges reported in the literature, as project-level cost data remains limited and geographically variable. In contrast, revenue estimates reflect currently available mechanisms in the United States, with a focus on California, where applicable. This distinction is important, as while costs are broadly comparable across jurisdictions, access to revenue is highly policy-dependent.

Across all pathways, the central constraint is not only that revenues fall below costs, but that they are uncertain, fragmented, and in many cases unavailable. This prevents projects from reaching FID even where technologies are technically viable. The nature of this constraint differs by pathway.

DAC

DACCS has the broadest existing market access of any engineered pathway: federal 45Q tax credits provide on the order of $180 per tonne for projects with dedicated geologic storage,[189] and California's LCFS CCS Protocol offers additional credit value when eligibility conditions are met.[190] However, both mechanisms are conditional on stringent requirements, secure Class VI–permitted storage, and certified CCS Protocol compliance, which remain binding for most California projects. Even where these conditions are satisfied, combined revenues fall well below first-of-a-kind cost estimates of $400–1,000 per tonne,[191] leaving a substantial gap that compliance revenue alone cannot close. The binding constraint for DACCS is therefore not policy access but the magnitude of the residual gap, which determines whether projects can reach FID.

BiCRS/biochar

Biochar has the most active market access among durable CDR pathways, accounting for more than 90 percent of contracted durable CDR volume between 2022 and mid-2025[192]. However, techno-economic analyses suggest that production economics remain challenging for many producers[193], with average credit prices in 2025 sitting in the $150–175 per tonne range across major marketplaces[194], frequently at or below current removal costs. Tightening regulatory methodologies on permanence — particularly in the EU — adds further uncertainty about how much durable, policy-grade revenue biochar projects can rely on.[195] The binding constraint for biochar is not access but margin: credit prices are not stabilizing above production costs, and methodological revisions could compress them further.

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189 Carbon Capture Coalition, *What Is the Section 45Q Carbon Capture Tax Credit?*, 2025.

190 26 C.F.R. § 1.45Q-3.

191 IEAGHG, *Global Assessment of Direct Air Capture Costs*, Report 2021-05, 2021.

192 IBI and USBI, *2023 Global Biochar Market Report*, 2024.

193 Patel and Panwar, "Evaluating the Agronomic and Economic Viability of Biochar in Sustainable Crop Production," 2024.

194 Supercritical, *Boom or Bust? 2024 Biochar Market Outlook*, 2024.

195 Sanei et al., "Evaluating the Two-Pool Decay Model for Biochar Carbon Permanence," 2025.

BECCS/ bio-oil

BECCS and bio-oil sequestration can in principle, stack federal 45Q with California LCFS revenue when captured CO_2 is linked to low-carbon transportation fuel production.[196] In practice, access depends on permitted geologic storage and MRV compliance that few California projects can document,[197] and standalone biomass-with-CCS that does not feed fuel production is excluded from LCFS crediting entirely. Cost estimates for early BECCS and bio-oil systems in the low-to-mid hundreds of dollars per tonne leave a material gap even when policy revenues stack.[198] The binding constraint is regulatory eligibility, not cost: most California BECCS configurations have no compliance market pathway at all.

ERW

Enhanced rock weathering is recognized as a high-durability CDR pathway with potential agronomic co-benefits,[199] but currently lacks systematic access to compliance-based revenue. ERW credits transact on voluntary markets at prices in the low-to-mid hundreds of dollars per tonne, broadly comparable to other engineered removals.[200] However, cost structures are dominated by mining, grinding, transport, field application, and intensive MRV — placing levelized costs in a similar range and leaving narrow or negative margins at prevailing credit prices.[201] No CARB-recognized methodology exists for surface ERW, and the regulatory pathway remains undefined. The binding constraint for ERW is the absence of any state-recognized crediting pathway, which leaves projects dependent on voluntary buyers at prices that do not reliably cover costs.

Ocean CDR

Ocean-based CDR pathways are the most dependent on grants, philanthropic capital, and a nascent voluntary CDR market, with no mature compliance mechanism yet recognizing ocean CDR as a distinct crediting category[202.] Early offtake agreements for ocean alkalinity enhancement and direct ocean capture demonstrate buyer interest, but contracted volumes remain modest relative to deployment needs. Current costs for pilot and early commercial projects sit in the mid-hundreds of dollars per tonne once technology, MRV, and environmental risk management are included, and existing voluntary demand at these prices is insufficient to close the commercialization gap.[203] The binding constraint is twofold: no recognized compliance category for ocean CDR, and ongoing regulatory and scientific uncertainty that limits the market's willingness to price ocean removals at parity with engineered pathways.

4.3 Why the Gap is Structural

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196 Thompson et al., *A Policy Framework for Scaling Up Permanent Carbon Dioxide Removal in the United States*, 2025.

197 Thompson et al., *A Policy Framework for Scaling Up Permanent Carbon Dioxide Removal in the United States*, 2025.

198 Almena, Pashakolaie, and Martín, "Unlocking BECCS Viability through Monetizing Societal Benefits," 2025.

199 WEF, *Carbon Dioxide Removal Technologies: Market Overview and Offtake*, 2026; Cascade Climate, "Recommendations from *Foundations*," 2025.

200 WEF, "Clearing the Air: Exploring the Pathways of Carbon Removal Technologies," 2025.

201 Kumar and Russell, "Between a Rock and a Hard Cost: The Economics of Enhanced Weathering," 2025.

202 Warren and Gibson, "Marine Carbon Credit Sales, 2020–2025," 2026.

203 Carbon Direct, "Key Trends in the 2026 Voluntary Carbon Market," 2026.

The gap between cost and revenue is structural rather than temporary. It does not arise solely from high costs associated with early-stage technologies, but from the absence of a durable and policy-backed demand signal.

