Massachusetts Carbon Dioxide Removal Study

By RMI for MassCEC

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List of Figures and Tables

[Work in progress]

Acknowledgements

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Acronyms and Abbreviations

[Work in progress]

Executive Summary

In 2024, the Massachusetts Legislature passed An Act Promoting a Clean Energy Grid, Advancing Equity and Protecting Ratepayers which directs the Massachusetts Clean Energy Center (MassCEC) to conduct and publish a study on the "prospects and opportunities for carbon dioxide removal (CDR) innovation and operations within the commonwealth or in waters not more than 50 nautical miles off the commonwealth."[1] CDR refers to human activities that remove carbon dioxide (CO_2) from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products.[2] Unlike emissions reductions, which prevent new CO_2 from entering the atmosphere, CDR focuses on removing CO_2 that is already present. CDR is a broad term that encompasses a diverse range of pathways that differ in their underlying mechanisms, maturity, reversal risk, and cost.

The state has identified nature-based and engineered CDR methods as likely necessary to counteract a portion of emissions in accordance with its 2050 Net Zero mandate. Specifically, the Commonwealth committed to achieving at least an 85% reduction in gross greenhouse gas (GHG) emissions from 1990 levels and net zero emissions by 2050. The state estimates that up to 15%, or 14 million tons of CO_2 (tCO_2) per year, of the 1990 baseline emissions may need to be addressed using removals. Previous analyses by the state, including the Forest Carbon Study, have estimated the sequestration potential for natural and working lands (NWL) in the state; however, even the best-case scenario for NWL sequestration is not sufficient to meet the state's need for CDR.

This Study builds on Massachusetts' prior planning, including its assessment of NWL, to assess which CDR pathways are most feasible and scalable in the state's policy, economic, and natural resource context. The outcomes of this effort will inform future iterations of the state's flagship climate planning documents, the Clean Energy and Climate Plans (CECPs), providing an assessment of best practices and policy options that Massachusetts should consider when responsibly integrating CDR into its net-zero strategy.

This Study describes and assesses 23 CDR and storage pathways across several characteristics, analyzing their suitability for deployment and research and development (R&D) leadership in Massachusetts. CDR pathways are categorized into biogenic, geochemical, and synthetic pathways as well as CO_2 storage, as outlined below.[3]

- **Biogenic CDR -** pathways that use naturally occurring, biomass-based processes such as photosynthesis to capture CO_2 from the atmosphere.
- **Geochemical CDR -** pathways that use naturally occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.
- **Synthetic CDR -** pathways that use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it or to alter water chemistry to indirectly remove CO_2 from the air.
- **CO_2 storage** - pathways that store captured and concentrated streams of CO_2 through trapping, mineralization, or other physical or chemical processes. CO_2 storage is typically paired with a biogenic, geochemical, or synthetic capture pathway.

Figure ES-1: The Portfolio of CDR Pathways

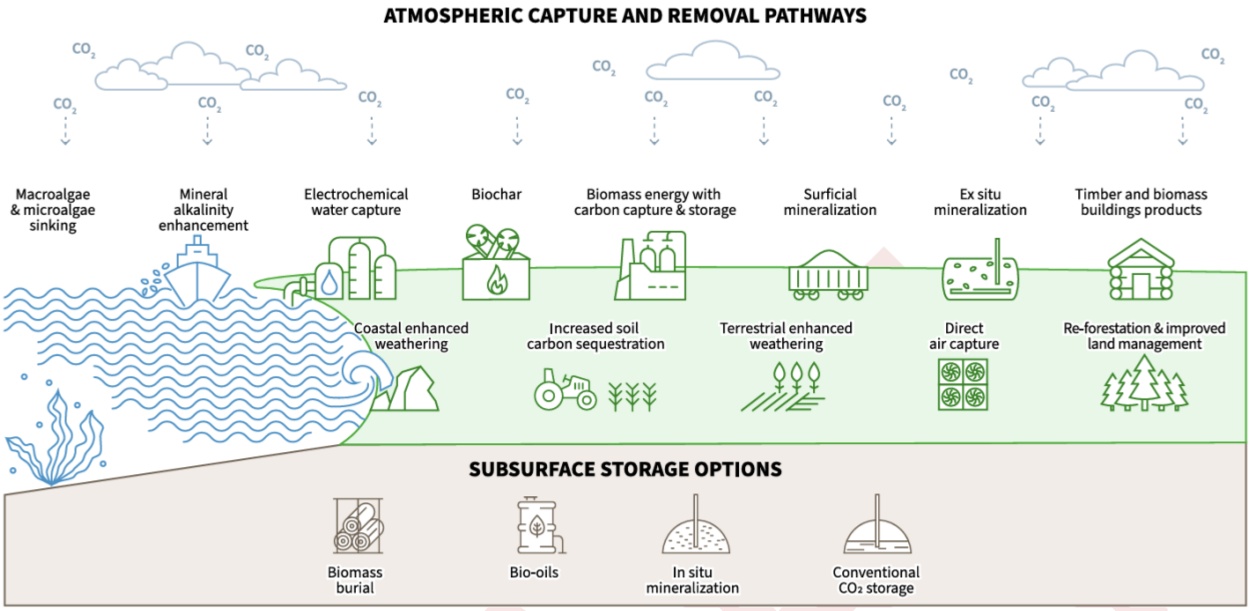

Figure ES-1: The Portfolio of CDR pathways. Figure sourced from RMI's Publication, From Trees to Tech and Beyond: Carbon Dioxide Removal (CDR) in All Its Variations[4]

Suitability for deployment was determined as a function of a pathway's scale potential, risks to growth, co-benefits and potential negative impacts, resource requirements, economic benefit and job creation, local supply chain relevance, and the potential for cost reduction in the context of Massachusetts. Suitability for R&D leadership was determined as a function of a pathway's technology readiness level (TRL), state of development in measurement, monitoring, reporting, and verification (MMRV), and existing R&D landscape. The Study's main findings include:

Deployment suitability

- Many CDR pathways may be suitable for deployment by midcentury in Massachusetts at a scale that is significant relative to Massachusetts' need (>7%, or about 1 million tCO_2 per year, of the 14 million tCO_2 per year of removals needed by 2050.
- Biomass direct storage, terrestrial enhanced weathering, and ex-situ mineralization are rated as likely to be well-suited for deployment in the state by mid-century. These pathways have moderate to high scale potentials, meaning it is estimated they will meet at least 7%, or about 1 million tCO_2 per year, of the 14 million tCO_2 needed in Massachusetts, in addition to other favorable characteristics (Table ES-1).
- There are ten pathways that could possibly be well-suited for deployment in Massachusetts depending on the state's priorities, how CDR evolves as a field, and how uncertainties are addressed (Table ES-1).
- For each pathway that is identified as possibly or likely well-suited for deployment, the Study includes policy options that the state may consider enacting to support the pathway.

R&D leadership potential

- It is likely that Massachusetts could be a leader in R&D and innovation for eight pathways, ranging across biogenic, geochemical, and synthetic CDR, as well as storage. The state has a unique opportunity to become an innovation hub for these pathways: forests, microalgae in open water, macroalgae in open water, coastal enhanced weathering, mineral alkalinity enhancement, CO_2 stripping, electrochemical alkalinity production, and ex-situ mineralization (Table ES-1).

- There are an additional nine pathways for which the state may be well-suited to lead on R&D depending on priorities and resource constraints (Table ES-1).
- Much of the state's R&D leadership potential is related to marine CDR due to the state's existing marine infrastructure, access to coastline, and leading academic and research institutions.
- For each pathway that is identified as possibly or likely well-suited for R&D leadership, policy options are included that could be pursued by the state to support innovation.

Removal targets

- Even with the opportunity for deployment and R&D leadership in the state, it is unlikely that deployment of CDR solely within the state can achieve the state's likely total need (the 14 million tCO_2 per year of removals needed to counteract ongoing emissions compared to the 1990 baseline).
- Additional emissions reductions, regional coordination, and out-of-state procurement of CDR will likely be needed for the state to achieve its net zero mandate in 2050.

Best practices and policy options

This Study identifies policy interventions from other jurisdictions that Massachusetts could learn from to support responsible innovation and deployment of CDR in support of the state's climate and economic goals. These interventions must be assessed during the forthcoming 2035 CECP process in light of other policy priorities and resource capacity.

These interventions span a variety of policy types, including governance and planning, demand creation, supply support, standard setting, permitting, and other policies. These policy options for the state to consider include but are not limited to:

- Adopt a definition of CDR that is performance-based and pathway-agnostic.
- Establish interim removals targets that are aligned with existing GHG limits and CECP timelines.
- Create and fund a body that specializes in CDR for the Commonwealth.
- Build on or launch regional partnerships to coordinate on CDR development and deployment.
- Develop and launch a pilot procurement program.
- Consider inclusion of CDR practices in existing programs (e.g., Climate Smart Agriculture Program, accelerator programs).
- Create competitive grant programs for universities and research institutions focusing on filling priority research gaps.
- Create special economic zones for specific CDR pathways that include economic incentives and safe, streamlined permitting for projects that site within the zone.
- Consolidate guidance around existing permitting pathways and align on and publish guidance for new permitting pathways.
- Develop standards, or adopt existing standards, for CDR in the state of Massachusetts.

Overall, Massachusetts' existing industrial ecosystem (large ports, concrete manufacturing, waste treatment facilities) and natural resources (coastline, forestland, and other biomass) position it well to deploy CDR in support of its climate goals. Massachusetts is also well positioned to lead on CDR R&D, given its existing innovation ecosystem, including its leading academic and research institutions (e.g., Woods Hole Oceanographic Institute), innovation hubs (e.g., Boston, Cambridge), and existing innovation support (e.g., MassCEC). By investing in R&D, the state can advance its own CDR priorities while also advancing the field globally. Targeted policy action and investment at this early stage could be well-timed to set the state up for success but would need to be considered in the context of other priorities and resource capacity. The state should consider the outcomes of this Study as part of future climate planning that is occurring through the development of the 2035 Clean Energy and Climate Plan.

Table ES-1: CDR Pathway Assessment and Conclusions

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($/$tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
Forests *biogenic*	Medium	High	High (5.0-6.0)	Medium	1-80	Low	Positive	9
Agricultural soils *biogenic*	Medium	Medium	Low (0.01-0.4)	Medium	5-25	Low	Positive	9
Salt marshes *biogenic*	Medium	Medium	Low (0.04-0.1)	Medium	25-45	Low	Positive	9
Biomass direct storage *biogenic*	High	Medium	Medium (0.8-1.2)	Low	10-60	Medium	Positive	6-8
Timber building products *biogenic*	Medium	Medium	High (4.5)	Medium	500-1,500	Low	Positive	9
Other biomass building products *biogenic*	Low	Medium	Low (0.1)	High	50-10,000	Medium	Positive	9
Pyrolysis (biochar) and storage *biogenic*	Medium	Low	Low (0.4- 1.1)	Low	10-350	Medium	Positive	7-9
Pyrolysis (bioliquid) and storage *biogenic*	Medium	Medium	Low (0.4-0.5)	Medium	450-600	Medium	Positive	6-7
Microalgae in ponds *biogenic*	Low	Low	High (1.8-7.8)	High	250-1,200	Medium	Neutral	7-8

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($/$tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
Microalgae in open water *biogenic*	Low	High	Unknown	High	7-1,500	Medium	Negative	3-4
Macroalgae in open water *biogenic*	Low	High	Unknown	High	480-17,000	Medium	Neutral	4-6
Bioenergy with carbon capture and storage (BECCS) to electricity *biogenic*	Low	Medium	Low (0.6-1.0)	High	75-300	Low	Neutral	6-8
Bioenergy with carbon capture and storage (BECCS) to fuels *biogenic*	Low	Low	Low (0.1-1.0)	High	75-300	Low	Neutral	9
Surficial mineralization *geochemical*	Low	Low	Low (0.6-1.2)	High	55-500	Medium	Neutral	5-6
Terrestrial enhanced weathering *geochemical*	High	Medium	High (3.1-11.7)	Medium	50-500	Medium	Neutral	6-7
Coastal enhanced weathering *geochemical*	Low	High	Low (0.04-0.1)	High	55-225	Medium	Neutral	5-6
Mineral alkalinity enhancement	Medium	High	Medium (1.5-2.0)	High	55-225	Medium	Neutral	4-6

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($/$tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
geochemical								
CO_2 stripping *synthetic*	Medium	High	Medium (1.5-2.0)	High	400-2,400	Medium	Negative	5-6
Electrochemical alkalinity enhancement *synthetic*	Medium	High	Medium (1.5-2.0)	High	400-2,400	High	Neutral	5-6
Direct air capture *synthetic*	Medium	Medium	High (1.8-4.1)	Medium	500-2,000	Medium	Neutral	2-9
Conventional storage *CO_2 storage*	Low	Low	Low (0.0)	High	10-30	Low	Neutral	9
In-situ mineralization *CO_2 storage*	Low	Low	Low (0.0)	High	10-400	Medium	Neutral	7-8
Ex-situ mineralization *CO_2 storage*	High	High	High (19.5)	Medium	10-600	High	Neutral	6-7

Table ES-1: CDR Pathway Assessment and Conclusions. The column outlined in red, deployment suitability, or the suitability for a pathway to help Massachusetts achieve its climate goals, is the main finding of this report. This rating is determined using the other characteristics outlined in this table. More detail can be found in Section 4, CDR Pathway Suitability Methodology. [i]Scale estimate is not an estimate of the likely deployment scale in Massachusetts. It is an overestimate due to feasibility limits discussed in the risks to growth sections of the report.

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1 Study Context

1.1 What is carbon dioxide removal (CDR)?

Carbon dioxide removal (CDR) refers to human activities that remove carbon dioxide (CO_2) from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products.[5] Unlike emissions reductions, which prevent new CO_2 from entering the atmosphere, CDR focuses on removing CO_2 that is already present. It encompasses a diverse range of pathways that differ in their underlying mechanisms, maturity, reversal risk, and cost. Many CDR pathways are continuing to evolve, and consideration of a variety of pathways, whether operating at commercial scale, just beginning pilots, or still in early lab or concept phases, is necessary to understand the full breadth of solutions.

A variety of taxonomies, or ways to categorize CDR, exist. Some separate *nature-based* and *engineered* solutions; others differentiate between *conventional* and *novel* pathways.[6,7] This Study utilizes RMI's Applied Innovation Roadmap for Carbon Dioxide Removal which categorizes CDR into biogenic, geochemical, and synthetic, as well as storage pathways.[8] Biogenic CDR harnesses biological processes to store carbon in biomass or durable products derived from it, such as living biomass, biochar, bioenergy with carbon capture and storage (BECCS), and other pathways that rely on biomass as a primary feedstock. Geochemical CDR accelerates naturally occurring mineral processes that remove and store CO_2, such as enhanced weathering, mineralization, and mineral alkalinity enhancement. Synthetic CDR uses engineered processes to separate CO_2 from ambient air and permanently stores it, including direct air capture (DAC) and marine pathways. Together, these pathways form a portfolio of tools capable of removing emissions across sectors and timescales.

1.2 Motivation for CDR

The scientific consensus is that CDR is essential to limiting global warming to 1.5°C or well below 2°C given the amount of CO_2 already amassed in the atmosphere, the need to avoid climate tipping points, and the likelihood of certain emissions continuing because of the absence of feasible decarbonization solutions. The IPCC's Special Report on Global Warming of 1.5°C concluded that all modelled pathways consistent with these temperature goals require CDR alongside deep emissions reductions.[9] ***This means that CDR must complement, not replace, aggressive decarbonization efforts.*** CDR serves three primary purposes. In the near term, it reduces net emissions to avoid climate tipping points. In the medium term, it counteracts residual emissions, or emissions that are economically or technologically infeasible to reduce. In the long-term, CDR draws down historical emissions which will help achieve net-negativity, when more emissions are being removed from the atmosphere than being added to it.[10]

Rapid and thoughtful deployment and scale-up of CDR is needed to establish reliable, verifiable, trusted technologies and systems and to lower costs through learning and innovation. Implemented responsibly, CDR can also stimulate co-benefits such as job creation, ecosystem enhancement, and others. However, the integrity of CDR depends on rigorous measurement, monitoring, reporting, and verification (MMRV) to ensure removals are real, additional (or that they would not have happened in the business-as-usual scenario), and high-quality.[11] This Study explores CDR in Massachusetts, uncovering which pathways are best suited for the state and surfacing best practices from other jurisdictions on how to support CDR in a safe, sustainable, efficient manner.

1.3 Massachusetts Climate and CDR Context

In 2008, Massachusetts established one of the nation's first comprehensive climate governance frameworks through landmark legislation, the 2008 Global Warming Solutions Act (GWSA), which required an economy-wide 10-15% reduction in greenhouse gas (GHG) emissions below a 1990 baseline by 2020 and an 80% reduction by 2050. Thirteen years later, in 2021, these targets were amended under An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy which sets a 50% reduction target by 2030, a 75% reduction by 2040, and at least an 85% reduction and net-zero emissions by 2050, all in comparison to a 1990 baseline.[12] Together, these laws set binding statewide GHG emission limits and a process for setting sector-specific sublimits for every 5 years through 2050. These targets are set by the Executive Office of Energy and Environmental Affairs (EEA) in consultation with other state agencies.

To operationalize these statutory requirements, the state also requires the publication of a roadmap in parallel with each 5-year GHG limit, titled the Clean Energy and Climate Plans (CECPs). Thus far, Massachusetts has developed CECPs for 2025, 2030, and 2050, building on a prior analysis, the Massachusetts 2050 Decarbonization Roadmap.[13, 14 15] These plans outline detailed sectoral pathways to achieve GHG limits and provide an analytical foundation for program creation and investment. Through these plans, the Commonwealth further determines how to achieve net zero in 2050.

While natural and working lands (NWL) are identified as a primary source of carbon removal, the 2050 CECP states that additional CDR will be needed beyond what natural sequestration can provide and that the Commonwealth will likely have to fill this gap by procuring CDR outside the state or by leveraging engineered solutions.[16] More specifically, the state estimates, through its Forest Carbon Study, that forests in Massachusetts could remove between 5 million and 6 million tCO_2e per year through mid-century, which is approximately 40% of the 14 million tCO_2 per year that Massachusetts will likely need in 2050 to achieve its net zero mandate. If this estimate holds true, that means an additional 8 to 9 million tCO_2e per year of CDR, in addition to forests, will be needed. However, it is likely the need for additional CDR will be much greater given the potential for natural disturbances, land competition that could reduce forest sequestration, and because of questions around additionality. For more information on additionality, see Section 6.4.2 and Forests in Appendix A.

Beyond these core mandates and roadmaps, the state of Massachusetts is conducting a Blue Carbon Feasibility Study, has convened the Embodied Carbon Intergovernmental Coordinating Council (ECICC), is working with other states to explore best practices around net zero accounting and strategies to balance emissions, and has several ongoing initiatives that could intersect with removals efforts, expanded on in Section 6.[17, 18, 19]

Most recently, in 2024, the Legislature passed An Act Promoting a Clean Energy Grid, Advancing Equity and Protecting Ratepayers which directs the Massachusetts Clean Energy Center (MassCEC) to conduct and publish a study on the "prospects and opportunities for carbon dioxide removal innovation and operations within the commonwealth or in waters not more than 50 nautical miles off the commonwealth," which is what this document aims to do.[20] This Study builds upon the state's existing climate legislation and plans and assesses which CDR pathways are most feasible, equitable, and scalable in Massachusetts' policy, economic, and resource context. The outcomes of this effort will inform future iterations of the state's CECPs and identify policy recommendations to responsibly integrate CDR into Massachusetts' net-zero strategy.

2 Global CDR Landscape

Governments across the globe have been making strides passing supportive CDR policy. This section examines existing policies and policies in development that support CDR in a variety of ways either through planning (e.g., setting CDR targets), demand support (e.g., integrating CDR into compliance mechanisms such as emissions trading systems), supply support (e.g., R&D grants or industrial hubs), standards, and permitting. These existing policies can provide examples of how other jurisdictions are making progress on CDR and inform possible policy interventions the state of Massachusetts could consider implementing. This section is not exhaustive; it intends to provide key examples of policy. Section 6, Policy Lessons and Best Practices, synthesizes these examples with Massachusetts-specific context to provide key takeaways and policy options that Massachusetts may decide to pursue. For more information on these categories of policy (e.g., CDR governance and planning), please see the Glossary for a definition of each.

2.1 Policy Landscape

2.1.1 CDR governance and planning

One way to support CDR is through governance and planning such as creating agencies or bodies to plan for CDR, setting explicit CDR targets, or developing roadmaps for how to support CDR. One example of this is the European Union's (EU) Carbon Removals and Carbon Farming (CRCF) Regulation which is a voluntary framework for certifying carbon removals in the EU. Through this regulation, the EU has created clear delineation between permanent carbon removals, carbon farming practices, and carbon stored in products. Although it is yet to be seen how the CRCF is integrated with other mechanisms in the EU (such as the Emissions Trading System), the CRCF is a strong example of a jurisdiction leading on CDR governance.[21] Another example of CDR governance and planning is setting explicit targets for removals. Several governments have set targets for removals, including Switzerland's goal to achieve 2 million tCO_2 within its borders and 5 million tCO_2 abroad by 2050, the United Kingdom's (UK) goal to do 5 million tons of "engineered" CDR by 2030 and around 80 million tons by 2050, and California's goal to do 7 million tCO_2 by 2030 and 75 million tCO_2 by 2045, outlined in their 2022 Scoping Plan.[22] By setting explicit targets that are based on analysis of likely residual emissions, the capacity for an area to do CDR, and how quickly CDR is likely to scale, these governments have been able to lead on governing how CDR will play a role in their climate strategies.

2.1.2 Demand policies

Beyond governance, a diversity of policies that spur demand for CDR in different ways are beginning to be established. One way to create demand for CDR is by integrating CDR credits into existing compliance mechanisms such as emissions trading systems (or schemes, ETSs) or clean fuel standards. California's Low Carbon Fuel Standard (LCFS) already includes a direct air capture (DAC) protocol to allow for offsetting, and the legislature has directed the California Air and Resources Board (CARB) to consider including carbon removal protocols in its cap-and-invest program.[23,24]

Outside of the US, the UK has committed to integrate "engineered" removals into the UK ETS, the EU is assessing whether and how to integrate removals into the EU ETS or establish a connected mechanism, and Japan's Green Transformation ETS (GX-ETS) already allows up to 5% of emissions to be covered by removals credits.[25,26,27] Another compliance mechanism that is integrating CDR credits is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).[28] CORSIA allows covered aviation emissions to be offset with Eligible Emissions Units and certain registries that include carbon removal projects have recently been approved for CORSIA's next phase. Other compliance mechanisms to consider are carbon taxes (e.g., Singapore allows offsetting in their Carbon Tax) or carbon-border adjustment mechanisms (CBAMs) (e.g., the EU CBAM does not include CDR but could).[29,30]

In addition to compliance mechanisms, direct procurement is another way to spur demand for CDR. The US Department of Energy's (DOE) Carbon Dioxide Removal Purchase Pilot Prize is an example of direct government procurement of CDR in which the DOE planned to directly pay CDR suppliers to conduct pilots across four CDR categories. Although this program has not progressed past determining semi-finalists given changing administrations, it was an example of how a government could directly procure CDR.[31] Another example is Canada's Low Carbon Fuel Procurement Program. In 2024, Canada committed to purchase $10 million of CDR by 2030 to simultaneously lower net government emissions and support early-stage technologies.[32] Although no state in the US has established a direct CDR procurement program, California SB 643, introduced in 2025, would have required the California Air Resources Board (CARB) to fund $50 million of CDR projects by 2035; however, it was vetoed because of budget constraints.[33] These examples show how compliance mechanisms and other demand policies can be tools to create durable demand signals that complement state targets.

2.1.3 Supply policies

On the supply side, governments have passed tax credits, created industrial hubs, and granted R&D funding to support CDR. The US 45Q tax credit and the Canada Carbon Capture Utilization and Storage (CCUS) Investment Tax Credit (ITC) are two leading tax credits for incentivizing geologic CO2 sequestration.[34] [35] DAC projects are eligible within both tax credits, and the tax incentive is based on the amount of CO_2 sequestered.

In addition to tax credits, governments can support supply by providing grants for infrastructure or project build-out. The US DOE began funding the Regional DAC Hubs program to demonstrate million-ton-scale DAC projects with storage and associated CO_2 networks.[36] Although the DAC Hubs Program has been cancelled, this is one example of how governments can support regions well-suited to developing CDR. The EU's Innovation Fund and Australia's CarbonLock program are additional examples of government funding that spur innovation in CDR.[37,38] For Massachusetts, rich in universities and R&D strengths, incentivizing supply and innovation like these examples is a possible avenue for scaling CDR. This will be further explored in Section 6.

2.1.4 Standards and certification

A central pillar of CDR policy is standards creation and certification. Ensuring that CDR is being held to a high-quality standard is central to ensuring the industry scales in a responsible, safe way. Standards address key issues such as additionality *(did the removal happen beyond business-as-usual?)*, risk of reversal *(what are the risks that could cause reversals, over what time period, and how will they be mitigated?)*, leakage *(did the removal create emissions elsewhere?)*, double-counting *(was the same removal claimed more than once?)*, and transparency in accounting and claims.

Standards being developed for global policy and voluntary transactions are beginning to set the stage for how markets will operate. One example is the United Nations Framework Convention on Climate Change (UNFCCC) Article 6.4 Removals Standard which provides shared rules for high-integrity removals that underpin cross-border purchases.[39] This standard applies to CDR activities that occur within the Paris Agreement Crediting Mechanism (PACM), a mechanism that enables international cooperation and transfer of carbon credits to help meet climate targets. Additionally, the standards adopted under PACM are likely to be adopted by other global carbon credit mechanisms such as CORSIA which means the rules outlined in the Removals Standard will have a large influence on international carbon markets.[40]

Beyond the Paris Agreement, the EU CRCF is another framework that was adopted in 2024, providing another model for how government can certify removals.[41] The CRCF establishes the first EU-wide voluntary certification framework for carbon removals. The CRCF splits removals into three categories: permanent carbon removals, carbon farming and soil emissions reductions, and carbon storage in long-lasting products. The European Commission is now working on the adoption of tailored methodologies for a variety of activities and the adoption of third-party verification rules. While the creation of this framework could be foundational to the certification of a diversity of removals in the EU, it is not yet clear how the CRCF will integrate into compliance mechanisms such as the EU ETS and therefore unclear the level of impact it will have.

In the voluntary market, several overarching sets of principles and guidance support robust crediting and claims. The Integrity Council for the Voluntary Carbon Market's (ICVCM) Core Carbon Principles (CCPs) are principles that aim to raise the bar for carbon credit quality on the voluntary carbon markets. These principles range from governance to emissions impact to sustainable development.[42] Meanwhile, the International Organization for Standardization (ISO), a non-governmental organization that has a series of standards related to climate change mitigation, and the Greenhouse Gas Protocol (GHG Protocol), a multi-stakeholder group that establishes widely used standards for corporate GHG emissions, are beginning to harmonize their existing standards to create new ones for GHG emissions accounting and reporting.[43,44,45]

At the US level, other states are beginning to define CDR standards. For example, the California legislature has directed CARB to consider including CDR protocols in its cap-and-invest program and CARB is in the process of implementing SB 905, which requires the establishment of a Carbon Capture, Removal, Utilization, and Storage Program in California. Both efforts have spurred action in the state on standard development.[46] Additionally, California Senate Bill 285 (introduced in 2025) proposed a definition for qualified CDR and required that the state use this definition to determine eligibility for CDR pathways to support meeting California's climate targets.[47] The definition of qualified CDR included principles related to sustainable biomass use, reporting requirements, and what types of CDR could be used to counteract different emissions. However, this bill did not pass. Beyond California, the Colorado Carbon Management Roadmap recommends that the state create standards for sustainably sourced biomass and standards for MMRV, although action taken in response to this recommendation is unclear.[48]

2.1.5 Permitting

Because of their novelty, many types of CDR do not have clear permitting pathways, and, to support suppliers, some jurisdictions are establishing bodies to clarify these pathways. For example, CA SB 905 not only established the Carbon Capture, Removal, Utilization, and Storage Program to evaluate CCUS and CDR in the state but also requires CARB to establish a unified permit application for CCUS and CDR projects to expedite the issuance of permits for these projects. By doing so, California aims to create a clear avenue for CDR suppliers to become permitted and to avoid confusion and delay in the process.[49] Efforts to clarify or reform permitting should not undermine important guardrails in place to protect ecosystems or resources but rather determine how to simultaneously uphold protections and provide a clear path for projects.

It is important to note that many CDR pathways are early-stage, and regulations are still being determined. This is true for many pathways, but one are of focus in the CDR community is permitting for certain marine CDR pathways. The oceans are governed by multi-national agreements, national bodies, and subnational bodies to protect marine ecosystems, uses, and resources, which makes permitting and regulation complicated. At an international level, the London Protocol and London Convention influence dumping and research in international waters (>200 nautical miles for coastlines). While the US is not party to this international agreement, it has an impact on how ocean fertilization (which leads to microalgae growth), mineral alkalinity enhancement, electrochemical alkalinity enhancement, and macroalgae and sinking are administered outside of state and national waters.[50] At a national level, the Marine Protection, Research and Sanctuaries Act (MPRSA) is the domestic implementation of the London Convention, and it regulates ocean dumping in the US up to 12 miles off the coast (or further if a vessel flagged or registered in the US is used), which means that some CDR projects will need to be permitted by the EPA.[51] Beyond marine CDR, there are many national and subnational laws that will likely come into consideration when pursuing a permit for CDR pathways on land, such as those that require hazardous waste handling, pipeline and well construction and monitoring, and mineral additions to terrestrial environments.

2.2 Market Outlook

In addition to movement on policy, it is important to consider how carbon, and specifically CDR, markets are developing. Globally, carbon removal is emerging as a distinct and rapidly evolving segment within both voluntary and compliance carbon markets. On the voluntary side, the voluntary carbon market (VCM) has seen ups-and-downs in the last few years regarding credit retirements and overall prices. However, CDR credits continue to grow as a portion of the VCM, adding value to the market overall. In 2024, “engineered removals” added $500 million to market value.[52] This growth has continued in 2025. The third quarter of 2025 saw the second highest number of tons contracted in a quarter and was larger than all of 2024. Carbon removal purchases are dominated by a few corporate leaders such as Microsoft and Google.[53] Leading pathways for sales include BECCS, DAC, biochar, enhanced weathering, and other pathways, but biochar led in terms of deliveries.[54] Prices for removal credits remain substantially higher than those for emission-reduction credits, reflecting their long-term storage and scarcity.[55] These trends could indicate that the voluntary market is shifting from general offsets toward verifiable, durable carbon removal.[56]

In compliance markets, carbon removal is also gaining formal recognition. As mentioned in previous sections, CORSIA is integrating registries that provide removal credits as supply constraints intensify, the EU has adopted the CRCF to standardize and verify removals across member states, the UK is designing mechanisms to integrate removals into its ETS in the next decade, and Japan's GX-ETS explicitly allows the use of durable carbon-removal credits for compliance starting in 2026.[57,58,59,60] At the international level, PACM will issue both reduction and removal units under UN oversight.[61] Collectively, these actions demonstrate growing regulatory momentum that could anchor carbon removal within global compliance systems. However, questions remain relating to how these systems will connect to one another and how to ensure that the high cost of CDR does not prevent these pathways from competing in compliance regimes.

Looking forward, estimates suggest that the overall CDR market size could range from $300 billion to $1 trillion by 2050 depending on whether commercial, nature-based solutions or early-stage technological solutions are more relied on.[62] Further, although engineered CDR prices are currently high, ranging mostly from $50-$500/ton with exceptions such as CO_2 stripping costing over $1000/ton, these prices are expected to decrease, especially with more innovation. Some models estimate prices for engineered CDR could decrease by 30-60% through 2035 and continue decreasing beyond that. On the other hand, prices for nature-based CDR could rise overtime alongside resource (land) constraints and a push for engineered removals.[63] [64]

3 Massachusetts Context

Section 2 considers how different governments are supporting CDR through a variety of policies. The types of CDR that are best suited to each geography will vary based on differences in environment, natural resources, industry, and more. The best ways to support and leverage CDR will vary by government based on differences in priorities, history, policy landscape, and more. Section 3 delves into the Massachusetts context relevant to CDR to begin to determine what types of CDR and support mechanisms will be most needed and best suited for the state.

3.1 Massachusetts Advantages and Disadvantages

Massachusetts possesses many of the foundational conditions to support CDR development. The Commonwealth's net-zero by 2050 mandate, comprehensive CECPs, and active innovation ecosystem provide strong policy and institutional frameworks for CDR exploration. The state's coasts create opportunities to pilot a range of coastal and marine removal methods.[65] Moreover, Massachusetts' existing clean-energy workforce and research institutions offer a foundation for advancing research and innovation.

Despite these advantages, Massachusetts faces inherent constraints to achieving large-scale CDR deployment. To start, the state's relatively small size (44th largest in the US) limits the scale of CDR that can be deployed to reach the state's CDR needs.[66] Additionally, the state lacks substantial geologic formations for geologic CO_2 storage, which limits options for storage associated with BECCS or DAC.[67] In addition, relatively high electricity and land costs compared to other regions pose economic challenges for energy- and/or land-intensive CDR pathways. [68] [69]

This section dives into the advantages and disadvantages that Massachusetts faces when scaling CDR, broken into 6 categories (natural resources, infrastructure, work force, supply chains, academic environments, and political / social environments). For more detailed analyses of which CDR pathways rely on which natural resources, infrastructure, etc., see Appendix A, a detailed technical analysis of 23 CDR pathways, including a scale estimate for each based on constraining factors in the state.