First, the demand signal itself is fundamentally fragile. CDR purchases are driven by voluntary corporate commitments that may shift with internal climate strategies, ESG framing, or leadership changes. For capital-intensive infrastructure with 10-to-15-year payback horizons, this uncertainty alone is disqualifying: demand is concentrated among a small set of buyers, and the time horizons required for project financing exceed the time horizons over which corporate commitments can credibly be sustained.

Second, available revenue streams do not provide the long-term certainty required for project financing. Even where prices appear relatively high, they are not guaranteed over the time horizons required to support capital-intensive investments. As a result, projects cannot rely on these revenues to secure financing or reach final investment decisions.

Third, market access is uneven across pathways. While DACCS has partial access to compliance mechanisms such as 45Q and LCFS, most other pathways remain outside compliance markets. This creates a fragmented landscape in which some projects can generate revenue under existing frameworks while others cannot.

Finally, the absence of widely accepted MRV methodologies limits the ability of several pathways to generate credits that buyers are willing to purchase at scale. This is particularly relevant for ERW and ocean-based approaches, where methodological uncertainty directly constrains demand.

Taken together, these factors mean that current market mechanisms are insufficient to support CDR deployment at the scale required by California's climate targets. The binding constraint across pathways is not technological readiness alone, but the absence of a credible and durable demand signal that can support project financing. This is precisely the gap that public procurement is uniquely positioned to address.

V. PUBLIC PROCUREMENT AND THE SB 840 OPPORTUNITY

Section IV shows that across CDR pathways, the binding constraint on reaching final investment decision (FID) is not technological readiness, but the absence of revenues that are sufficient, certain, and accessible. The constraint is not supply, but the absence of a credible and durable demand signal.

Public procurement directly addresses this constraint. Unlike voluntary markets or fragmented policy incentives, procurement creates a binding commitment to purchase a defined quantity of carbon removal at a predictable price over time. In doing so, it converts uncertain and discretionary demand into bankable revenue, enabling projects to secure financing and proceed to deployment.

In this context, SB 840 represents a partial but incomplete opportunity. The legislation provides a potential funding source for climate innovation, including carbon removal, but does not establish a mechanism to translate funding into demand. The key policy question is therefore not whether resources exist, but how they should be deployed to create a credible market signal.

5.1 SB 840 — scope, status, and open design questions

SB 840 (Limón), enacted as Chapter 121 of 2025 and signed by Governor Newsom on September 19, 2025,[204] primarily restructures how revenues from the Greenhouse Gas Reduction Fund (GGRF) are allocated. The Legislative Analyst's Office (LAO) characterizes the bill as focused on "modifications to the allocation of the associated GGRF revenues," with companion bill AB 1207 containing most of the substantive changes to the cap-and-invest program itself.[205]

Before SB 840, several programs received automatic, ongoing funding from the GGRF through continuous appropriations. SB 840 ends those continuous appropriations on July 1, 2026.[206] Starting in fiscal year 2026–27, GGRF revenues flow through a new four-tier priority structure. This means that programs are funded in a set order, and lower-priority programs receive funding only after higher-priority programs are fully covered.[207] Within this structure, Tier 2 includes both a $1 billion allocation to high-speed rail and a separate $1 billion annual set-aside that the Legislature appropriates each year through the budget process, without a predetermined recipient.[208] CDR does not appear as a named program or funding category anywhere in SB 840. The most immediate opening for CDR funding identified in the statute is within the $1 billion discretionary set-aside. Specifically, the statute expresses as a non-binding legislative intent, not a mandatory appropriation, $85 million of the set-aside to be allocated in 2026–27 to "an entity chosen by the Legislature to support climate-focused technological innovation, related research, and the deployment of climate solutions identified in the scoping plan prepared pursuant to Section 38561".[209] The entity has not yet been designated, and the $85 million must be re-appropriated annually through the budget process.[210]

[204] LAO, *Overview of New Updates to the Cap-and-Invest Program*, 2025.

[205] LAO, *Overview of New Updates to the Cap-and-Invest Program*, 2025.

[206] SB 840 (Limón), 2025.

[207] LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

[208] LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

[209] SB 840 (Limón), 2025, § on GGRF allocations.

[210] LAO, *Overview of New Updates to the Cap-and-Invest Program*, 2025.

The statutory language does not name CDR, designate an administering agency, specify how the funds should be deployed, or set the percentage allocations contemplated for the future climate-focused innovation fund. The Senate Environmental Quality Committee analysis notes that, beyond the reconfigured appropriations and the initial set-aside, SB 840 provides minimal direction on how the remaining GGRF funds are to be used.[211]

How the Sb 643 Veto Shapes What is Politically and Institutionally Feasible

SB 643 (Caballero), the Carbon Dioxide Removal Purchase Program, would have required CARB to establish and administer a program to purchase $50 million worth of CDR credits from eligible projects between July 1, 2026, and December 31, 2035, with no more than $25 million directed to a single CDR category and no more than $12.5 million to a single supplier.[212] The bill required projects to secure third-party matching funds equal to or greater than the grant value and to undergo independent third-party verification. SB 643 passed both houses with majority support and was vetoed by Governor Newsom on October 13, 2025.[213]

In his veto message, Governor Newsom acknowledged that “deploying CDR technologies and projects is an increasingly necessary strategy to achieve our 2045 carbon neutrality goal”. However, he describes SB 643 as “duplicative” of recently enacted legislation, citing in particular SB 840, which he characterized as providing “a continuous appropriation from the Greenhouse Reduction Fund of $85 million per year for climate-focused innovation that may include CDR technologies”. The Governor also cited fiscal grounds, stating that "the program created by this bill is duplicative and not accounted for in this year's budget" and that "it is vital that we remain disciplined when considering bills with significant fiscal implications that are not included in the budget."[214]

Notably, the Governor's characterization of SB 840 as providing a "continuous appropriation" does not fully align with the statutory structure itself: as described above, the $85 million is expressed as non-binding legislative intent and must be re-appropriated annually through the budget process. This distinction is consequential, because the principal justification for the veto—that SB 840 already provides the mechanism SB 643 would have created—rests on this characterization.

Types of Climate Innovation Eligibility under the Current Language

The operative statutory phrase is "climate-focused technological innovation, related research, and the deployment of climate solutions identified in the scoping plan prepared pursuant to Section 38561”.[215] A Governor’s Office release dated October 10, 2025, states that "SB 840 (Limon) allocates $85 million in the 2026-27 budget year from the Greenhouse Gas Reduction Fund (GGRF) to advance climate-

211 Senate Environmental Quality Committee, *SB 840 Analysis*, 2025.

212 Lebling et al., "4 Takeaways from California's Carbon Dioxide Removal Policies," 2025.

213 Carbon Direct, "California Advances $50M Public-Private Carbon Removal Program," 2025.

214 Newsom, Veto Message, SB 643, 2025.

215 California Senate Bill 840 (Limón), Chapter 121, Statutes of 2025.

focused technological innovation, related research, and the deployment of climate solutions, such as carbon capture and removal projects[216]."

Outside analysis has characterized the practical scope of eligible activities. A summary of the legislative package by Net-Zero California describes the $85 million allocation as supporting "climate-focused technological innovation (e.g., industrial decarbonization; carbon removal)," signaling that carbon removal is understood as one potential use within this category.[217] The Clean Air Task Force similarly describes climate-focused technological innovation as "a yet-to-be-fully-defined category of technologies.[218]"

Open Design Questions

While these characterizations clarify the practical scope of SB 840, several parameters that will ultimately determine whether and how CDR receives funding under the statute remain unresolved.

1. **Continuity and multi-year funding.** The LAO's February 2026 analysis of the 2026–27 expenditure plan projects, in Figure 3, shows that the $250 million in SB 840 intent items — including the $85 million — appear in 2026–27 only, with no equivalent line item in 2027–28, 2028–29, or 2029–2030[219]. WRI has recommended that "[i]n 2026, the legislature should consider multi-year appropriations to ensure there is continuous funding available to support CDR deployment, building on any funding already allocated in fiscal year 2026-2027[220].
2. **Revenue insufficiency relative to statutory commitments.** The California Department of Finance forecasts $3.8 billion in cap-and-invest auction proceeds for 2026–27, while the Legislative Analyst's Office estimates that meeting all existing statutory funding obligations would require approximately $4.3 billion annually, roughly $500 million above project revenues. This gap is not theoretical: the Department of Finance projects that Tier 3 programs will receive only about 70 percent of their statutory funding levels, with similar proportional reductions expected through 2029–30[221]. Within this context, the Legislative Analyst's Office advises that the Legislature apply a "very high bar" to new spending proposals, citing projected multiyear deficits of $20–35 billion annually[222]. Together, these projections indicate that current GGRF commitments exceed expected revenues and will be rationed through systematic funding reductions under binding fiscal constraints.
3. **Statutory ambiguity in the implementation.** The legislation expresses intent to allocate "specific percentages" of GGRF revenues across priority funds but does not define those percentages[223]. The Legislative Analyst's Office further notes that the statute does not specify which revenues this directive applies to—whether the $1 billion Tier 2 set-aside, residual funds after statutory allocations, or another funding base. In practice, the Governor's 2026–27

[216] Newsom, Veto Message, SB 643, 2025.

[217] Net-Zero California, *State Leaders Deliver Transformational Package of Climate, Energy Affordability Bills*, 2025.

[218] CATF, *Balancing Climate Ambition and Affordability: Reflecting on California's 2025 Legislative Session*, 2025.

[219] LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

[220] Nagabhushan, Lashof, and Lebling, "How California Can Seize Momentum to Advance Carbon Dioxide Removal," 2026.

[221] LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

[222] LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

[223] SB 840 (Limón), 2025.

expenditure plan proposes allocating the $1 billion set-aside unevenly, with $250 million directed to SB 840-related activities and $750 million used to partially backfill General Fund obligations, alongside proposed trailer legislation clarifying that SB 840 applies only to auction revenues rather than interest earnings or fund balances.[224] Given this ambiguity, the Legislative Analyst's Office recommends that the Legislature carefully review the administration's implementation approach to ensure consistency with legislative intent. This ambiguity has direct implications for CDR. The World Resources Institute notes that, without an explicit allocation, emerging technologies such as carbon removal may not receive sufficient support and recommends dedicating a portion of GGRF funding specifically to CDR procurement to provide an initial demand signal and help mobilize private investment.[225]

Taken together, these three parameters—continuity, fiscal capacity, and statutory ambiguity—define the operational space within which any CDR procurement strategy under SB 840 must be designed. The following subsection develops a recommendation for operationalizing SB 840 within these constraints.