3.1.1 Natural Resources

Massachusetts' natural environment offers several enabling characteristics for CDR. The state has over 1500 miles of coastline, making it the 16th longest coastline by state in the US, and its coastal and territorial water area makes up over 15% of its total area.[70] [71] Access to coasts and marine waters are important for several pathways including coastal enhanced weathering, microalgae and macroalgae sinking, and other marine pathways. Beyond access to the ocean, Massachusetts is over 50% forested and over 14,000 acres of forestland are managed annually.[72] Access to forest and woody residual biomass is important for pathways that rely on sustainable biomass as a feedstock such as biochar, bioliquid, and biomass burial. Finally, about 10% of Massachusetts is covered in farms, which could create opportunities for pathways like enhanced rock weathering or biochar. Overall, its variety of natural resources positions Massachusetts for diversified CDR research and deployment.

However, the small size of the state leads to natural resource constraints that could limit scalability of pathways. Despite Massachusetts farm coverage, the average farm size is about 60-70 acres, as compared to the US average farm size of over 450 acres. This could limit the ability for farmland-reliant pathways to scale. Limited in-state access to alkaline silicate rock and the absence of major mining sectors in the state could constrain opportunities for geochemical CDR.[73] It is important to note, however, that Massachusetts could import alkaline minerals for pathways that require them and, as long as projects are occurring in state, get credit for CDR done with imported feedstocks. This means Massachusetts may not be constrained by lack of mineral feedstock; however, importing feedstock would likely increase cost and emissions. Finally, shallow or fractured geology and dense urbanization leave few locations for secure in-state geologic CO_2 storage, which could limit DAC, BECCS, and other pathways that result in a stream of CO_2 to be stored.[74]

3.1.2 Infrastructure

Massachusetts benefits from robust industrial, research, and port infrastructure that can support early CDR activities. Existing industrial parcels, concrete facilities, and wastewater treatment sites offer possible co-location for pathways that can take advantage of industrial waste residues or industrial processes such as surficial mineralization, ex-situ mineralization, and electrochemical alkalinity production. Ports such as New Bedford and Boston provide possible capacity for marine CDR pilots and shipment of captured or mineralized carbon materials.[75] [76] Massachusetts has a well-developed supply of renewable energy, and, in 2023, over 1/3 of in-state generation was from renewables.[77] These assets could make Massachusetts well-suited for pilot-scale projects that are able to access this in-state renewable generation.

On the other hand, Massachusetts lacks the heavy industrial infrastructure typical of large-scale CO_2 geologic storage or utilization. There is no CO_2 pipeline network, and there are currently no Class VI storage wells in the state.[78] Any project requiring deep injection would therefore depend on out-of-state or offshore transport and storage, increasing costs and permitting complexity. Additionally, although renewables make up a large part of in-state generation, the state consumes 25 times more energy than it produces and demand for clean energy will continue to grow and strain the current supply; energy-intensive pathways could be very expensive, strain local grid resources, and face siting constraints near dense residential areas for this reason.[79]

3.1.3 Workforce

The Commonwealth has a strong clean-energy workforce exceeding 115,000 workers, including engineers, tradespeople, and scientists experienced in low-carbon technology.[80] This workforce provides transferable skills for constructing and operating CDR facilities, for conducting MMRV, and for supporting CDR research and innovation. MassCEC is an economic development agency specifically focused on job creation in clean energy sectors, further positioning the state to support a relevant workforce for CDR. Finally, Massachusetts has a large workforce in aquaculture and water transportation which could support marine CDR project development.[81]

Pathways that lack natural resources and infrastructure are also likely to lack relevant workforce in Massachusetts. The state lacks an experienced workforce in geologic storage operations and CO_2 transport, given its lack of adequate CO_2 storage. Further, the state lacks a large mining industry and therefore a relevant workforce for activities related to mining feedstocks for geochemical pathways.[82] As mentioned previously, while having an in-state mining sector would be advantageous for geochemical pathways, not having one does not preclude Massachusetts from being able to do geochemical pathways using imported feedstocks.

3.1.4 Supply Chains

Massachusetts has certain developed supply chains that could make it well suited for some CDR pathways. To start, the state already manages biogenic residues through its food waste-diversion policies. Beginning over a decade ago, these policies divert food waste at several steps in the food supply chain including managing end of lifecycle biogenic residues.[83] The state may be able to expand and leverage these policies and infrastructure to manage other residual biomass from agricultural land and forested lands which could create a steady and efficient supply chain for biogenic CDR pathways like biochar, bioliquid, and biomass burial. Further, robust transportation corridors and port logistics could enable the import of necessary feedstocks to the state or export of captured CO_2 or carbon materials.[84] The region's advanced manufacturing and clean-tech sectors could also produce sorbents, electrolyzers, and modular capture components for small-scale CDR systems.[85] Finally, Massachusetts has a very developed aquaculture industry including propagation programs and existing farms.[86] Although most of this industry is dedicated to shellfish and finfish, the Commonwealth has five commercial kelp farms which gives Massachusetts an advantage in building out CDR pathways that rely on marine biomass seeding, growing, and processing. Leveraging existing supply chains could both help spur CDR development and create additional revenue streams for local industries.

However, as mentioned, Massachusetts is missing the feedstocks and therefore associated supply chains for certain CDR pathways. Massachusetts' limited alkaline mineral feedstock and therefore limited mining, processing, and transporting supply chains for these minerals could constrain certain pathways. Reliance on acquiring these feedstocks from out of state and on external transportation raises costs and emissions. The supply of critical materials for electrochemical and DAC pathways (such as specialized sorbents) remains globally concentrated, which could also lengthen the time it will take for pathways to scale in Massachusetts. While Massachusetts has general supply chains that could be customized and advantaged (e.g., manufacturing, marine transport), it currently lacks several specialized CDR supply chains because of a lack of relevant feedstocks and large infrastructure.

3.1.5 Academic and Innovation Environment

Massachusetts' research institutions, including the Woods Hole Oceanographic Institute (WHOI), the Massachusetts Institute of Technology (MIT), Harvard University, and the University of Massachusetts university system, are world leaders in climate and environmental science and clean energy. The WHOI received a permit from the EPA to conduct a small-scale trial of alkalinity enhancement in the Gulf of Maine, titled LOC-NESS.[87] Additionally, the WHOI has expertise across a range of ocean research topics including the interaction between climate and the ocean, coastal science, ocean chemistry, ocean research tools and technologies, and more. Additionally, MIT is in partnership with CarbonCure, a CDR supplier, to study CO_2 injection and mineralization in concrete.[88] Beyond this partnership, MIT has published research on a variety of CDR topics.[89,90,91] Harvard and UMass similarly have specializations in climate science.[92,93] Overall, Massachusetts ranks as the second highest innovation state in the country and the highest state for technology and science.[94] This capacity enables Massachusetts to act as a leader in early-stage research and field trials for CDR pathways and MMRV.

Despite its academic strength, Massachusetts-specific data gaps persist for several pathways given the early-stage nature of many CDR pathways. Lack of existing long-term field trials in the Commonwealth means there are still many technologies that need to be tested and further developed with the support of Massachusetts stakeholders. Without expanded applied research funding and pilot project development, laboratory innovations may not translate into deployable projects within the state.

3.1.6 Political and Sociocultural Environment

Massachusetts' political environment is strongly supportive of climate action, with a history of supportive climate policies that illustrate a general consensus around the importance of decarbonization and innovation.[95] Beyond policies, Massachusetts residents also view climate change as a serious problem (over 70% of residents as compared to the national average of 63% according to one poll), support a move towards renewable energy (¾ of residents according to one poll), and believe CO_2 should be regulated as a pollutant (80% of residents according to one poll).[96 97] Public familiarity with climate change and clean energy, combined with civic trust in science institutions, can be a helpful starting point for residents learning about CDR. Further, the majority of Massachusetts residents believe climate should be a priority for the President, Congress, state and local officials, corporations, and even individual citizens.[98] This culture of motivation and participation could make Massachusetts a promising place to kickstart transparent, equitable CDR.

Nevertheless, public acceptance risks are significant. CDR is distinct from renewable energy and other decarbonization methods, and concerns exist that CDR deployment excuses deep decarbonization. Uncertainty and concerns about marine ecology, land use, or industrial siting could slow or prevent CDR permitting, especially in coastal communities dependent on fisheries. Although polling shows general support for climate action, communities in Massachusetts, like anywhere, will vary depending on geography, history, demographics, and priorities. It is important that the state clearly articulates the role of CDR in its net zero strategy, tailors conversations about CDR to the variety of communities statewide, and is proactive in garnering feedback from communities about state action on CDR.

3.2 Massachusetts CDR Stakeholder Landscape

In addition to inherent advantages and disadvantages in the state, there are actors that may be relevant to and may benefit from supporting and scaling CDR. This section provides an overview of key actors working on or adjacent to CDR in Massachusetts. For more detailed analyses, see Appendix A; within the analysis for each CDR pathway there are pathway-specific stakeholder landscapes in the subsections titled *local supply chain* and *solution providers*.

3.2.1 Institutional research and development actors

Massachusetts has a variety of institutional research and development actors that are focused on innovation and filling research gaps. As mentioned in the previous section, institutions such as MIT, Harvard, the UMass system, and the WHOI are pursuing research and innovation either directly on CDR or filling research gaps that could support the development of CDR pathways (e.g., ocean chemistry, environmental impacts, etc.). In addition to these research institutions, Cascade Climate, a non-profit working to scale CDR is headquartered in Massachusetts and is especially focused on supporting enhanced weathering pathways by developing databases on MMRV and cost, identifying policy priorities, and granting research funds.

Further, the Greater Boston area is home to nationally recognized hotbeds of innovation. These are areas that have a high density of leading academic institutions and companies that focus on cutting edge research and development. These innovation districts have supported Massachusetts in leading on pharmaceuticals and life sciences and are emerging as support systems for climate technologies broadly. There are opportunities to leverage existing expertise in these areas to create similar support for CDR.[99]

Finally, throughout Massachusetts, there are several existing incubators, accelerators, and other organizations that are supportive of climate technology and could be expanded to support CDR innovation in the state.[100] For example, Greentown Labs is a large climatetech and energy incubator, based in Somerville, Massachusetts, and The Engine is a nonprofit incubator focused on supporting “Tough Tech” companies, based in Cambridge, Massachusetts.[101]

3.2.2 Startups and incumbent private sector actors

Beyond research and innovation institutions, there are several startups and private sector actors in Massachusetts that are beginning to participate in the CDR value chain, including both CDR suppliers and startups working on MMRV technologies. Atdepth MRV is based in Boston and is focused on developing an ocean modeling system that improves the speed of modeling. It is funded by ARPA-E through the SEA-O2 program.[102] Aquatic Labs is another MMRV-focused start-up that works on sensing technologies, including for CDR.[103] Indigo Ag is another company that partners with farmers and conducts MMRV to generate credits from soil carbon.[104] These are just a few examples of start-ups in Massachusetts.[105]

3.2.3 CDR projects, existing and planned

CDR deployment in Massachusetts is still early stage, but there are a few small-scale projects being kickstarted. In April of 2025, the EPA issued a research permit to the WHOI to conduct a field study of alkalinity enhancement in the Wilkinson Basin in the Gulf of Maine.[106] Overall, despite a strong innovation ecosystem for climate solutions, the CDR industry remains nascent, and a robust pipeline of pilots, demonstrations and commercial projects needs more time to develop.

3.2.4 CDR adopters / buyers

Another important component of the CDR ecosystem are those actors who adopt or purchase CDR. A variety of stakeholders can purchase CDR for different aims. For example, many private actors purchase CDR voluntarily to offset emissions and work toward sustainability goals. A high-profile example based in Massachusetts is the Boston Consulting Group (BCG), a management consulting firm. BCG purchased over 50,000 tons of CDR in an effort to neutralize its emissions by 2030.[107] BCG collaborated with ClimeFi, a portfolio manager for CDR with low risk of reversal, to conduct this purchase.

However, there are other stakeholder types that can purchase CDR outside of private, voluntary actors. Some governments have enacted compliance mechanisms, as explore in Section 2, and have included CDR as a type of offset allowed, to varying degrees. However, Massachusetts has not enacted a compliance mechanism that allows for the purchasing of CDR credits. Additionally, governments can be purchasers of CDR to offset their own operations and meet climate goals. Massachusetts has not established a procurement program for CDR, but, as discussed, one aim of this study is to further explore the option of procuring CDR for Massachusetts to meet climate goals.

Beyond credit purchasing, CDR can be adopted through pay for practice programs (or paying for CDR to be done rather than for the final credit). One example of this is paying for farmers to do CDR (such as biochar or enhanced rock weathering) rather than purchasing credits. Massachusetts has the Climate Smart Agriculture Program which lends itself to funding agricultural practices beneficial to the climate, but there is not explicit inclusion of CDR in this program. Potentially integrating CDR into this program will be discussed again in Section 6.

3.2.5 CDR investors

Massachusetts has a network of public and private investors with a portfolio that includes CDR pathways. One venture capitalist in the Commonwealth is the MCJ collective which has invested in CDR companies from Charm Industrial (bioliquid and storage) to Heirloom (DAC).[108] Clean Energy Ventures is another venture capital firm in Massachusetts with carbon removal in their portfolio.[109]

Beyond private investors, there are existing public investors that support CDR pathways. MassCEC is a state agency that disperses grants to a variety of clean energy technology startups. A number of startups working in MMRV technologies have been awarded grants, including atdepth MRV, Yardstick PBC, Haystack Ag, and Aquatic Labs. Additional research at UMass Lowell and Harvard University in carbon dioxide removal has been funded through the Catalyst grant program. At least three companies developing novel CDR technologies have been funded through grant programs, including Elimentra, Verdox, and Anvil Capture Systems.[110] Additionally, MassCEC awarded pre-seed funding to BlueShift, a geochemical CDR company, in March of 2025.[111]

4 CDR Pathway Suitability Methodology

This Study aims to provide an assessment of a variety of CDR pathways and their suitability for the state of Massachusetts, either to deploy in an effort to meet GHG limits or to support through R&D to become a leader in the space. Section 4 defines the CDR pathways that were analyzed and the methodology used to determine suitability for Massachusetts.

4.1 Pathway Taxonomy and Glossary

CDR pathways are specified using the taxonomy in RMI's Applied Innovation Roadmap for Carbon Dioxide Removal, with some adjustments, which categorizes CDR methods into biogenic, geochemical, and synthetic removal pathways and CO_2 storage, as outlined below.[112] Definitions for forests, agricultural soils, salt marshes, and marine permaculture were adapted from Griscom et al.[113]

Figure 4-1: Portfolio of CDR Pathways

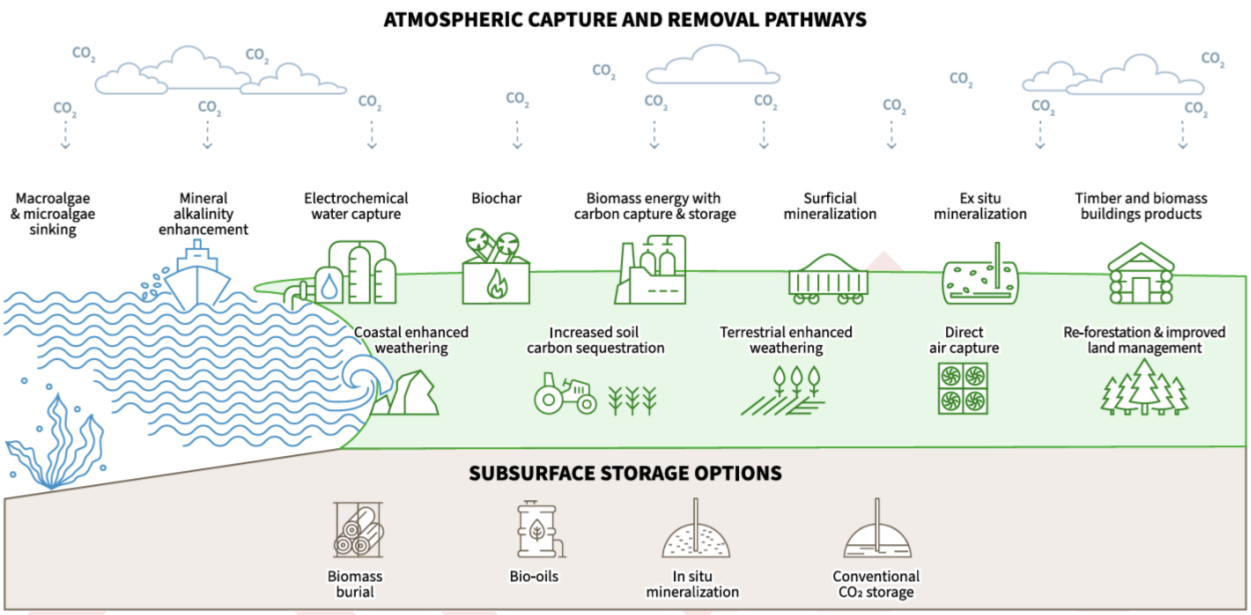


Figure 4-1. Portfolio of CDR pathways. Figure sourced from RMI's Report: From Trees to Tech and Beyond: Carbon Dioxide Removal (CDR) in All Its Variations[114]

Biogenic CDR - includes any CDR pathway that uses naturally occurring, biomass-based processes, such as photosynthesis, to capture CO_2 from the atmosphere.