5.2 Recommendation for CDR allocations within SB 840

This diagnosis—a demand constraint, not a technology constraint—is consistent with evidence across jurisdictions identifying the absence of reliable, long-term demand as the central barrier to scaling CDR. Without a clear market signal, projects remain non-bankable, and private investment does not materialize at scale.[226]

Two implications follow. First, no single policy instrument can address CDR deployment uniformly: pathways differ in cost structure, compliance access, regulatory constraint, and political context. A procurement design that ignores those differences will produce blunt outcomes. Second, California already has many of the components required to scale CDR, but they are not designed to function together. Effective policy must differentiate instruments by pathway and sequence them across the deployment trajectory, drawing on demand-side mechanisms—procurement and compliance obligations—to complement existing research, demonstration, and regulatory authority.[227]

The recommendations below are organized around three design principles, followed by pathway-differentiated guidance for the immediate horizon (2026–2030), explicit treatment of risks, and the parallel mechanisms required in the medium-term (2030–2035) and long-term (2035–2045) horizons.

Three principles for SB 840 design

Three principles should govern how SB 840 is deployed.

224 LAO, *The 2026–27 Budget: Cap-and-Invest Expenditure Plan*, 2026.

225 Nagabhushan, Lashof, and Lebling, "How California Can Seize Momentum to Advance Carbon Dioxide Removal," 2026.

226 Smith et al., *The State of Carbon Dioxide Removal – 1st Edition*, 2023.

227 Smith et al., *The State of Carbon Dioxide Removal – 2nd Edition*, 2024.

First — Marginal value of the public dollar. SB 840 should fund activities where the state dollar shifts an outcome that would not otherwise occur. Several CDR pathways already receive public support through existing instruments: DACCS through the federal 45Q tax credit, conditional LCFS access, and CRISP. Where this support stack exists, adding a fourth public revenue stream produces less effect than directing the same dollar to a pathway with no compliance access or to a constraint other instruments cannot address.

Second — Differentiation by the structure of the gap. Section IV shows that the gap between cost and available revenue is not uniform across pathways. For some, the gap is primarily a demand problem solvable through procurement. For others, the binding constraint is regulatory infrastructure, MRV development, or stakeholder alignment—none addressable through procurement spending. SB 840 should apply the appropriate instrument to the appropriate constraint, not treat all pathways as procurement targets.

Third — Risk management and political defensibility. Given the veto of SB 643 on grounds of duplication and fiscal discipline, and the LAO's projected $20–35 billion annual deficits, SB 840 must withstand the same scrutiny. This requires inheriting the safeguards SB 643 included—caps by category and supplier, independent third-party verification, matching-funds requirements—and adding additionality criteria to avoid displacing voluntary market activity that would have occurred regardless. At its full $85 million annual allocation, SB 840 represents less than 0.5 percent of the procurement value implied by the 2045 target. It is therefore a catalytic instrument, not a procurement vehicle at scale; its value depends on whether it enables the larger structural mechanisms required to deliver the target.

Immediate horizon (2026–2030): Pathway-differentiated SB 840 deployment

The objective in the near term is not to procure removals at scale but to establish conditions under which projects can reach final investment decision. Applied to specific pathways, the three principles produce a pathway-by-pathway allocation that differs substantively from a uniform procurement approach.

Biochar and biomass-waste pathways: primary procurement allocation

Section III establishes that biochar and biomass-waste pathways are the closest to deployment in California, with the lowest cost gap relative to current revenue (Section IV: approximately $50–100 per tonne), zero access to California's compliance carbon market, and strong alignment with sectoral priorities the state already manages, including wildfire residue utilization, biosolids management, and agricultural soil health. The Clean Air Task Force's 2025 analysis identifies a "chicken-and-egg" coordination failure across BiCRS sub-pathways: without guaranteed feedstock supply chains, bioconversion facilities will not be built; without operating facilities, supply chains will not form. This is precisely the type of coordination failure that public procurement is designed to resolve.

SB 840's primary procurement allocation should therefore be directed to biochar and other biomass-waste pathways using California-sourced feedstocks. Public procurement is specifically identified as a critical early-stage policy instrument because it provides credible revenue expectations to developers and enables project financing.[228] Procurement contracts should be structured as multi-year advance market commitments tied to delivered tonnes of verified removal, drawing on the design principles

[228] Smith et al., *The State of Carbon Dioxide Removal – 1st Edition*, 2023.

established by the Frontier AMC and the DOE CDR Purchase Pilot Prize.[229] Contract-based instruments are consistently identified as more effective in creating investable conditions because they provide stable price signals and reduce exposure to policy and market volatility, which are among the primary barriers to private investment in CDR.[230] Contract design should require independent third-party verification under established registries (Isometric, Puro.earth, or equivalent), inherit the supplier caps included in SB 643 (no more than $12.5 million to a single supplier), and incorporate additionality criteria that require demonstration that the state contract is the marginal factor enabling project deployment.

This allocation is justified on three grounds. First, the marginal-value test: biochar has no existing compliance pathway, so SB 840 dollars open a market that would not otherwise exist. Second, the dollar-per-tonne calculation: at $150–300 per tonne, an SB 840 allocation generates substantially greater tonnage and stronger price discovery than at $400–1,000 per tonne. Third, sectoral alignment: biochar procurement leverages feedstocks that California is already paying to dispose of through pile burning and landfilling, generating measurable co-benefits in air quality, wildfire risk reduction, and soil health.

This does not mean treating biochar as equivalent to permanent geologic storage, but rather prioritizing it as the most immediately deployable procurement category within a durability-tiered system.

DACCS: regulatory capacity, not procurement

SB 840 should not be used for the direct procurement of DACCS removals. Four findings developed in the prior sections support this recommendation.

First, dollar-per-tonne efficiency. At current DACCS costs of $400–1,000 per tonne (Section IV), the full $85 million SB 840 allocation procures roughly 85,000 to 210,000 tonnes annually—approximately 0.1 to 0.3 percent of the 2045 target—at a cost three to six times higher per tonne than biochar.