- **Forests** - Conservation, restoration, and improved management of forests to enhance atmospheric carbon removal. Methods considered are changing harvesting practices, afforestation, and reforestation.
- **Agricultural soils** - Implementing agricultural management practices that increase carbon storage in soil and build soil health. This includes methods such as reduced tillage, perennialization, cover cropping, double cropping, crop rotation, managed grazing, and compost application.
- **Salt marshes -** Conservation, restoration, and improved management of salt marshes to maintain and re-establish their ability to act as carbon sinks.

- **Biomass direct storage** - Storing terrestrial biomass underground or other environments with conditions to prevent significant decomposition. In practice, biomass direct storage may look like taking forestry residues and storing them in a vault underground.
- **Timber building products** - Using timber products to leverage the carbon removal of trees and store it as long-lived building materials, especially structural wood products. A project could include using cross laminated timber in building construction.
- **Other biomass building products** - Converting biomass, including purpose grown crops, algal, and fungal matter, agricultural and forestry waste, and synthetic biomaterial, into construction products and component materials other than timber. These building products may include polymers, fibers, framing, and paneling.
- **Pyrolysis (biochar) and storage** - Thermal conversion of biomass while excluding oxygen, optimized to produce solid char for storage in open or controlled environments. In practice, biochar is often added to fields or soils as a soil amendment. Additionally, biochar can be combined with compost, added to concrete, or buried as stable carbon.
- **Pyrolysis (bioliquid) and storage** - Thermal conversion of biomass while excluding oxygen, optimized to produce crude bioliquid that can be stored underground, geologically, or in other environments. A project could include taking agricultural waste, turning it into bioliquid, and then injecting it underground.
- **Microalgae in ponds** - Harvest and storage of microalgae biomass grown in land-based systems. This can include growing algae in raceway ponds or bioreactors, then cultivating, drying, and burying the algae.
- **Microalgae in open water** - Sinking microalgae, either cultivated or grown naturally, in open water environments. A project could include adding nutrients to the ocean to create algal blooms, then sinking the algae into the deep ocean.
- **Macroalgae in open water** - Enhancing macroalgae growth either in cultivated algae farms or in the open ocean, then sinking the biomass in the open ocean. A project could include growing algae on buoys, collecting the algae, and sinking it into the deep ocean.
    - **Marine permaculture** - The cultivation of marine biomass, such as kelp and seagrasses, to enhance atmospheric carbon removal. If the marine biomass is harvested and sequestered, it becomes the CDR pathway macroalgae in open water.
- **BECCS to electricity**- Thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO_2 that is captured with CCS technology. A project could include combusting biomass waste to generate electricity, then capturing and sequestering the CO_2 produced.
- **BECCS to fuels** - Thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO_2 that is captured with CCS technology. A project could include converting biomass waste to liquid fuels, then capturing and sequestering the CO_2 produced.

Geochemical CDR - pathways that use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.

- **Surficial (solid carbonate) mineralization** - Enhancing the natural capacity of excavated or processed alkaline feedstock to passively react with atmospheric CO_2 – through crushing, grinding, spreading, heating, or other physical or chemical means – to form solid carbonate minerals. In practice, this means exposing reactive mine wastes, such as nickel or asbestos mine tailings, excavated rock, or recycled concrete fines and some ashes, to air, potentially after processing steps like crushing and spreading. This process produces stable carbonate minerals that lock away CO_2.

- **Terrestrial enhanced weathering** - Acceleration of the natural geologic weathering process through the spreading of finely ground alkaline materials in agricultural, urban, or forest soils, where it reacts with CO_2 and water to produce dissolved inorganic carbon. A project may include spreading alkaline minerals, such as basalt, onto farmland.
- **Coastal enhanced weathering** - Distribution of crushed or pulverized alkaline minerals onto beaches and coastal shelves where it reacts under water with CO_2 to produce dissolved inorganic carbon. A project may include spreading alkaline minerals, such as olivine, onto coastal areas like beaches.
- **Mineral alkalinity enhancement** - Direct addition of alkaline minerals to lakes, oceans, rivers, wastewaters, or other bodies of water to increase the alkalinity of the water and its capacity to absorb CO_2. In practice, mineral alkalinity enhancement can include adding alkaline minerals to the open ocean or to wastewater treatment facilities.

Synthetic CDR - pathways that use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it, or to alter water chemistry to indirectly remove CO_2 from the air.

- **CO_2 stripping** - Electrochemical processes that split water from oceans, lakes, or other bodies of water into acid and base streams, then use the acid stream to push dissolved CO_2 out of the water to be captured, and, finally, recombine the acid and base streams to re-neutralize the water and return it to the source. A project could include a facility that takes in ocean water, uses electrochemistry to remove a stream of CO_2, and then store that CO_2.
- **Electrochemical alkalinity production** - The use of electrochemistry to create alkalinity that is added to the ocean or another body of water, enabling it to absorb additional CO_2. This is performed by either changing the pH of a stream of water with electricity in a wastewater treatment facility to enable the water to uptake additional CO2 or by splitting ocean water into acid and base streams with electricity, then using the base stream to raise the pH of seawater locally while the acid stream is removed or disposed of elsewhere.
- **Direct air capture** - Approaches that use machines to capture CO_2 from the atmosphere in a concentrated stream. A project could include a facility that takes in air from the atmosphere, uses chemistry to remove a stream of CO_2, and then stores that CO_2.

CO_2 storage - pathways that store captured and concentrated streams of CO_2 through trapping, mineralization, or other physical or chemical processes.

- **Conventional storage** - Storage of CO_2 by injection into depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization rates in order to confine the CO_2 underground via structural, residual, or solubility trapping. A project could include injecting a stream of CO_2 into a saline aquifer deep underground.
- **In-situ mineralization** - Circulation of either supercritical CO_2 or CO_2-rich fluid through subsurface alkaline rocks, stabilizing carbon underground via mineral trapping, i.e., conversion to solid carbonate minerals. A project could include injecting a stream of CO_2 into underground basaltic rock formations.
- **Ex-situ mineralization** - Reacting CO_2 with either natural alkaline minerals or artificial alkaline byproducts and wastes in engineered reactors, rather than under ambient conditions. These reactions typically go to completion within minutes using high temperatures, pressures, electrochemistry, and/or pH changes to accelerate the mineralization process. A project could include reacting a stream of CO_2 with alkaline minerals in a reactor to produce solid carbonate minerals that can be integrated into aggregates.

Given the geography of Massachusetts, exploring the opportunity presented by marine CDR pathways is of particular relevance to the state. These pathways are not grouped into a single category in this report but can be found in the sections indicated in the table below.

Table 4-1: Marine CDR Pathway Mapping

Marine CDR pathway	Report location
Blue carbon restoration and carbon sequestration	Salt marshes
Ocean electrochemical alkalinity enhancement	Electrochemical alkalinity production
Ocean mineral alkalinity enhancement	Mineral alkalinity enhancement
Coastal enhanced weathering	Coastal enhanced weathering
Marine permaculture; macroalgae cultivation and carbon sequestration	Macroalgae in open water
Deep ocean sequestration and storage of biomass	Microalgae in open water Macroalgae in open water
Microalgae cultivation and carbon sequestration; nutrient fertilization in ocean	Microalgae in open water
Direct ocean capture	CO_2 stripping

Table 4-1: Marine CDR Pathway Mapping

There are also multiple CDR pathways that involve the addition of alkalinity directly or indirectly to water to remove CO_2 from the atmosphere that are relevant to Massachusetts for deployment or for R&D opportunities. These pathways are distinguished in the report by their location and mode of application, as outlined in the table below.

Table 4-2: Differences in Pathways with Alkalinity Addition to Water

CDR pathway	Succinct definition	Key characteristics
Terrestrial enhanced weathering	Direct addition of alkaline materials to soils, which react with CO_2 and water to form dissolved inorganic carbon	• Requires alkaline materials • Application is on land, by spreading onto soils
Coastal enhanced weathering	Direct addition of alkaline materials to beaches and coastal shelves, which react underwater with CO_2 to form dissolved inorganic carbon	• Requires alkaline materials • Application is on beaches or coastal shelves, by spreading
Mineral alkalinity enhancement	Direct addition of alkaline minerals to the ocean, wastewater, and other bodies of water to increase the alkalinity of the water and its ability to absorb CO_2	• Requires alkaline minerals • Application is directly in water or integrated with water treatment facilities
Electrochemical alkalinity production	Using electrochemistry to create alkalinity that is added to a body of	• High energy requirements to create alkalinity

CDR pathway	Succinct definition	Key characteristics
	water, to increase the alkalinity of the water and its ability to absorb CO_2	• Application is directly in water or integrated with water treatment facilities

Table 4-2: Differences in Pathways with Alkalinity Addition to Water.

4.2 Pathway Characteristics Glossary and Rating Methodology

Each of the 23 pathways mentioned in Section 4.1 was evaluated across ten different characteristics, as described below. These characteristics were determined by the authorizing legislation (see Appendix F for more information).

Cost – Range of current cost per net ton removed and assessment of potential for future cost reduction.

The cost of each pathway indicated in this Study represents the total cost to implement that pathway. These values do not take into account marginal costs (e.g., if a CDR pathway produces an output in addition to carbon removal or if the CDR pathway uses a resource, such as land, that could be used for other applications). Costs are presented as ranges sourced from literature, are given in US dollars per ton removed, and do not include tax incentives. Cost estimates are based on national and international data, and so additional analysis of site-specific costs in Massachusetts will be important to conduct, beyond this Study. Consideration of how resource requirements and availability will affect costs in Massachusetts is qualitatively discussed in the cost subsections of Appendix A. The cost range is intended to include MMRV costs; however, MMRV is still developing for many pathways and so the total MMRV cost is highly uncertain.[115] MMRV cost uncertainty is factored into the potential for future cost reduction as described below.

The potential for future cost reduction is assessed on a low, medium, high scale. The ratings are anchored on a technology's learning rate potential (see Appendix D for more information) and then adjusted based on the potential for technology development not related to scale, process improvement not related to scale, resource constraints, and MMRV uncertainty:

- **Low** - A low learning rate; a medium learning rate with the potential for resource constraints and/or MMRV uncertainty
- **Medium** - A medium learning rate; a high learning rate with the potential for resource constraints and/or MMRV uncertainty; a low learning rate with the potential for technology development and/or process improvement
- **High** - A high learning rate learning rate; a medium learning rate with the potential for technology development and/or process improvement

Duration – Risk of reversal of CO_2 storage for a pathway over relevant timeframes and the operating life of plants/projects.

While this Study evaluates risk of reversal, it is not considered in the final deployment suitability rating. The way that Massachusetts deals with risk of reversal will be important to decide moving forward, and additional information can be found in Section 6.4.3. The risk of reversal is evaluated as:

- Significant over 100 years
- Significant over 1000 years

- Negligible over greater than 10,000 years

The operating life of plants/projects is given in years.

Technology readiness level (TRL) – The degree of technology maturity for a pathway. TRL can range from 1 (very early-stage, fundamental research) to 9 (commercially deployed at scale). See Appendix C for more information.

Measurement, monitoring, reporting, and verification (MMRV) – Readiness of the standards and technology for the measurement, monitoring, reporting and verification of carbon removal for a pathway.

MMRV readiness is rated as early stage, developing, or established:

- **Early stage** - High uncertainty in MMRV; no existence of registry-approved MMRV methodologies
- **Developing** - Uncertainty in some parts of MMRV; existence of one to two registry-approved MMRV methodologies
- **Established** - Limited uncertainty in MMRV or a widely accepted way to address uncertainty; existence of multiple registry-approved MMRV methodologies

Deployment timelines – Estimated lead times and projected start times of CDR activities for a pathway.

Resource requirements – Use of water, land area (or ocean area), energy, and major feedstock (i.e., biomass, alkaline minerals) for a pathway. Resource requirements are rated as low, medium, or high, based on a relative scale across CDR pathways. For ranges, the average is used for evaluation.

- Water
  - **Low** - near zero consumptive water use;
  - **Medium** - non-negligible consumptive water use, but less than 5 t water per tCO_2
  - **High** - 5 t water per tCO_2 or greater
- Land
  - **Low** - near zero land footprint
  - **Medium** - non-negligible dedicated land use, but less than 0.1 hectare (ha) per tCO_2
  - **High** - 0.1 hectare (ha) per tCO_2 or greater of dedicated land use
- Energy
  - **Low** - near zero dedicated energy use
  - **Medium** - non-negligible dedicated energy use, but less than 5 Gigajoule (GJ) per tCO_2
  - **High** - 5 Gigajoule (GJ) per tCO_2 or greater of dedicated energy use
- Feedstock
  - **Low** - near zero major feedstock use
  - **Medium** - non-negligible feedstock use, but less than 2 t feedstock per tCO_2
  - **High** - 2 t feedstock per tCO_2 or greater

Local Supply Chain Relevance - The extent to which CDR would involve purchases of equipment and supplies from businesses located in Massachusetts.

- **Low –** 0 or 2 sectors with significant Massachusetts presence stand to gain significant economic benefit from the deployment of the CDR pathway within Massachusetts via the production of components, supply of materials, provision of services, etc.

- **Medium –** 3 to 4 sectors with significant Massachusetts presence stand to gain significant economic benefit from the deployment of the CDR pathway within Massachusetts via the production of components, supply of materials, provision of services, etc.
- **High –** 5 or sectors with significant Massachusetts presence stand to gain significant economic benefit from the deployment of the CDR pathway within Massachusetts via the production of components, supply of materials, provision of services, etc.

Scale and growth – Estimated maximum deployment possible in Massachusetts, and risks to deployment growth in Massachusetts. Both the scale potential and risks to growth are evaluated as follows:

Scale Potential: Massachusetts is required to reduce emissions by 85% relative to the 1990 baseline level and to achieve net zero by 2050. Therefore, up to 15% of the 1990 baseline level emissions may be used to achieve this target, which is equal to approximately 14 million tCO_2e per year under accounting used in the CECP for 2050. For ranges, the average is used for evaluation.

- **Low** - Removals from the CDR pathway within Massachusetts have the potential to generate less than 1 million tCO_2e per year (<7% of the 15% allowed removals).
- **Medium** - Removals from the CDR pathway within Massachusetts have the potential to generate between approximately 1 to 3 million tCO_2e per year (7-20% of the 15% allowed removals).
- **High** - Removals from the CDR pathway within Massachusetts have the potential to greater than approximately 3 million tCO_2e per year (>20% of the 15% allowed removals).

Please note that the scale estimates represent the potential deployment scale if all of one of the state's resources (e.g., biomass, coastal area) were devoted to a CDR pathway. These values are not an estimate of the likely deployment scale in Massachusetts. They are an overestimate due to feasibility limits discussed in the risks to growth sections of the report.

***Risks to Growth*:** Factors that limit the feasibility or advisability of deployment for a pathway.

- **Low –** Few (0-2) risks exist to deployment of the CDR pathway within Massachusetts, and none of the risks are high impact.
- **Medium –** Risks to deployment of the CDR pathway within Massachusetts do not meet the criteria for the Low or High ratings.
- **High –** Multiple (2 or more) high impact risks with medium or high probability exist to deployment of the CDR pathway within Massachusetts.
- **High/medium/low probability –** How likely/unlikely the risk is to occur
- **High/medium/low impact –** How severe the impact would be if the risk occurs, (e.g., deployment could not take place if a high impact risk occurs)

Co-benefits and potential negative impacts – Social, ecological, and health co-benefits and risks/concerns associated with operations.

- **Negative** - Has 1 or more negative impacts that are not manageable by current regulations or safety protocols
- **Neutral** - Has very few co-benefits and all negative impacts are manageable by current regulations or safety protocols
- **Positive** - Has 1 or more co-benefits and all negative impacts are manageable by current regulations or safety protocols

Economic benefit and job creation – Estimate of the number of jobs (research and development, construction, and operations) that could potentially be created by CDR activities and an estimate of potential economic benefit to disadvantaged communities (DACs).

The total number of jobs is calculated by multiplying a pathway's scale potential (in millions of tons) by the jobs it would create per million ton. For ranges, the average is used for evaluation. The total number of jobs is rated as high, medium, or low as follows:

- **High total jobs** - greater than 3,000 jobs
- **Medium total jobs** - between 1,000 and 3,000 jobs
- **Low total jobs** - less than 1,000 jobs

The overall job rating is then based on the rating for the number of jobs and then adjusted as follows:

- **High** - High total jobs; medium total jobs and all of: high jobs per million ton (>2,000 jobs per million ton), high jobs per dollar (50 jobs per million dollars), potential economic benefits to DACs
- **Medium** - Medium total jobs; low total jobs and all of: high jobs per million (>2,000 jobs per million ton), high jobs per dollar (50 jobs per million dollars), potential economic benefits to DACs
- **Low** - Low total jobs

With this method of calculation, a pathway's research and development jobs depend on the scale of deployment in Massachusetts. This may not necessarily be true, because research and development jobs for a pathway can occur in Massachusetts even if deployment is happening globally. Research and development jobs may more likely be determined by the state's investment and support for CDR innovation.