Second, the existing support stack and political defensibility together cut against procurement. DACCS projects in California can already access the federal 45Q tax credit (~$180 per tonne for permanently stored CO_2), conditional LCFS crediting when linked to transportation fuel production, and CRISP funding for research and demonstration. SB 840 procurement would constitute a fourth public revenue stream for a pathway already supported by three, and this matters both substantively and politically. The Governor's veto of SB 643 explicitly cited duplication and fiscal discipline, and SB 840 procurement of DACCS is vulnerable to the same objection. Directing SB 840 instead to activities that 45Q, LCFS, and CRISP do not fund is structurally distinct and defensible.

Third, the binding constraint for DACCS in California is regulatory, not financial. Section III identifies Class VI permitting, intrastate CO_2 pipeline framework, SB 905 MRV methodology development, and air permitting in non-attainment districts as the structural barriers limiting deployment. None of these are addressable through procurement spending; all are addressable through targeted investment in agency capacity. The October 2025 DOE cancellation of approximately $7.56 billion in clean energy awards, including FEED funding for CalDAC and the Aera DAC Hub, reinforces rather than

[229] Frontier Climate, "An Advance Market Commitment to Accelerate Carbon Removal," https://frontierclimate.com; U.S. Department of Energy, Office of Clean Energy Demonstrations, "Carbon Dioxide Removal Purchase Pilot Prize," https://www.energy.gov/oced/carbon-dioxide-removal-purchase-pilot-prize.

[230] Smith et al., *The State of Carbon Dioxide Removal – 1st Edition*, 2023.

complicates this logic: the cancellations eliminated engineering and feasibility funding, not construction capital, and the state cannot meaningfully substitute either at SB 840 scale. What the state can do is ensure that when capital returns—federal, private, or both—the regulatory pathway is operational rather than mired in the current multi-year permitting timeline.

Fourth, voluntary market displacement. Section IV documents that high-durability CDR demand is concentrated in DACCS, with Microsoft alone accounting for approximately 58 percent of forward offtake volumes. State procurement of DACCS at SB 840 scale risks substituting for voluntary buyers in the segment where they are most active, rather than generating additional demand.

The DACCS allocation under SB 840 should therefore fund a defined set of regulatory capacity activities: California's application to EPA for Class VI primacy, which would substantially shorten the permitting timelines documented in Section III; staffing at the State Fire Marshal to complete SB 614 implementing regulations by the July 2026 deadline; staffing at CARB to develop DAC-specific MRV methodology under SB 905; and technical support to the California Geological Survey for site characterization in priority storage basins. This allocation creates conditions for DACCS deployment at scale through the structural mechanisms—45Q, LCFS expansion, and eventual Cap-and-Invest integration—that can deliver the target-level volumes SB 840 cannot.

BECCS and bio-oil: MRV development and community processes, not procurement

BECCS and bio-oil sit at a different point in the readiness spectrum: deployment is closer than for ERW or ocean CDR, but the conditions for procurement are not yet in place. Section III establishes that these pathways face binding regulatory uncertainty (UIC classification for bio-oil, intrastate pipeline framework for BECCS), organized environmental justice opposition documented through the 80-organization petition to EPA, ongoing litigation (Earthjustice v. Kern County on Carbon TerraVault I; Communities for a Better Environment v. CARB on LCFS amendments), and incomplete SB 905 implementation.

SB 840 should not procure BECCS or bio-oil removals before these conditions are resolved. Instead, a modest allocation should support: (a) CARB's development of BiCRS-specific MRV methodology under SB 905, prioritizing fuel-linked configurations eligible for LCFS expansion; (b) structured community engagement processes that meet the conditional-support thresholds documented in the Bakersfield workshop research and the CALDAC Letter of Intent, particularly in Kern County and the San Joaquin Valley; and (c) coordinated implementation work to complete the SB 905 framework gaps. These activities position BECCS for integration into the medium-term compliance architecture without committing public procurement dollars to a pathway whose deployment conditions are not yet in place.

Enhanced rock weathering and ocean CDR: pilot-to-MRV bridge

ERW and ocean CDR sit furthest from deployment-ready procurement. Section III documents that ERW has no California regulatory home and faces material asbestos hazard considerations, while ocean CDR pathways (DOC and OAE) operate at pilot or pre-pilot scale. A modest SB 840 allocation should fund pilot-to-MRV bridges for both pathway families: for ERW, in partnership with the University of California system, producing California-specific MRV protocols, feedstock inventories distinguishing asbestos-free basalt from ultramafic material, and environmental and public-health screening criteria; for ocean CDR, supporting continued DOC pilot operations through the Ocean Protection Council interagency process and pre-pilot research for OAE. As with the BECCS allocation, the deliverable is methodological readiness for compliance recognition, not procured tonnes.

Summary of immediate-horizon allocation

The pathway-differentiated allocation can be summarized as follows: biochar and biomass-waste pathways receive the primary procurement allocation through multi-year advance market commitments; DACCS receives regulatory capacity-building funds rather than procurement; BECCS and bio-oil pathways receive MRV and community engagement support to prepare for medium-term integration; and ERW and ocean CDR receive pilot-to-MRV bridge funding. Allocation balance should be determined through a scoping process led by the designated SB 840 administering entity, in consultation with CARB, relevant sectoral agencies, and stakeholders. The principles established above—marginal value, gap differentiation, and risk management—should guide that balance rather than a predetermined percentage formula.

Risks and mitigations

The recommended approach carries identifiable risks that should be addressed in program design.
Pathway concentration in biochar. Directing the largest share of procurement to a single pathway category creates concentration risk if biochar MRV is challenged, if feedstock supply chains fail to form, or if the durability of biochar carbon storage is revised downward in the literature. Mitigations include maintaining supplier caps consistent with SB 643's $12.5 million per-supplier ceiling; setting tiered durability requirements that prioritize biochar produced under conditions documented to deliver multi-century stability; and structuring contracts with milestone-based delivery rather than upfront payment.

Lock-in to lower-durability options. Procurement of biochar at the immediate-horizon scale may signal that California's compliance architecture will treat biochar as equivalent to permanent geological storage. Mitigation: explicit durability tiering in procurement contracts, so that procurement choices do not preempt compliance design.

Voluntary market displacement. State procurement risks substituting for voluntary buyers rather than generating additional demand. Mitigation: additionality criteria in procurement design, requiring applicant projects to demonstrate that the state contract is the marginal factor enabling final investment decision; preference for first-of-kind projects in California; and coordination with major voluntary buyers (Frontier, Microsoft) to identify gaps rather than overlap.

Federal funding volatility. The October 2025 DOE cancellations demonstrate that federal CDR support is exposed to administration-level reversal. SB 840 cannot substitute for billions in federal capital, but its design should account for federal uncertainty by prioritizing investments (regulatory capacity, MRV development) that retain value independent of the federal funding cycle.

Verification and quality risks. CDR markets have documented cases of quality challenges across pathways. Mitigation: requirement of independent third-party verification under established registries; published methodology disclosure; ongoing performance monitoring for procured projects, with provisions for recovery of public funds in cases of verified non-delivery.

Environmental justice and community impact. Procurement of BECCS or bio-oil in the San Joaquin Valley would intersect with ongoing litigation and organized community opposition documented in Section III. Mitigation: the immediate-horizon allocation explicitly excludes combustion-based BECCS procurement; biochar procurement design should incorporate the community-centered framework documented in the CALDAC Letter of Intent and the Bakersfield workshop research; and any pathway involving siting near disadvantaged communities should require documented community benefit agreements.

Medium-term horizon (2030–2035): From procurement to compliance integration

As immediate-horizon investments mature—biochar deployment underway, MRV protocols operational for additional pathways, Class VI permitting capacity in place, SB 614 pipeline framework implemented—the policy objective shifts from market creation to structural demand. Three mechanisms should advance in parallel.

CDR sub-mandate within Cap-and-Invest

The most direct mechanism to convert SB 840-era market creation into durable demand is the introduction of a CDR sub-mandate within the Cap-and-Invest Program. Rather than full integration at an early stage, a sub-mandate would require regulated entities to meet a small but increasing share of their compliance obligations through verified carbon removals. Evidence from emerging compliance system design, particularly in the EU context, shows that partial obligations can generate predictable demand while allowing policy to adjust as technologies mature and costs decline.[231] Carbon Direct's analysis of the EU 2040 climate target framework documents that compliance integration of CDR can be designed with phased entry points,[232] and the Clean Air Task Force's recommendations on EU ETS integration of carbon removals provide design guidance on durability tiering, separate pools for permanent versus shorter-duration removals, and supply-demand calibration.[233] This approach leverages existing market infrastructure while limiting exposure to uncertainties in supply, cost, and MRV.

The placeholder Section 95852.3 introduced by CARB's January 2026 Initial Statement of Reasons provides the statutory entry point. The medium-term task is to populate that placeholder with operational rules, methodology references, and a calibrated supply pathway. CARB should be tasked with this rulemaking on a timeline aligned to the January 2029 protocol update deadline established by AB 1207.

LCFS expansion to include BECCS, biochar, and additional DAC configurations

Section II documents that the LCFS Carbon Capture and Sequestration Protocol currently provides crediting for CCS linked to LCFS-regulated fuel production but does not award compliance credits to DAC removals disconnected from fuel production, and does not provide a standalone crediting pathway for biochar, bio-oil, or ocean CDR. LCFS amendments should be developed in the medium-term horizon to extend project-based crediting to: (a) standalone DACCS removals with geological

[231] Smith et al., *The State of Carbon Dioxide Removal – 2nd Edition*, 2024.

[232] Carbon Direct, "2040 Climate Target: Implications for Carbon Dioxide Removal," https://www.carbon-direct.com/insights/2040-climate-target-implications-for-carbon-dioxide-removal.

[233] Clean Air Task Force, "Carbon Removals in the EU Emissions Trading System," 2024, https://cdn.catf.us/wp-content/uploads/2024/06/24114156/carbon-removals-ets.pdf.

storage; (b) hydrogen-BECCS and biomass-to-fuel pathways with CCS, configurations the 2022 Scoping Plan already anticipates; and (c) verified biochar from California feedstocks meeting durability criteria. This expansion does not require new legislative authority; it can be accomplished through CARB rulemaking under existing LCFS authority.

MRV methodology development

In parallel, CARB should accelerate the development of pathway-specific MRV methodologies. As discussed in Section II, regulatory authority is largely in place, but operational methodologies remain incomplete. MRV is a prerequisite for any compliance market, as credible quantification and verification are necessary to ensure environmental integrity and enable regulatory recognition of removals.[234] Prioritizing methodologies for pathways with near-term deployment potential, particularly BiCRS and DACCS, is therefore essential.

Sectoral integration through state contracting

Several CDR pathways align with policy areas California already manages through agency contracting: forest residue utilization (CAL FIRE), agricultural residue management (CDFA), biosolids handling (State Water Resources Control Board), and urban wood waste (CalRecycle). Embedding CDR procurement into existing state contracting in these domains creates a parallel demand channel that does not depend on either Cap-and-Invest integration or SB 840 reauthorization. Where carbon removal is a co-benefit of activities the state already funds for other purposes, the cost burden falls on existing sectoral budgets rather than on the GGRF.