4.2.1 Additional context on disadvantaged communities

In Massachusetts, disadvantaged communities (DACs) are defined as communities that fall into one of three tiers using the adjusted per capita income (APCI) of each city and town in Massachusetts compared to the state overall. APCI is a metric based on per capita income, employment rate, and population change. Tier 1 communities have an APCI of more than 80% but less than 100% of the state's APCI; Tier 2 communities have an APCI between 60% and 80% of the state's APCI; Tier 3 communities have an APCI less than 60% of the state's APCI.[1]

As required by the authorizing legislation, this Study includes consideration of economic benefits to DACs in the job creation section of each pathway. Because Massachusetts' definition for DACs is based primarily on geographic specification of economic factors like per capita income and employment rate, economic benefits to DACs are assessed based on whether a pathway is likely to be located near or disproportionally employ members of DACs.

This Study also includes a co-benefits and negative impacts section for each CDR pathway that includes potential social, environmental, and health co-benefits and risks. Although the discussion in these sections is not limited to DAC populations, benefits or risks that may be relevant to these populations have been noted in some cases. Additionally, categories of CDR pathways may have similar impacts on DAC populations, and these are noted below.

- **Biogenic –** Pathways that rely on biomass as a feedstock could provide DACs with opportunities to utilize residue biomass in ways that reduce environmental concerns and provide revenue. However, if these pathways rely on purpose-grown biomass, resource use change could pose a threat to DACs through, e.g., land loss, rising food prices, and water scarcity.
- **Geochemical –** Pathways that rely on alkaline minerals as a feedstock could provide DACs with possible revenue streams (e.g., TEW on farms) while also managing pH of soil and waterways. However, if proper safeguards are not in place, leaching could occur which can contaminate groundwater.
- **Synthetic –** Pathways that rely on low-carbon energy as a feedstock could strain energy access for DACs.
- **Storage –** Pathways that store a concentrated stream of CO_2 usually require large scale infrastructure development and might pose land use change and other risks to DACs.

Overall, each CDR pathway and project will vary, and it is important that the needs of DACs are understood and prioritized early and throughout project development. It is important that the Massachusetts government support and elevate the perspectives of communities when developing CDR programs.

4.3 Suitability Evaluation

Each pathway is evaluated on its suitability for Massachusetts across two dimensions: 1) the suitability for deployment in Massachusetts, in the context of the state's climate goals, and 2) the potential for Massachusetts to lead on research and development (R&D) and enable the state to have an outsized economic impact through R&D jobs. Each suitability rating depends on the ratings of a pathway's characteristics (described in the section above), using the methodology described below.

Deployment suitability is defined as the potential for Massachusetts to use a CDR pathway to achieve its climate goals (CDR goals) in a safe, sustainable, efficient, cost-effective way. These criteria map to the pathway characteristics as described in Table 4-3.

Table 4-3: Deployment Suitability Methodology

Deployment suitability criteria	Pathway characteristic(s)
Potential to achieve the state's climate goals	• Scale potential • Risks to growth
Safety of a pathway	• Potential negative impacts
Sustainability of a pathway	• Resource requirements
Efficiency of a pathway	• Co-benefits • Job creation • Local supply chain
Cost-effectiveness of a pathway	• Cost and cost reduction potential

Table 4-3: Deployment Suitability Methodology. Deployment suitability characteristics and the corresponding pathway characteristics.

The deployment suitability rating is driven initially by the scale potential rating. If a pathway has a limited potential for deployment at scale within the state, then it is unlikely that the pathway can contribute to reaching the state's climate goals. Conversely, if a pathway has a high potential for deployment within

Massachusetts, then that pathway is more likely to be well-suited to help achieve the state's climate goals.

However, all pathway characteristics described in the table above impact the suitability for deployment of a pathway within Massachusetts. For example, a pathway may not be well-suited for deployment even with a high scale potential if there are significant risks to growth or potential negative impacts. The deployment suitability ratings are therefore adjusted based on these characteristic ratings.

Finally, each overall deployment suitability rating is evaluated by expert judgment, to ensure that the result from combining multiple pathway characteristic ratings makes sense within the context of Massachusetts and the CDR field. For example, deployment suitability ratings may be modified due to expert understanding of a pathway's uncertainty and the quality of available data. Deployment suitability ratings may also be modified due to expert understanding of existing, complementary efforts in the state. These ratings also incorporated feedback from Massachusetts state experts and CDR subject matter experts, including academics, practitioners, and the CDR initiative at RMI.

R&D leadership potential is defined as the potential for Massachusetts to lead on innovation for a CDR pathway and drive disproportionate economic impact through R&D jobs. R&D leadership potential was evaluated by considering the state of development for the pathway (e.g., whether the pathway is low TRL, whether there are many open questions on MMRV), the current landscape of R&D for the pathway (e.g., whether innovation hubs already exist), and the potential resources Massachusetts already has to lead on R&D (e.g., existing research institutions, access to important resources).

Similar to deployment potential, each R&D leadership potential rating is validated by expert judgment, to ensure that the result from combining multiple pathway characteristic ratings makes sense within the context of Massachusetts and the CDR field. For example, R&D leadership ratings may be modified based on expert understanding of the potential for innovation in a pathway. These ratings also incorporated feedback from Massachusetts state experts and CDR subject matter experts, including academics, practitioners, and the CDR initiative at RMI.

5 CDR Pathway Suitability Assessment

The results of the analysis described in Section 4 are discussed in Section 5 of the study, including an overview table that summarizes the conclusions for each pathway and a section that categorizes pathways into likely to be well-suited, possibly well-suited, or unlikely to be well-suited for deployment and R&D leadership in the state. For more details, see Appendix A, which is the technical assessment of each CDR pathway. This section also provides policy options that Massachusetts could decide to pursue to fill identified gaps for each CDR pathway is rated as likely or possibly well-suited.

5.1 Table 5-1: CDR Pathway Assessment and Conclusions

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($\$/tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
Forests *biogenic*	Medium	High	High (5.0-6.0)	Medium	1-80	Low	Positive	9
Agricultural soils *biogenic*	Medium	Medium	Low (0.01-0.4)	Medium	5-25	Low	Positive	9
Salt marshes *biogenic*	Medium	Medium	Low (0.04-0.1)	Medium	25-45	Low	Positive	9
Biomass direct storage *biogenic*	High	Medium	Medium (0.8-1.2)	Low	10-60	Medium	Positive	6-8
Timber building products *biogenic*	Medium	Medium	High (4.5)	Medium	500-1,500	Low	Positive	9
Other biomass building products *biogenic*	Low	Medium	Low (0.1)	High	50-10,000	Medium	Positive	9
Pyrolysis (biochar) and storage	Medium	Low	Low (0.4- 1.1)	Low	10-350	Medium	Positive	7-9

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($\$/tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
biogenic								
Pyrolysis (bioliquid) and storage *biogenic*	Medium	Medium	Low (0.4-0.5)	Medium	450-600	Medium	Positive	6-7
Microalgae in ponds *biogenic*	Low	Low	High (1.8-7.8)	High	250-1,200	Medium	Neutral	7-8
Microalgae in open water *biogenic*	Low	High	Unknown	High	7-1,500	Medium	Negative	3-4
Macroalgae in open water *biogenic*	Low	High	Unknown	High	480-17,000	Medium	Neutral	4-6
Bioenergy with carbon capture and storage (BECCS) to electricity *biogenic*	Low	Medium	Low (0.6-1.0)	High	75-300	Low	Neutral	6-8
Bioenergy with carbon capture and storage (BECCS) to fuels *biogenic*	Low	Low	Low (0.1-1.0)	High	75-300	Low	Neutral	9
Surficial mineralization *geochemical*	Low	Low	Low (0.6-1.2)	High	55-500	Medium	Neutral	5-6
Terrestrial enhanced weathering	High	Medium	High (3.1-11.7)	Medium	50-500	Medium	Neutral	6-7

Draft, for consideration, not final

Pathway	Deployment Suitability	R&D Leadership Potential	Scale Potential (million tCO_2/ year)[i]	Risks to Growth	Current Cost Range ($/$tCO_2$)	Cost Reduction Potential	Co-benefits and impacts	Technology Readiness Level
geochemical								
Coastal enhanced weathering *geochemical*	Low	High	Low (0.04-0.1)	High	55-225	Medium	Neutral	5-6
Mineral alkalinity enhancement *geochemical*	Medium	High	Medium (1.5-2.0)	High	55-225	Medium	Neutral	4-6
CO_2 stripping *synthetic*	Medium	High	Medium (1.5-2.0)	High	400-2,400	Medium	Negative	5-6
Electrochemical alkalinity enhancement *synthetic*	Medium	High	Medium (1.5-2.0)	High	400-2,400	High	Neutral	5-6
Direct air capture *synthetic*	Medium	Medium	High (1.8-4.1)	Medium	500-2,000	Medium	Neutral	2-9
Conventional storage *CO_2 storage*	Low	Low	Low (0.0)	High	10-30	Low	Neutral	9
In-situ mineralization *CO_2 storage*	Low	Low	Low (0.0)	High	10-400	Medium	Neutral	7-8
Ex-situ mineralization *CO_2 storage*	High	High	High (19.5)	Medium	10-600	High	Neutral	6-7

1

Draft, for consideration, not final

Table 5-1: CDR Pathway Assessment and Conclusions. The column outlined in red, deployment suitability, or the suitability for a pathway to help Massachusetts achieve its climate goals, is the main finding of this report. This rating is determined using the other characteristics outlined in this table. More details can be found in Section 4, CDR Pathway Suitability Methodology. [i]Scale estimate is not an estimate of the likely deployment scale in Massachusetts. It is an overestimate due to feasibility limits discussed in the risks to growth sections of the report.

5.1.1 Deployment suitability

Throughout this report, pathways are evaluated based on whether they are suitable for deployment in Massachusetts, especially focused on whether they could be deployed at a scale to have impact on Massachusetts' climate goals. This section summarizes which pathways are likely to be well-suited, possibly well-suited, or unlikely to be well-suited for deployment. This rating is distinct from R&D leadership potential which means, even if a pathway is well-suited for deployment, it may not be well-suited for R&D in the state, or, even if a pathway is not well-suited for deployment, it may be well-suited for R&D leadership. For more information on these pathways, see Section 4 and Appendix A.

Pathways likely to be well-suited for deployment

There are three CDR pathways that are likely to be well-suited for deployment in Massachusetts for a variety of reasons. We include policy options that the state of Massachusetts can consider to support the research, scale-up, and deployment of these pathways to help meet climate goals, create co-benefits in the state, create jobs, and take advantage of local supply chains.

- **Biomass direct storage –** Biomass direct storage is well-suited to Massachusetts as a pathway for deployment. Given Massachusetts has available biomass residue such as agricultural and forestry wastes in state, there is a moderate potential scale of deployment. Limited risks to growth due to the use of waste biomass as feedstock, limited land, water, and energy needs, and locations within the state for suitable deployment increases the ability of biomass direct storage to contribute to Massachusetts' climate goals. Additionally, Massachusetts already has a local supply chain that could aid in biomass direct storage deployment and biomass direct storage is already low-cost compared to other CDR pathways.
  Policy options
    - Consider funding pilot projects in the state that are diverse in biomass used (e.g., forest, agricultural, or municipal waste) and burial technology (e.g., wood vaults, underground slurry injection). Report findings related to cost, removal efficiency, resource use, and other important metrics.
    - Consider, in the state's work to clarify permitting for all CDR pathways, a carve out for biomass direct storage projects under existing solid waste management regulations.
- **Terrestrial enhanced weathering -** Terrestrial enhanced weathering is likely to be well-suited as a pathway for deployment. This rating is driven by the high scale potential of the pathway, which stems from the significant farmland and forest area in the state that could be suitable for alkaline mineral application, due to low pH levels. Additionally, there is the potential for terrestrial enhanced weathering to be integrated into state pH management programs, which could facilitate deployment as a co-benefit.
  Policy options
    - Explore enacting rigorous standards for the amount and rate of addition of minerals to farmlands and other lands to prevent potential harms from metals leaching.
    - Explore regional partnerships to establish a regional soil pH management regime that utilizes terrestrial enhanced weathering. Build on existing regional efforts and leverage existing programs at the federal level.
- **Ex-situ mineralization -** Ex-situ mineralization is likely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the high scale potential for deployment in the state, due to the state's large production of aggregate that ex-situ mineralization could be integrated into. Additionally, due to this high scale potential, there is a significant opportunity for job creation from ex-situ mineralization in the state. However, taking advantage of this large-

scale potential means that Massachusetts will need to convert to low-carbon aggregate, which is more expensive than conventional aggregate.

Policy options

- Consider establishing Massachusetts grants or tax credits for ex-situ mineralization projects that use locally available industries (e.g., concrete) to capture and store CO_2.
- Explore launching a state or municipal procurement program of concrete that has been produced using ex-situ mineralization.

Pathways possibly well-suited for deployment

There are ten CDR pathways that may be well-suited to Massachusetts depending on support actions the state decides to take. The Study recommends Massachusetts further explores the barriers to scaling these pathways and determines whether they should be priority pathways to meet climate goals.

- **Forests -** Forests are possibly well-suited to Massachusetts as a pathway for deployment. This rating is driven by the potential for large scale deployment in the state, due to the presence of suitable land, such as existing timber forests for improved management practices, though there will be competing land uses. Forests also have the potential to create significant jobs and take advantage of a local supply chain. However, forests as a CDR pathway face unanswered questions on additionality, which will be important for the state to address if relying on this pathway for CDR. Forests also face a significant risk of reversal over 100 years. For example, if trends within the state continue and forest acreage decreases as land is developed, any previously stored carbon from the forest will be re-released to the atmosphere. The state will have to consider these potential impacts if using forests for CDR deployment.

  Policy Options

  - Consider increasing funding for incentives for private landowners in Massachusetts to enroll in long-term forest conservation and stewardship programs (e.g., through grants or tax credits) building on the existing Climate Forestry initiative.[116]
- **Agricultural soils –** Agricultural soils are possibly well-suited to Massachusetts as a pathway for deployment. Limited farmland within the state limits the maximum scale of deployment, which in turn limits the opportunity for job creation from agricultural soils. However, a strong local supply chain and existing agricultural industry within the state provides infrastructure that can help enable deployment. Like forests, agricultural soils as a CDR pathway face unanswered questions on additionality, which will be important for the state to address if relying on this pathway for CDR.

  Policy Options

  - Explore integrating incentives for agricultural soil practices with a specific focus on CDR into existing agricultural programs, such as the Climate Smart Agriculture Program.[117]
- **Salt marshes -** Salt marshes are possibly well-suited to Massachusetts as a pathway for deployment. This rating may seem contradictory to the low scale potential for deployment in the state (although salt marshes are efficient at removing carbon per square foot, there is limited available salt marsh area within the state). However, low resource requirements, significant co-benefits such as habitat and flood protection, and existing momentum in the state on salt marsh restoration increases the likelihood of deployment. Like forests and agricultural soils, salt marshes as a CDR pathway face unanswered questions on additionality, which will be important for the state to address if relying on this pathway for CDR.

  Policy Options

  - Consider additional funding to develop and implement a carbon removal program through salt marsh restoration that builds on the Massachusetts Blue Carbon Incentives Program Feasibility Study.[118]

- **Timber building products -** Timber building products are possibly well-suited to Massachusetts as a pathway for deployment. This rating is driven by the high scale potential for deployment in the state, due to the state's available timberland. Additionally, due to this high scale potential, there is a significant opportunity for job creation from timber building products. However, timber building products as a CDR pathway do face unanswered questions on additionality, which will be important for the state to address if counting on this pathway for its CDR needs. Timber building products also face a significant risk of reversal over 100 years, which the state will need to consider, and is resource intensive, which leads to an overall rating of medium.

  Policy Options
  - Explore replicating the Boston Mass Timber Accelerator for other cities in Massachusetts that could benefit from large scale timber building product roll-out, especially dense areas undergoing rapid development.[119]
  - Consider modeling a building certification program after Massachusetts LEED Plus program to incentivize use of timber building products to make building development more sustainable and possibly net-negative.[120]
- **Pyrolysis (biochar) and storage –** Pyrolysis (biochar) and storage is possibly well-suited to Massachusetts as a pathway for deployment. However, pyrolysis (biochar) and storage has a low scale potential for deployment in the state. Although biochar can use the same biomass residue in state as biomass direct storage, including agricultural and forestry wastes, the pyrolysis process reduces the total carbon stored in the biomass. Due to this lower scale potential, there is also limited opportunity for job creation from biochar and storage. However, minimal risks to growth and potential co-benefits increases the likelihood of deployment, resulting in an overall deployment suitability rating of medium.

  Policy Options
  - Explore how best to support logistics and infrastructure (e.g., biomass collection, transportation, storage facilities) through regional planning in Massachusetts so biochar projects might scale cost-effectively.
- **Pyrolysis (bioliquid) and storage –** Pyrolysis (bioliquid) and storage is possibly well-suited to Massachusetts as a pathway for deployment. However, this pathway has a low scale potential for deployment in the state. Although bioliquid can use the same biomass residue in state as biomass direct storage, including agricultural and forestry wastes, the pyrolysis process reduces the total carbon stored in the biomass. Due to this low scale potential, there is also limited opportunity for job creation from bioliquid and storage. However, high local supply chain relevance increases the likelihood of deployment, resulting in an overall deployment suitability rating of medium.

  Policy Options
  - Explore funding and permitting small modular pyrolyzers that convert waste wood, forestry residues, or agricultural biomass into stable bioliquid. Streamline permitting for projects utilizing modular pyrolyzers.
- **Mineral alkalinity enhancement -** Mineral alkalinity enhancement is possibly well-suited to Massachusetts as a pathway for deployment. This rating is driven by the moderate scale potential of the pathway, which depends on the rate of alkalinity that can be added to the ocean or wastewater without causing secondary precipitation, which would reduce the total CO_2 removed. Open MMRV questions as well as questions around ocean health impacts will need to be answered before large-scale deployment, which pose a high risk to growth. Community engagement will also be essential before any deployment, to ensure any potential impacts on surrounding communities such as fishers are minimized.

  Policy options

- Consider hosting workshops, modeled on existing projects in Washington, to understand perspectives around MAE, especially from coastal communities and workforces in Massachusetts.[121]

- **CO_2 stripping -** CO_2 stripping is possibly well-suited to Massachusetts as a pathway for deployment. This rating is driven by the moderate scale potential of the pathway, which depends on the rate of alkalinity that can be added to the ocean without causing secondary precipitation, which would reduce the total CO_2 removed. Additionally, the state's lack of in-state geologic storage means that any CO_2 captured from CO_2 stripping will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges. The high energy requirements of CO_2 stripping will need to be met with clean energy to ensure net overall carbon removal.

  Policy options
  - Encourage co-location of CO_2 stripping facilities in Massachusetts with existing industrial sites (e.g., wastewater treatment facilities) to reduce infrastructure cost.
  - Assess acid byproduct offtake opportunities to create additional revenue from CO_2 stripping projects and reduce hazard of large-scale acid production.
- **Electrochemical alkalinity production -** Electrochemical alkalinity production is possibly well-suited to Massachusetts as a pathway for deployment. This rating is driven by the moderate scale potential of the pathway, which, like MAE, depends on the rate of alkalinity that can be added to the ocean without causing secondary precipitation, which would reduce the total CO_2 removed. Open MMRV questions will also need to be answered before large-scale deployment, which pose a high risk to growth. Additionally, the high energy requirements will need to be met with clean energy to ensure net overall carbon removal.

  Policy options
  - Encourage co-location of alkalinity production facilities in Massachusetts with existing industrial sites (e.g., wastewater treatment facilities) to reduce infrastructure cost.
- **Direct air capture -** DAC is possibly well-suited for deployment in Massachusetts as a pathway for deployment. Although DAC has a high scale potential and there is significant opportunity for job creation, DAC is energy intensive. Energy in Massachusetts is expensive, in high demand, and will likely increase in demand as decarbonization efforts progress. The high energy requirements will also need to be met with clean energy to ensure net overall carbon removal. Additionally, the state's lack of in-state geologic storage means that any CO_2 captured from DAC will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges.

  Policy options
  - Evaluate collaboration opportunities with other states in the region to develop or support regional CO_2 transport and storage infrastructure or offshore storage, making it more viable for DAC in Massachusetts to connect to storage.
  - Explore increasing access to clean power for DAC projects through long-term renewable PPAs, grid interconnections, or co-located renewables, ensuring DAC contributes to net-zero rather than straining decarbonization goals.

Pathways unlikely to be well-suited for deployment

There are 10 CDR pathways that are unlikely to be well-suited for deployment in Massachusetts, based on the assessment in this study. However, these pathways may be well-suited for R&D potential even if they are not for deployment, and their low ratings could change if resources, actors, or priorities in the state do.

- **Other biomass building products -** Other biomass building products are unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the low scale potential in the state, which is limited by the available biomass residue in the state because only a subset of the state's biomass waste is suitable to become building products. Due to this low scale potential, there is also limited opportunity for job creation from other biomass building products. Other biomass building products also face a significant risk of reversal over 100 years.
- **Microalgae in ponds** - Microalgae in ponds is unlikely to be well-suited to Massachusetts as a pathway for deployment. Despite a large theoretical scale of deployment, there are significant risks to growth and uncertainties that would limit deployment, such as competing land use for the land necessary to host the ponds and the likelihood of high costs for deployment in the state, due to the state's climate.
- **Microalgae in open water -** Microalgae in open water is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the high degree of uncertainty in microalgae for CDR due to its nascency, as well as the potential unsuitability of Massachusetts coastal waters for this pathway. Significant technical, environmental, and governance questions will need to be answered before microalgae in open water is deployed at scale.
- **Macroalgae in open water -** Macroalgae in open water is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the high uncertainty in the feasibility of deployment in Massachusetts. Due to the shallow waters off the Massachusetts coast, high uncertainty in MMRV and efficacy, and legal feasibility, there are significant risks to growth for macroalgae in open water.
- **BECCS to electricity -** BECCS to electricity is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the low scale potential for deployment in the state. Although BECCS to electricity can use the same biomass residue in state as biomass direct storage, including agricultural and forestry wastes, the combustion process reduces the total amount of CO_2 ultimately sequestered. There are also significant risks to growth for BECCS to electricity in Massachusetts. The state's lack of in-state geologic storage means that any CO_2 captured from BECCS to electricity will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges.
- **BECCS to fuels -** BECCS to fuels is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state. Although BECCS to electricity can use the same biomass residue in state as biomass direct storage, including agricultural and forestry wastes, the combustion process reduces the total amount of CO_2 ultimately sequestered. There are also significant risks to growth for BECCS to fuels in Massachusetts. The state's lack of in-state geologic storage means that any CO_2 captured from BECCS to fuels will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges.
- **Surficial mineralization -** Surficial mineralization is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the low scale potential of the pathway, due to the lack of available in-state alkaline minerals such as mining wastes and the unlikelihood of transporting feedstock into the state due to environmental and safety concerns. Open MMRV questions pose a high risk to growth as well.
- **Coastal enhanced weathering** - Coastal enhanced weathering is unlikely to be well-suited to Massachusetts as a pathway for deployment. The potential scale for deployment is low within the state due to limited suitable coastal area. Although Massachusetts has significant access to the coast, many of the beaches are broken into smaller sections by various aquaculture and wetland resources, which limit application area, and the medium to coarse grained nature of

the state's beaches pose a mismatch with the fine-grained alkaline minerals typically applied in CEW. Open MMRV questions will also need to be answered before large-scale deployment, which pose a risk to growth.
- **Conventional storage -** Conventional CO_2 storage is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the low scale potential for deployment in the state, due to the lack of onshore geologic storage. Due to this low scale potential, there is also limited opportunity for job creation from conventional CO_2 storage.
- **In-situ mineralization** - In-situ mineralization is unlikely to be well-suited to Massachusetts as a pathway for deployment. This rating is driven by the low scale potential for deployment in the state, due to the lack of onshore geologic storage. Due to this low scale potential, there is also limited opportunity for job creation from in-situ mineralization.

5.1.2 R&D leadership potential

Throughout this report, pathways are evaluated based on whether Massachusetts could be a leader in R&D. This section summarizes which pathways are likely to be well-suited, possibly well-suited, or unlikely to be well-suited for R&D leadership potential. For more information on these pathways, see Section 4 and Appendix A.

Pathways likely to be well-suited for R&D leadership

There are eight pathways that, even if they do not have a high deployment rating, are rated high for R&D leadership potential. For these pathways, Massachusetts has the opportunity to lead in early-stage research and innovation and become a hub for these pathways; the Study includes policy options specific to R&D for these pathways for the state to consider.

- **Forests –** There is a high potential for Massachusetts to be a leader in R&D for forests, specifically on the issue of additionality. The state has substantial state-owned forest area that could be leveraged to monitor forest carbon stocks and advance research on dynamic baselines.
  Policy Options
  - Consider funding additional studies following on the Forest Carbon Study to ensure estimates of carbon sequestration are updated and take into account changing trends related to forest disturbances, wood use, and conservation programs, with a focus on answering questions of additionality.
- **Microalgae in open water -** There is a high potential for Massachusetts to be a leader in R&D for microalgae in open water. The pathway is very early-stage and has numerous open research questions that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Massachusetts is specifically well-suited for MMRV and ocean modeling R&D rather than field trials due to questions of suitability in Massachusetts coastal waters.
  Policy options
  - Consider funding modeling research that aims to fill gaps in MMRV and can help determine the possible scale of deployment for this pathway in Massachusetts.
- **Macroalgae in open water -** There is a high potential for Massachusetts to be a leader in R&D for macroalgae in open water. The pathway is still early-stage and has open research questions, such as on MMRV, that the state can lead on due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean.
  Policy options

- Consider funding field trials especially focused on the development of hardware for harvesting and sinking biomass in addition to the production of data that can inform measurement models.

- **Coastal enhanced weathering -** There is a high potential for Massachusetts to be a leader in R&D for coastal enhanced weathering. The pathway is still developing and has open research questions, such as on MMRV, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the coast. Additionally, research institutions in the State are actively investigating the effectiveness and safety of applying CEW to tidal wetlands, positioning Massachusetts well to lead on innovation in this early-stage area of research as well.

  Policy options
  - Through competitive grant programs, consider funding CEW-specific research to fill gaps in understanding related to environmental and ecosystem impacts.
  - Evaluate existing data transparency requirements and gaps for state-funded research. Consider adopting a standardized data protocol.[122]
  - Evaluate potential amendments to Massachusetts coastal zone regulations to streamline permitting for enhanced weathering research, while ensuring ecosystem safeguards and public engagement.

- **Mineral alkalinity enhancement -** There is a high potential for Massachusetts to be a leader in R&D for mineral alkalinity enhancement. The pathway is still early-stage and has open research questions, such as on MMRV and governance, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Additionally, the state could lead on the integration of this pathway with wastewater treatment processes.

  Policy options
  - Through competitive grant programs, consider funding MAE-specific research to fill gaps in understanding related to environmental and ecosystem impacts.
  - Evaluate existing data transparency requirements and gaps for state-funded research. Consider adopting a standardized data protocol.[123]

- **CO_2 stripping -** There is a high potential for Massachusetts to be a leader in R&D for CO_2 stripping. The pathway is still developing and has open research questions, including ones related to energy efficiency and ocean modeling, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean.

  Policy options
  - Through competitive grant programs, consider funding CO_2 stripping-specific research to fill gaps in understanding related to energy efficiency, ocean modeling, and environmental and ecosystem impacts.
  - Evaluate existing data transparency requirements and gaps for state-funded research. Consider adopting a standardized data protocol.[124]

- **Electrochemical alkalinity production -** There is a high potential for Massachusetts to be a leader in R&D for electrochemical alkalinity enhancement. The pathway is still developing and has open research questions, including ones related to energy efficiency and co-product creation, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Additionally, the state could lead on the integration of this pathway with wastewater treatment processes.

  Policy options
  - Through competitive grant programs, consider funding EAP-specific research to fill gaps in understanding related to energy efficiency, co-product creation, and environmental and ecosystem impacts.

- Evaluate existing data transparency requirements and gaps for state-funded research. Consider adopting a standardized data protocol.[125]

- **Ex-situ mineralization –** There is a high potential for Massachusetts to be a leader in R&D for ex-situ mineralization as well, because this pathway is still developing and has open research questions, such as on the use of alkaline industrial wastes and the production of aggregate. Massachusetts may be especially well-suited to lead on this due to the potential for ex-situ mineralization to be a huge CO_2 sink for the state.
  Policy options
  - Consider funding field trials especially focused on the integration of ex-situ mineralization with existing industrial processes.

Pathways possibly well-suited for R&D leadership

There are nine pathways that, regardless of their deployment rating, are rated as medium for R&D leadership potential. Massachusetts should further explore their capacity to and interest in becoming an innovation hub focused on early-stage research to support these pathways.

- **Agricultural soils -** There is a medium potential for Massachusetts to be a leader in R&D for agricultural soils, due to the existing momentum behind regenerative agricultural practices in the New England region. Massachusetts can leverage the significant research capacity in the state to develop improved soil sampling technologies and to establish soil carbon baselines.
  Policy options
  - Explore establishing a grant program for researching and conducting CDR through agricultural soils under the Massachusetts Healthy Soils Initiative.[126] Prioritize projects that aim to answer open questions around soil carbon MMRV.
- **Salt marshes –** There is a medium potential for Massachusetts to be a leader in R&D for salt marshes. Open questions still exist on the uptake of greenhouse gases, such as methane, by salt marshes. The state can leverage its existing salt marsh research and restoration efforts to advance salt marshes as a CDR pathway.
  Policy options
  - Evaluate and build on the Office of Coastal Zone Management's and the Division of Ecological Restoration's ongoing salt marsh restoration and coastal habitat work by prioritizing salt marsh projects that answer open questions related to salt marsh MMRV.[127]
- **Biomass direct storage –** There is a medium potential for Massachusetts to be a leader in R&D for biomass direct storage, because the state can lead on evolving research in storage decomposition modeling and monitoring, especially if the state leads on deployment of the pathway. Additionally, Massachusetts can leverage in-state waste biomass, such as forestry and agricultural residues, to lead on innovation in project logistics.
  Policy options
  - Consider funding modeling research that aims to increase understanding of long-term biomass decomposition and improve long-term monitoring requirements.
- **Timber building products –** There is a moderate potential for Massachusetts to be a leader in R&D for timber building products. Timber building products are well-established and so there are not significant R&D needs for implementation; however, Massachusetts has the potential to deploy timber building products at scale and innovate in process efficiencies, taking advantage of existing mass timber programs already occurring in-state.
  Policy options
  - Consider funding innovative companies and research institutions focused on the deployment of timber building products, especially those that could help achieve Massachusetts' low embodied carbon goals.

- **Other biomass building products -** There is a moderate potential for Massachusetts to be a leader in R&D for other biomass building products, because these products are still early in development. Although Massachusetts has minimal scale potential for this pathway, the state can integrate R&D efforts into its existing building decarbonization efforts.
  Policy options
  - Consider funding innovative companies and research institutions focused on the development of other biomass building products, especially those that could help achieve Massachusetts low embodied carbon goals.
- **Pyrolysis (bioliquid) and storage –** There is a moderate potential for Massachusetts to be a leader in R&D for pyrolysis (bioliquid) and storage. The pathway still has open research questions, such as on MMRV, and Massachusetts may be well-suited to lead on bio-liquid injection into Class V wells, which are present in-state.
  Policy options
  - Explore launching financial incentives for projects that conduct research on the use of Class V wells in the state for bioliquid injection.
- **BECCS to electricity –** There is a moderate potential for Massachusetts to be a leader in R&D for BECCS to electricity. The state's existing facilities that handle biomass, such as paper and pulp mills, could offer key opportunities to pioneer BECCS integration into existing industries.
  Policy options
  - Consider funding a study assessing the opportunity to retrofit existing biomass waste combustion operations in Massachusetts with CCS technologies. Explore further actions to take so these operations are net-negative and have the potential to deliver removals.
- **Terrestrial enhanced weathering –** There is a moderate potential for Massachusetts to be a leader in R&D for terrestrial enhanced weathering. The pathway is still developing and has open research questions, such as on MMRV, for which the state can lead. Additionally, although significant research on terrestrial enhanced weathering on croplands is already occurring, the large-scale potential on forested land in the state creates a key opportunity to lead on research.
  Policy options
  - Consider conducting TEW pilots on state-owned lands to test logistics around mineral transportation, MMRV technologies, and co-benefits on soil and crop yields.
- **Direct air capture -** There is a moderate potential for Massachusetts to be a leader in R&D for direct air capture. Novel materials and methods are still being developed for DAC. Though there are already geographic areas, such as in the US Southeast and Northwest, that are leading in deployment, Massachusetts may be well-suited to lead on lab-scale and pilot-scale research on sorbents, solvents, and electrochemical processes.
  Policy options
  - Consider funding innovative companies and research institutions focused on the development of sorbents, solvents, and electrochemical processes.

Pathways unlikely to be well-suited for R&D leadership

There are six pathways that, regardless of their deployment rating, are rated as low for R&D leadership potential. These pathways have been rated low because of a lack of innovation opportunities generally, the presence of existing innovation hubs elsewhere, or the unlikelihood that, based on Massachusetts' resources, the state would prioritize becoming a hub for a pathway. Although these pathways are rated low, this could change as priorities, actors, or resources in the state shift.

- **Pyrolysis (biochar) and storage –** There is a low potential for Massachusetts to be a leader in R&D for pyrolysis (biochar) and storage because the pathway is mid-to-late TRL and has narrowed its R&D needs. Though there are still open research questions on the duration of storage, the relatively developed nature of pyrolysis (biochar) and storage limits the state's R&D leadership potential.