A final priority in this phase is investment in enabling infrastructure. Section III identifies storage availability, Class VI permitting, and CO_2 transport as binding constraints for DACCS. Regulatory barriers are beginning to be addressed, but infrastructure deployment remains limited; without coordinated investment, these constraints risk becoming bottlenecks as demand begins to scale.

Long-term horizon (2035–2045): Scaling to the target

Meeting California's 2045 climate target requires scaling CDR to approximately 75 MMT per year. At this level, discretionary procurement mechanisms are insufficient. A durable, system-wide demand signal must be embedded within the state's compliance framework.

The first component of this architecture is the full integration of CDR into the Cap-and-Invest Program. Once MRV methodologies are established and supply begins to scale, removals can be recognized as compliance instruments alongside emissions reductions. Mandatory compliance mechanisms are consistently found to be more effective than voluntary approaches in generating the scale of demand required for durable removals, as they create legally binding obligations rather than relying on fluctuating corporate preferences.[235]

Full integration also requires resolving allocation design as emissions decline. Under AB 1279's 85 percent reduction trajectory, a purely emissions-based compliance obligation concentrates the burden of CDR procurement on a shrinking set of regulated entities. Whether this concentration is sustainable—or whether alternative allocation mechanisms are required—is a design question that

234 Smith et al., *The State of Carbon Dioxide Removal – 1st Edition*, 2023.

235 Smith et al., *The State of Carbon Dioxide Removal – 1st Edition*, 2023.

should be addressed in the medium-term Cap and Invest rulemaking before reaching the long-term horizon.[236]

Finally, CDR deployment should be embedded within sectoral policy domains where removal is a co-benefit of existing state priorities. As noted in Section I, several pathways align with policy areas already managed by California, including forest management, agriculture, waste systems, and water infrastructure. Integrating carbon removal into these domains allows the state to leverage existing institutional capacity while delivering multiple policy objectives simultaneously. In this context, CDR is not treated as a standalone sector, but as an outcome of interventions designed to address broader environmental and economic challenges.

Target accounting and pathway portfolio

By 2045, the recommended architecture would deliver removals through a portfolio of mechanisms, each scaled to the pathway it best serves. Indicative pathway contributions to the 75 MMT target, drawing on the 2022 Scoping Plan for DACCS and hydrogen-BECCS and on Roads to Removal and Getting to Neutral for biomass-waste, ERW, and ocean pathways,[237][238] are approximately: DACCS, 20–25 MMT/year, scaled primarily through 45Q, LCFS expansion, and Cap-and-Invest integration; hydrogen-BECCS and biomass-to-fuel with CCS, 9–15 MMT/year, scaled through LCFS expansion and compliance integration; biochar and biomass-waste pathways, 5–10 MMT/year, scaled through state procurement, sectoral integration, and eventual compliance recognition; and ERW and ocean-based CDR, 2–10 MMT/year combined, scaled through compliance recognition once MRV is operational.

These ranges are indicative and depend on assumptions about cost reduction trajectories, infrastructure deployment, and methodology development. The point is not the precision of any single estimate but the structural observation that no single pathway or mechanism delivers the target. The architecture must be portfolio-based, multi-instrument, and sequenced.

From fragmented support to a coherent demand system

The core recommendation across these three horizons is not a single instrument but a sequencing strategy: early-stage procurement creates initial demand and enables deployment; intermediate mechanisms establish predictable market signals and reduce investment risk; long-term integration embeds CDR within compliance architecture and sectoral budgets. California has many of the necessary elements; what remains is to connect them into a system that evolves over time.

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236 Smith et al., *The State of Carbon Dioxide Removal – 2nd Edition*, 2024.

237 Lawrence Livermore National Laboratory and the National Renewable Energy Laboratory, *Roads to Removal: Options for Carbon Dioxide Removal in the United States*, 2023, https://roads2removal.org.

238 Lawrence Livermore National Laboratory, *Getting to Neutral: Options for Negative Carbon Emissions in California*, 2020, https://gs.llnl.gov/sites/gs/files/2021-08/getting_to_neutral.pdf.

VI. CONCLUSION

California has set the most ambitious carbon neutrality target of any major economy and has built much of the regulatory authority required to support it. What it does not yet have is a procurement architecture capable of translating that ambition into deployed carbon dioxide removal capacity at the scale the 2045 target requires. This paper has argued that closing that gap cannot wait: the trajectory from approximately zero in-state CDR procurement today to a Scoping Plan deployment level of 75 MMT CO_2e annually by 2045 is not achievable through linear scaling from a late start. The deployment lead times of geologic storage permitting, the project finance horizons of capital-intensive removal infrastructure, and the methodological development cycles for compliance-grade MRV all extend over five to ten years. Decisions made in 2026–2030 about whether to create credible in-state demand will determine whether California enters the 2030s with deployable capacity or remains in a pilot phase with strong targets and limited operational reality.

The case for acting now rests on three convergent grounds developed throughout this paper. First, California will need to purchase removals regardless of where deployment occurs, and only in-state projects operate under the state's compliance framework, MRV standards, and environmental review from day one. Second, the economic return on procurement spending differs substantially depending on whether contracts flow to California-based projects, which generate in-state jobs, tax revenue, and supply chain investment, or to imported credits, which deliver the carbon ton without the broader economic value. Third, several CDR pathways deliver carbon removal as a co-benefit of addressing sector-specific challenges California already manages, from wildfire-driven forest residue accumulation to urban biosolids management to soil health in the Central Valley, embedding removal within existing institutional capacity rather than creating it from scratch.