- **Microalgae in ponds –** There is a low potential for Massachusetts to be a leader in R&D for microalgae in ponds. Although the application of microalgae cultivation in ponds for carbon removal is still developing, substantial research on microalgae cultivation in ponds more broadly exists and other research hubs may be better suited to lead.
- **BECCS to fuels –** There is a low potential for Massachusetts to be a leader in R&D for BECCS to fuels, since BECCS to fuels technologies are established. Although there is additional research needed for the creation of fuels like hydrogen, existing research hubs for bio-fuel production, such as those in the Midwest, are better-suited to lead on these questions.
- **Surficial mineralization –** There is a low potential for Massachusetts to be a leader in R&D for surficial mineralization. The pathway is still developing and has open research questions, such as on MMRV. However, regions with greater current or historical mining have already begun to lead on R&D. Massachusetts has limited suitable feedstock for surficial mineralization.
- **Conventional storage –** There is a low potential for Massachusetts to be a leader in R&D for conventional CO_2 storage. This pathway is already well-developed and deployed at scale and so R&D opportunities are limited, especially given the lack of geologic storage onshore in Massachusetts.
- **In-situ mineralization -** There is a low potential for Massachusetts to be a leader in R&D for in-situ mineralization, because this pathway is mid-to-late TRL and so has narrowed its R&D needs. Additionally, Massachusetts has minimal geologic storage options and so may be better suited to lead in R&D for other pathways.

6 Policy Lessons and Best Practices

Several governments (subnational, national, and supranational) have passed a variety of policies to support the development and scale of CDR, described in Section 2. The 2035 Clean Energy and Climate Plan provides an opportunity for Massachusetts to learn from these governments and consider how similar policies could be enacted in the state and interact with existing policies, regulations, resources, and priorities. While each of these interventions must be assessed alongside budgetary and statutory dynamics, the following section explores how Massachusetts could replicate or model action after other policies. The policy options are informed by the content of this Study, publications on high level CDR policy principles, and other CDR / carbon management roadmaps. [128,129,130,131,132,133] For more information on these categories of policy (e.g., CDR governance and planning), see the Glossary for a definition of each.

6.1 CDR governance and planning

6.1.1 Lessons from existing policy

As mentioned in Section 1, Massachusetts has established GHG emissions targets through the 2008 GWSA and follow-on amendments.[134] The 2050 Decarbonization Roadmap and the CECPs for 2025/2030 and 2050 operationalize these mandates, and, while some of the plans do mention CDR, future CECPs could integrate planning for the most promising interventions. Massachusetts may also consider setting pathway-agnostic benchmarks for CDR at certain intervals, replicating practices seen in Switzerland, the UK, and California.[135] [136] It is important that these benchmarks are pathway-agnostic to ensure a portfolio of solutions is being supported and to reduce the risk of individual technologies not meeting targets; additionally, it is important these benchmarks occur earlier than 2050 to ensure technologies have enough ramp-up time to hit 2050 goals. If the state sets interim targets, it could create a signal that CDR will be supported soon. These goals could be set in parallel with emissions limits already outlined in statute by determining what is ambitious and feasible by 2035, 2040, 2045, and 2050.

6.1.2 Governance policy options for Massachusetts

- **G1:** Evaluate adopting a definition of CDR in statute that is performance-based and pathway-agnostic, leading to the support of a diverse portfolio of CDR.[137] This definition could be modeled after and align with existing definitions that include a diversity of CDR (e.g., the IPCC definition), especially those in other US states if they uphold performance-based, pathway-agnostic CDR.[138]
- **G2:** Consider funding an interagency body (or similar body) that specializes in CDR for the Commonwealth; this body could lead work in the Commonwealth such as communication campaigns, producing guidance, and informing future CECPs and CDR programs.
- **G3:** Consider establishing interim targets for CDR aligned with existing GHG limits and CECP timelines. Determine these targets based on best available science, state progress towards net-zero targets, and progress on CDR R&D.
- **G4:** Track CDR progress in the state. Incorporate a periodic review to check progress against CDR targets, ensure the best available science is being used, and re-evaluate and recommend actions to safely further CDR development in the state.
- **G5:** Evaluate opportunities to build on or launch regional partnerships on CDR to fill gaps in feedstock availability and explore large scale cross-state deployment. The Regional Greenhouse Gas Initiative (RGGI) and the US Climate Alliance (USCA) are good examples of partnerships that Massachusetts takes part in focused on reducing emissions.
- **G6:** Build on this Study by further exploring options for integrating CDR into existing Massachusetts industry, especially focused on mineral offtake from industrial facilities and integration with the concrete industry.
- **G7:** Identify key research gaps and priorities, specific to Massachusetts and including social science research, that should be filled to support pathway scaling.

6.2 Demand policies

6.2.1 Lessons from existing policy

While Massachusetts currently lacks explicit demand-side incentives for carbon removal, existing models from other jurisdictions illustrate how compliance and voluntary markets could stimulate CDR deployment.

As mentioned, several jurisdictions are integrating CDR into compliance mechanisms, including California's LCFS allowing DAC credits, the UK ETS and GX-ETS integrating CDR, and CORSIA allowing CDR as Eligible Emissions Units (EEUs). Massachusetts does not currently have a clean fuel standard, although legislation has been introduced attempting to create one. The Regional Greenhouse Gas Initiative (RGGI), the cap-and-invest program that Massachusetts participates in alongside 10 other states, covers power sector emissions and the Massachusetts Limits on Emissions from Electricity Generators, complements RGGI.[139,140,141] Additionally, the Massachusetts Emission Reduction Credit Banking and Trading Program allows for the creation of surplus Emissions Reduction Credits (ERCs) to be voluntarily created and traded. Currently, most CDR is not integrated as a possible offset in these mechanisms (although forestry offsets are allowed to cover a small percent of emissions in RGGI). Moving forward, Massachusetts could consider how CDR could be integrated in existing systems in a way that will not detract from decarbonization efforts and could consider creating additional cap-and-invest programs that expand beyond the power sector.

Additionally, governments are exploring public procurement to support CDR. Programs modeled after the Buy Clean California Act or New York's Buy Clean policy could leverage Massachusetts' newly created Embodied Carbon Interagency Coordinating Council (ECICC) to drive demand for CDR-integrated materials.[142,143] These pathways would complement CECP goals to decarbonize construction and transportation while providing local markets for verifiable removals. Further, although Massachusetts does not currently have a direct procurement program for CDR, the 2050 CECP states that Commonwealth should develop a policy framework for procurement, including accounting parameters and a procurement process to begin well before 2050.[144] When developing this procurement program, Massachusetts could consider modeling after government procurement programs (like those started by the US DOE and Canada LCFPP) as well as voluntary purchasing programs (e.g., Frontier Climate).

6.2.2 Demand policy options for Massachusetts

- **D1:** Consider launching a pilot procurement program to not only support the goals outlined in the 2050 CECP but also to move CDR pathways along the TRL ladder and cost improvement curve, especially pathways rated by this Study as likely or possibly well-suited. Utilize learnings from public (DOE) and private (Frontier) purchase programs. This pilot program could be the first phase of a larger scale procurement program that the Commonwealth leverages to meet goals through 2050. Consider procurement of out-of-state CDR, including necessary accounting mechanisms, like avoiding double-counting, if the state decides to procure outside of Massachusetts.
- **D2:** Consider launching a task force to explore integrating CDR into existing compliance mechanisms and/or kickstarting new compliance mechanisms. This task force could also consider what mechanisms may be appropriate to mitigate and remediate risk of reversal in compliance mechanisms through tools like buffer pools, horizontal stacking, trusts, etc.
- **D3:** Consider establishing incentives that encourage investors to invest in CDR projects in the Commonwealth, including equity investors and private CDR credit purchasers.
- **D4:** Consider inclusion of CDR practices in the Climate Smart Agriculture Program to incentivize pathways like biochar, TEW, and agricultural soils carbon sequestration. Incentivize adoption of US Department of Agriculture practice standards that include CDR practices.
- **D5:** Explore launching a Buy Clean program to support procurement of CDR for publicly funded projects which could support pathways like timber building products, other biomass building products, and ex-situ mineralization.

6.3 Supply and R&D policies

6.3.1 Lessons from existing policy

Supply-side policies and R&D programs are essential for fostering early-stage carbon removal technologies in Massachusetts. Massachusetts could leverage MassCEC's and other agencies' existing grantmaking capacity to create supportive programs focused on CDR innovation and MMRV development aligned with state resources and leverage existing partnerships with research institutions to fund focused R&D.[145] By aligning new CDR R&D programs with existing clean energy and climate innovation funding, Massachusetts could position itself as a testbed for high-integrity, scalable carbon removal pathways that also advance local workforce and economic goals.

While tax credits like 45Q and Canada's CCUS ITC are likely less relevant for Massachusetts because of their focus on geologic storage, Massachusetts may consider modeling CDR tax credits on ones that already exist in the state, such as for offshore wind facilities.[146] The Offshore Wind 2024 Tax Incentives were based on number of employees, and a similar tax credit could be explored for CDR pilot or commercial projects.

6.3.2 Policy options for Massachusetts

- **S1:** Consider funding competitive grant programs for innovative companies and research institutions focused on filling priority research gaps, including filling research gaps for existing CDR pathways or innovating to discover new, additional pathways.
- **S2:** Consider funding competitive financial incentives such as grants, subsidies, or low interest loans to finance pilot or demonstration projects for pathways at TRL 5-7.
- **S3:** Consider funding a CDR tax credit modeled on existing tax credits in the state (e.g., Offshore Wind Tax Credit).
- **S4:** Evaluate the opportunity to create CDR special economic zones that include economic incentives and streamlined permitting, to a degree that is safe, for projects that site within the zone. Consider customizing these for specific pathways depending on geography and nearby resources.
- **S5:** For biogenic pathways, explore partnerships with farmers associations and existing wood processing infrastructure to spur offtake of residual biomass by CDR suppliers.[147]

6.4 Standards and certification

6.4.1 Lessons from existing frameworks

As mentioned in Section 2, CDR standards and certification frameworks are the principles and rules that ensure CDR activities deliver the removals claimed; they outline big picture principles to follow and specific protocols for projects including MMRV. For Massachusetts, which is exploring deployment of a variety of CDR pathways and looking to stand up supportive CDR policy, establishment of high-quality standards is critical for GHG accounting, investor confidence, and public trust. By leveraging established standards and frameworks rather than reinventing the wheel, Massachusetts can tap into global markets, maximize value, and avoid quality risks.

At the international level, the PACM Removals Standard sets out rules for removal credits, covering monitoring, reporting, accounting, addressing reversals, and avoiding leakage.[148] Depending on how PACM continues to evolve, it could offer Massachusetts a foundation for international interoperability and integrity. For example, if standards established by Massachusetts align with the PACM standard, they may more easily be able to plug in to global trading mechanisms in the future. Beyond PACM, the EU CRCF, adopted in 2024, provides another model for how government can certify removals.[149] For Massachusetts policymakers, the CRCF offers an example of a jurisdiction building removal certification into its policy ecosystem and a strong process for incorporating expert and public opinion into a certification framework.

Lessons can also be learned from voluntary standards creation. Several overarching sets of principles and guidance support robust crediting and claims in the voluntary market. The ICVCM Core Carbon Principles, the ISO standards related to climate change mitigation, and the GHG Protocol standards for corporate GHG emissions are a few leading examples.[150,151,152] These frameworks provide

Massachusetts with valuable tools for establishing high-level principles for carbon credits and GHG accounting and can shed light on which principles are most successful in motivating corporates to act.

Registries and methodology providers apply principles to real-world applications. Registries such as Puro.earth and Isometric translate high-level frameworks into actual credit issuance.[153,154] These registries, among others, matter for Massachusetts because they offer existing pathways for local and regional projects to issue credits without Massachusetts needing to build protocols or credit tracking systems from scratch.[155] However, if Massachusetts decides to stand up its own compliance mechanism that allows CDR credits or if it decides to launch a CDR procurement program, it is possible the Commonwealth will want to utilize its own registry and potentially its own methodologies. In this case, existing registries and methodologies could act as important reference points for Massachusetts to use when designing their own standards and certification infrastructure.

At the US state level, as mentioned in Section 2, some jurisdictions are beginning to think through CDR standards. For example, California SB 285 proposed both a definition for qualified CDR and that only certain types of CDR would be authorized to be used to reduce GHG emissions.[156] Though the bill did not pass, it illustrates how a US state is exploring regulating CDR quality in law, and Massachusetts could consider this pathway when creating its certification infrastructure.

For Massachusetts, the integration of, or alignment with, existing standards and certification frameworks will depend on its chosen CDR support mechanism(s). The state might reference the PACM Removals Standard or EU CRCF to define what eligible removals look like in any state-sponsored procurement or compliance scheme. It might uphold principles from the ICVCM/ISO/GHG Protocol when outlining guidance for corporates in the state. It might decide to tap into existing registries and methodologies to accelerate market development and avoid building internal protocols from scratch. It might learn from existing US state efforts to determine how it wishes to regulate the quality of CDR. By building on existing frameworks when incorporating CDR into Massachusetts policy and regulation, such as consideration of the MassDEP Greenhouse Gas Emissions Reporting Program, the Commonwealth is more likely to support high-quality CDR that builds trust in the industry and connections to existing markets and mechanisms than if it acted in a vacuum.[157]

6.4.2 Consideration of additionality

Additionality is a central question in CDR standards. CDR is additional if the carbon removed is over and above what would have happened in its absence.[158] For example, if an activity is already underway and removals are already occurring, but they are not yet being accounted for, the creation of credits or an accounting framework from these removals would not be additional. Alternatively, if a project or activity is started that leads to removals that would not otherwise have occurred, these removals would be considered additional. Determining additionality is dependent on first determining a baseline scenario. A baseline scenario establishes an understanding of existing emissions, removals, and practices that can be compared to when determining if a project or removal is additional.

Existing CDR standards include consideration of additionality, and these standards are shifting to have stringent rules around additionality. The PACM Removals Standard requires that any removal eligible for crediting must prove that the net change in GHG stored in a reservoir is positive. This is calculated by comparing the baseline scenario of storage reservoirs to the storage reservoirs at the end of an activity. This means, for a project to be approved under PACM, it must be additional.[159] Further, the ICVCM includes additionality as one of its core principles; for activities to be additional, they must not have occurred in the absence of the incentive created by carbon credit revenues.[160] Widely, standards are shifting to ensure removals deliver the climate benefits they claim, and additionality is a central component of this.

It is important for the state of Massachusetts to consider the topic of additionality when supporting CDR, especially when determining what types of CDR, especially those with questions around additionality, count toward net zero targets. In doing so, the state should be aware of the CDR field's macro trend toward stringent additionality rules when determining its policies.

6.4.3 Consideration of reversal risk

Reversal risk is the risk that a removal will be returned to the atmosphere over a specified time period, and is also central to the discussion of CDR. Under the scientific concept of net zero, the warming impacts of emissions sources and sinks must be matched to stabilize global temperatures over the long term.[161] This means that, to achieve net zero, neutralization of fossil CO_2 emissions through CDR requires carbon to be stored for millennia, while this may not be necessary for some emissions associated with, e.g., land use change.[162] To achieve this matching, it is necessary to consider factors that could cause CDR to be reversed, implement risk mitigation and compensation strategies (e.g., insurance, buffer pools), assign parties responsible for correcting any reversals, define the timeframe over which this responsibility exists, and define the conditions under which this responsibility can be released.

Existing standards deal with these considerations in a variety of ways. The PACM has a standard entirely dedicated to addressing non-permanence and reversals in its methodologies.[163] Under this standard, project monitoring requirements are only allowed to end if the risk of reversal for the project is negligible or if the risk of future reversals has been remediated as specified by the standard. The PACM Supervisory Body is also considering establishing a monetary permanence reserve or insurance as options for remediating future reversals.[164] The ICVCM includes permanence as a core principle, stating removals have to either be permanent or, if there are risks, measures are in place to address risks and remediate reversals.[165] The SBTi's Corporate Net Zero Standard v1.3 requires companies "remove carbon from the atmosphere and permanently store it to counterbalance the impact of any unabated emissions that remain" after the net zero date.[166] Finally, other frameworks are emerging to ensure that the cooling effect of a removal is matched to the warming impact of the emission being compensated for, which focus on the performance of the removal credit rather than which specific technology or carbon sink is being used, for example, using contracted permanence mechanisms (e.g., horizontal stacking, permanence trusts) to manage reversal risk and correct reversal events.[167]

As with additionality, it is important for Massachusetts to consider the topic of reversal risk when supporting CDR and, especially, when determining what types of CDR count towards net-zero targets. In doing so, the state should be aware of the CDR field's emerging macro trend toward stringent reversal risk rules when determining its policies.

6.4.4 Standards options for Massachusetts

- **St1:** Evaluate paths forward for CDR standard development, including developing new standards or adopting existing standards, in the state, with emphasize on market integration and trust. These standards should inform research as well as methodologies that are accepted in state-supported CDR programs. These standards should also consider the performance of a credit (e.g., risk of reversal, horizontal stacking) and outline which types of CDR can be used to counteract Massachusetts's residual emissions. These standards should also consider community engagement guidelines (CE4) and Massachusetts's existing GHG accounting framework.[168]
- **St2:** For biogenic pathways, consider creating a definition of, standards for, and a hierarchy of use cases for sustainably sourced biomass that evaluates existing and/or untapped feedstocks and supply chains in Massachusetts.