The path forward proposed in this paper is sequential rather than monolithic. In the immediate horizon, SB 840 should be operationalized as a pathway-differentiated instrument rather than a general innovation fund: advance market commitments for biochar and other biomass-waste pathways to establish price discovery and signal future demand; regulatory capacity-building for DACCS; and MRV and community engagement support for BECCS, ERW, and ocean CDR. In the medium term, a CDR sub-mandate within the Cap-and-Invest Program would convert that initial demand into a structured, predictable signal embedded in California's compliance architecture, supported by pathway-specific MRV methodologies that CARB has now begun developing through the SB 905 pre-rulemaking process. In the long term, full integration of CDR into compliance and the embedding of removal within sectoral policy domains create the durable system-wide demand needed to deliver tens of millions of tonnes annually. None of these horizons is sufficient on its own; the architecture works only as a sequence.

Limitations of this analysis

Several limitations of this paper should be acknowledged. The cost figures cited throughout, particularly the $7.5 to $34 billion annual range derived from current voluntary market prices applied to 75 MMT, are sensitive to assumptions about cost trajectories that remain highly uncertain. If learning rates in DACCS, BECCS, and ERW track the more optimistic end of published projections, the scale of public expenditure required would compress substantially; if they track the more conservative end, the gap between procurement need and available revenue widens further. The paper does not attempt to model these trajectories in detail, and the recommendations developed here should be read as robust to a range of cost outcomes rather than calibrated to any single forecast.

The pathway-level analysis in Section III draws on the publicly available record as of early 2026, which is uneven across pathways. DACCS and BECCS are well-documented because of their proximity to existing federal funding programs and Class VI permitting; ERW and ocean CDR rest on a thinner empirical base in California, with limited publicly available project data and few completed regulatory reviews. The deployment-readiness assessments for these pathways are therefore more provisional, and conclusions about pathway selection in any procurement program should be revisited as additional evidence becomes available.

The political economy of SB 840 implementation, including the discretionary nature of annual budget appropriations, the broader fiscal pressures on California's General Fund, and the contested allocation of GGRF revenues across competing priorities, is treated here primarily as context rather than as a variable that the analysis can resolve. Whether the $85 million identified in legislative intent for 2026–27 is sustained across multiple years, redirected to backfill federal program cuts, or reduced under fiscal pressure is a political question that this paper cannot adjudicate. The recommendations developed in Section V are designed to maximize the impact of available funding under each of these scenarios, but their full realization depends on political choices outside the scope of technical policy design.

The "economic return" rationale introduced in Section I — that in-state procurement spending generates jobs, tax revenue, and supply chain investment — is taken as motivating context in this paper but not quantitatively developed. A complementary analysis of these economic multipliers, drawing on existing literature on clean energy spending impacts in California, would strengthen the cost-benefit framing of the in-state procurement case.

Open questions for further research

Two areas in particular warrant further analytical work to support implementation.

The first concerns tradeoffs across pathways. This paper has presented pathway-specific deployment readiness assessments, but a more systematic comparative analysis would weigh durability against cost, speed of deployment against MRV maturity, in-state economic impact against pathway scalability, and environmental justice exposure against community benefit potential. These tradeoffs are not abstract: any procurement allocation under SB 840 implicitly takes a position on them, and implicit positions are harder to revise than explicit ones. A structured evaluation framework, ideally developed in coordination with CARB's SB 905 pre-rulemaking process, would help allocate scarce procurement dollars across pathways in a way that reflects California's stated priorities rather than the relative readiness of advocacy networks.

The second concerns co-benefits. Several CDR pathways examined in this paper, particularly biomass-based approaches and enhanced rock weathering, generate documented or potential benefits beyond carbon removal: wildfire risk reduction, agricultural soil health improvements, reduced agricultural burning in air-impacted communities, biosolids management with reduced land application footprint, and rural economic development. These co-benefits are referenced throughout the literature but have not been systematically quantified for California-specific deployment scenarios. A focused study estimating co-benefit value, in air quality savings, hectares of fire-vulnerable forest treated, tonnes of biosolids diverted from landfill, or productivity gains in treated soils, would substantially change the cost-benefit framing of in-state procurement. Removal that generates two or three billion dollars in non-carbon co-benefits per year is a different policy proposition than removal valued solely on its tonnes of CO_2.

Together, these two research streams would help translate the qualitative case made in this paper into a more operational basis for future procurement decisions. They are complementary to, not a substitute for, the procurement design recommendations developed here: California can begin operationalizing SB 840 on the immediate horizon while these analyses proceed in parallel, with later procurement rounds calibrated against improved evidence.

California's climate policy has consistently moved earlier and more ambitiously than peer jurisdictions, and the state's record demonstrates that stringent targets and broad regulatory authority are within reach when the political coalition exists to enact them. The question that remains is whether the same coalition will treat carbon dioxide removal as the deployment problem it has now become, rather than the research problem it was a decade ago. The technologies are imperfect, the costs are high, and the policy framework remains incomplete; none of these conditions can be resolved by deferring action. California already has most of the pieces it needs—binding targets, regulatory authority, funding vehicles, pathway-specific knowledge, and a maturing project landscape. What it lacks is a credible demand system capable of moving projects from feasibility into sustained operation, and the 2026–2030 window is when that system either takes shape or it does not. The most consequential decision the state can make in this window is to begin purchasing removals at a credible scale, under California-grade standards, from California-based projects, while the longer-term architecture of compliance integration and sectoral embedding is built. The alternative is not a pause. It is a perpetual pilot phase: strong targets, growing funding, and limited operational reality—arriving at 2045 with much of the residual emissions still residual.

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