6.5 Permitting

6.5.1 Lessons from existing policy

There is action around permitting that exists in Massachusetts that could be leveraged to support CDR. Massachusetts' ResilientCoasts Initiative and coastal management programs provide natural entry points for exploring blue carbon and other nature-based removal strategies. The Commonwealth's 50-year coastal resilience strategy, led by the Office of Coastal Zone Management, could support salt marsh or seagrass restoration pilots that include conservative carbon accounting methodologies.[169] Further, as mentioned previously, marine permitting will be complex and navigating Massachusetts-specific regulations alongside relevant federal regulations, which are informed by international laws, will be necessary for project developers.

Additionally, Massachusetts could follow suit after California's SB 905 and allocate time and resources to creating streamlined and safe permitting guidance and processes for CDR.[170] In the Massachusetts 2024 Climate Act, siting and permitting for small clean energy infrastructure was reformed to overcome what was identified as a key barrier to clean energy development in the state.[171] The law establishes a 12-month deadline for permit issuance. Although CDR is not included in the definition of a small clean energy infrastructure facility, Massachusetts could jumpstart CDR permitting by creating a similar streamlined process modeled both after internal permitting processes and/or California's permitting guidance for CDR.

6.5.2 Policy options for Massachusetts

- **P1**: Evaluate gaps in guidance on CDR permitting and publish guidance, including for existing and new permitting pathways. For some pathways, permits are required from federal agencies, and regulatory alignment will be required. For some pathways, legal paths forward are still being established at federal or international levels, and Massachusetts may not have full control over permitting capabilities. Permitting for open system pathways (e.g., TEW, MAE, etc.) will need to consider how impacts may cross state-jurisdictions (e.g., impact on shared watersheds, discharge into other coastal zones) and therefore will need buy-in from other jurisdictions as well.
- **P2:** Consider leveraging the process used for streamlining permitting of small clean energy infrastructure.

6.6 Additional policy considerations

In addition to the policy areas described previously, it is important for Massachusetts to consider other policy options to support the development of a safe, high-quality, beneficial CDR industry. This section explores a menu of policy options related to community engagement and workforce support.

Community engagement

- **CE1:** Evaluate the need for risk assessments for projects being funded by the state and consider requiring these assessments.
- **CE2:** Consider launching communication campaigns about CDR including by hosting public informational webinars and town halls and developing outreach materials.
- **CE3:** Improve access to data from CDR research, pilots, and larger scale deployments to the public through understandable public databases.
- **CE4:** Evaluate gaps in guidance on community engagement practices and publish guidance aligned with state priorities, best practices, and feedback from communities. This should include how to identify and engage with relevant communities, including Tribes, early and continually to create a trusted, two-way information exchange about concerns, knowledge gaps, perspectives, and priorities as they relate to CDR.
- **CE5:** Encourage community benefits plans (CBPs) or community benefits agreements (CBAs) for CDR projects.
- **CE7:** Consider integrating CDR into the appropriate existing environmental science or climate Elementary and Secondary Education curriculum.
- **CE8:** Consider creating financial incentives for projects that have community organizations as partners or leads.

Workforce support

- **W1:** Conduct an analysis of workforce advantages and gaps in Massachusetts to inform future policy and programs.
- **W2:** Consider launching workforce development programs, especially for well-suited or possibly well-suited CDR pathways. Ensure programs cover both early career apprenticeship and training and mid-career transition.

7 Conclusion

Many opportunities exist for the state of Massachusetts to pursue CDR in substantial and impactful ways. The state should carefully consider how best to support deployment of the most suitable CDR pathways—biomass direct storage, terrestrial enhanced weathering, and ex-situ mineralization. These pathways have the potential to contribute significantly to state GHG targets. Beyond these, there are ten other pathways that could possibly be well-suited for Massachusetts depending on the Commonwealth's priorities and how CDR evolves as a field. Massachusetts also has the potential to be a global leader in CDR R&D and innovation for eight pathways, ranging across biogenic, geochemical, and synthetic CDR, as well as storage pathways, and the state should determine if and how it would like to leverage resources to pursue leadership.

Massachusetts has the potential to use CDR to advance its climate goals and to become a powerhouse of innovation. The results of this Study should be used to inform the state's 2035 Clean Energy and Climate Plan process, especially using the CDR pathway suitability assessment to determine how best to achieve the net zero mandate. The state should also consider the policy options presented in this Study, in the context of the other policy priorities and resources within Massachusetts, to determine how best to create a supportive ecosystem for CDR R&D.

8 Appendixes

8.1 Appendix A: CDR Pathway Analysis

Biogenic CDR

Biogenic CDR (bCDR) pathways use naturally occurring, biomass-based processes such as photosynthesis to capture CO_2 from the atmosphere.

Forests

Table 8-1: Forests Overview

Pathway: Forests	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** High	
Current cost: \$1-80/tCO_2 **Cost reduction potential:** Low	**Scale potential:** High (5.0-6.0 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Significant over 100 years **Facility operating lifetime:** 20-150 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 9; deployed at scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Established	**Economic benefit and job creation:** High
Resource requirements ***Water:*** Low ***Land:*** Medium ***Energy:*** Low ***Feedstock:*** Low	**Earliest planned start time:** Underway

Table 8-1: Forests Overview

Overview

Forests as a CDR pathway refers to the conservation, restoration, and improved management of forests to enhance atmospheric carbon removal. Methods considered were changing harvesting practices, afforestation, and reforestation.

Forests are possibly well-suited to Massachusetts, particularly as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by a few counteracting factors. First, from a technical perspective, forests can be scaled significantly across the state, due to the presence of suitable land such as existing timber forests for improved management practices, though there will be competing land uses. Forests also have the potential to create significant jobs and take advantage of a local supply chain. However, forests as a CDR pathway do face unanswered questions on additionality, which will be important for the state to address if counting on this pathway for its CDR needs. The potential scale for removals from forests may decrease by a factor of ten if the state adopts stringent additionality requirements. Forests also face a significant risk of reversal over 100 years, which the state will have to consider, which results in an overall suitability rating of medium.

There is a high potential for Massachusetts to be a leader in R&D for forests, specifically on the issue of additionality. The state has substantial state-owned forest area that could be leveraged to monitor forest carbon stocks and advance research on dynamic baselines.

Deployment suitability rating: Medium
R&D leadership potential rating: High

Cost

Current cost: The current cost for forestry credits ranges from \$1 to \$80 per tCO_2.[172] The cost level will depend on geography, credit type, and quality, but the low cost is driven by the limited capital expenses and inexpensive feedstock needs. Costs for forestry credits produced in Massachusetts will depend on the available suitable land area, e.g., existing timber forests for improved management practices, degraded land that can be forested, or existing forests that can be protected. Although forests cover roughly 60% of the state,[173] costs may be on the higher end of this range due to competing uses for this land. Costs will also be on the higher end of this range if Massachusetts adopts stringent quality criteria. However, the cost of implementation of forestry efforts may be lower if integrated with wood product generation, such as timber building products.[174]

Range: \$1 to \$80 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

Forests as a CDR pathway have low design complexity (i.e., a moderate number of components, many of which are mass-produced) and require moderate customization to each site where it is implemented. Therefore, forests fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[175] This means that because forestry pathways can easily scale for a given land area but have site specific requirements (i.e., type of trees, amount of water), forests are likely to achieve moderate cost reductions on the basis of scale alone. Reforestation costs could also decrease with scale through the creation of a central tree nursery for the state. However, forestry pathways are highly developed and well-established already. Cost reductions due to scale have already occurred and thus costs are unlikely to significantly reduce with future scaling.[176] With increasing scale, costs may actually increase as the best-suited land is increasingly already in use. Competition for land may be increasingly challenging in Massachusetts simply due to its limited land area overall.

Rating: Low

Duration

Risk of reversal: Forests remove and store carbon with significant risk of reversal over 100 years.[177] Reversal can occur due to wildfire and other natural disasters, land-use change such as deforestation, and natural decomposition. Buffer pools, insurance policies, horizontal stacking, and other mechanisms can be used to help account for reversal risk, by putting structures in place to ensure replacement of any removals which are reversed. Mechanisms to replace any reversals require strong and consistent governance which Massachusetts may be well-positioned to implement due to its history of strong climate action. However, Massachusetts can expect a significant risk of reversal on a decadal timescale.

Rating: Significant risk of reversal over 100 years

Operating lifetime of a plant: For forestry-based carbon removal projects, the operating lifetime is 20 to 150 years. The lifetime depends on the crediting period, which is when the project generates carbon removal credits (i.e. the tree is growing), and the monitoring period, which is when the project is checked for reversals (damage from hurricanes, other environmental hazards, or old age). The lifetime typically varies by project type and registry requirements. Crediting periods can range from 20-50 years, with ongoing monitoring obligations often extending 100 years.[178] Massachusetts can expect forestry projects to operate on this timeframe due to the maturity of the pathway and the global applicability of the monitoring requirements.

Range: 20 to 150 years

Technology Readiness Level

Forestry as a method of carbon removal is well established and deployed commercially at scale (TRL 9).[179] Commercial projects exist globally at significant scale.[180] Forestry credits made up the greatest share of carbon removal credits from voluntary purchases in 2023, with approximately 10 Mt of forestry credits issued in 2023 on the voluntary carbon market.[181]

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for forests is established. CO_2 is measured by comparing forest carbon stocks to a pre-determined project baseline, through a combination of direct measurement and modeling.[182] Many methodologies for forest MMRV exist in registries, including the Climate Action Reserve,[183] ACR,[184] and Verra.[185] However, challenges to accurate measurement of carbon removal have been raised, such as establishing a credible baseline so that all carbon storage is additional. Another challenge is the need for continued monitoring on the time scale of decades to ensure no reversals occur, which creates continual monitoring, reporting, and verification steps.[186] Despite being established for multiple years, forest MMRV is still evolving to include new and stricter requirements. For example, a permanence trust mechanism has been proposed as a new requirement for forestry, which would allow forestry credits to meet a stricter reversal risk standard.[187]

Rating: Established

Deployment Timelines

Forestry CDR has already been deployed at commercial scale in the state. Massachusetts currently has two large scale forestry projects generating verified carbon removals and, since their inception, the two sites have generated a combined total of approximately 1,107,000 tCO_2e in removals as of November 2025.[188] [189] However, these projects have been flagged due to potential additionality issues, which is a major risk for forestry projects generating credits, potentially negating as much as 600,000 credits.[190] Deployments will need to navigate legislation and regulation that are typically applied to forestry operations in the state to protect forest ecosystems. These include the Massachusetts Forestry Cutting Practices Act, Massachusetts Endangered Species Act and Massachusetts Environmental Policy Act, and Wetland Protection Act.[191] [192] [193] Prior to generating removals, forestry CDR projects must go through several initial planning steps. These processes, depending on resources available and project size, can take 12-14 months.[194] Once initial planning is completed, deployed forestry projects begin generating removals as soon as they are registered with an accredited carbon registry.[195] However, proper verification of these removal credits is the longest part of the removal process; depending on the project and the existing data on forest age, growth rates, speciation, and the amount of acreage registered, credits can take between 10 and 28 months to be validated and awarded to the operating organization(s), making the overall timeline from inception to credit generation anywhere from 2 to 4 years.[196]

Resource Requirements

The main resource requirement for forests is land area, and specifically the opportunity cost of using that land area for forests over other end uses. The amount of land needed per tCO_2 removed will vary greatly based on the forest composition, but regardless the scale of carbon removal depends on the amount of land available for forestry pathways. Assuming an average carbon density in aboveground trees in Massachusetts means 1 hectare of land can remove approximately 300 to 350 tCO_2 over its crediting lifetime; the amount of land needed is approximately 0.002 to 0.003 ha per tCO_2.[197] Water needs are low, especially in a climate like Massachusetts where there is significant annual rainfall. Water needs can also be minimized by the choice of species used in forestry projects.[198] Energy requirements are minimal, comprising primarily the energy needed to plant (if part of the forestry pathway) and monitor the forest area. Feedstock (i.e., seedlings) needed will depend on the forestry method and species, as reforestation can require on the order of 1,000 seedlings per hectare, but are minimal.[199]

Rating (Water): Low
Rating (Land): Medium
Rating (Energy): Low
Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of forest CDR in Massachusetts is between 5 million and 6 million tCO_2e per year through mid-century, which is rated as high and represents approximately 36-43% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was determined in the Massachusetts' Forest Carbon Study, completed by Harvard Forest and UMass Amherst in February of 2025 on behalf of Massachusetts EEA.[200] The authors calculated this estimation by conducting land use change scenario modeling. Although the potential for forest removals could remain at 5 million to 6 million tCO_2e through mid-century with minimal disturbances, there are also high-disturbance scenarios that result in these removals dropping to 1 million tCO_2e or even resulting in net emissions annually. Further, the study indicates that forests are expected to decline to less than 1 million tCO_2e per year by 2100 due to forest aging which means, even if they contributed to 2050 targets, their contribution to atmospheric concentrations after 2050 would have to be re-evaluated. Finally, the 5 million to 6 million tCO_2e per year scale estimate is based on existing forests; this scale could be significantly smaller depending on the additionality requirements the state adopts. The Forest Carbon Study, for example, estimates that 100,000 to 600,000 tCO_2e per year would occur through reforestation and the planting of new trees rather than relying on removals from existing forests.[201]

Rating: High

Risks to growth: Massachusetts-specific risks include strengthening storms as climate change intensifies and hurricane seasons lengthens, disease and death as a result of species like the spongy moth and hemlock woolly adelgid, and planned land use change focused on solar PV systems and sprawl-oriented development.[202 203 204 205] Perhaps the biggest risk to the forest sink in Massachusetts is hurricanes, which state modeling shows are the single largest driver of variability in land-sector carbon net removals. An event akin to the famous 1938 hurricane could turn the state's forests from sink to source for as many as 10 years before removals began recovering from regrowth.[206] Greater variability in cold weather events also pose a risk to MA forest carbon. Ice storms, such as the December 2008 event, could cause damage to forest carbon stores, primarily via broad canopy damage that prolongs forest recovery.[207] Additionally, the composition and productivity of Massachusetts' forests are tied to the state's current climate; as climate change accelerates and impacts Massachusetts seasonality and environmental factors, the suitable habitat and forest composition in the state is very likely to change as well. Trees are slow growing species with generally short seed dispersal ranges, limiting adaptability and diversification. In the face of climate change, these factors can mean reduced productivity and increased tree mortality that lead to subsequent carbon losses which may not be accounted for in forestry removal modeling. As for invasive species and diseases associated with their expansion, MA forests have been victimized by local pests and blight; spongy moth defoliation peaked at about 923,000 acres in 2017, and hemlock woolly adelgid continues to weaken and kill the state's hemlock stands.[208 209] In terms of land use change, the state's Forest Carbon Study finds that if recent trends in land use continue out to 2050, that the associated emissions from development and timber utilization would reduce net removals from forest uptake by as much as 20%, or 1.2 million tCO_2e per year.[210] New building patterns, especially those that are sprawl-oriented, could emit as much as 28 million tCO_2e via forest conversion by 2050, while meeting state solar targets on greenfield sites could add an additional loss of removals totaling roughly 3.4 million to 13.6 million tCO_2e depending on siting.[211] Finally, land use change from persistent development that both utilizes forest resources and converts forested land to alternative land use (agriculture, residential, commercial, other uses) pose a threat to consistent removal benefits.[212]

Rating: Medium

Local supply chain

Forest CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact more than 5 sectors in the state's economy, including native seedling suppliers, silviculture and forestry consultants, logging operations, invasive species management groups, and heavy equipment suppliers. In Massachusetts, there are multiple native seedling suppliers and in-state nurseries who may see increased demand as they supply trees and native species for reforestation and afforestation projects.[213 214 215] Numerous Massachusetts silviculturists and certified foresters could support activities necessary for deployment, including planning projects, identifying ideal species composition, favorable siting locations, and ensuring forest stands are managed appropriately to maximize growth and avoid disease.[216 217] Massachusetts logging companies could play a role in helping to remove dead stands and harvesting in appropriate intervals to supply in-state timber demand.[218 219] The state also has various conservation-focused groups and planting companies who could ensure seedlings are planted appropriately and that threats to live stands are managed to preserve existing carbon stores.[220 221] Finally, the plethora of in-state heavy machinery suppliers could supply forestry professionals with the tools they need to remove dead wood, cull sick areas, and harvest wood for mass timber.[222 223]

Rating: High

Solution providers

Forestry CDR is already a widely deployed practice and has many solution providers already delivering meaningful forest-focused CDR projects on a global scale. That said, Massachusetts does not have any dedicated forestry CDR solution providers headquartered in-state who are deploying forest CDR projects. However, there are both independent actors and municipal initiatives in Massachusetts that are leading efforts to deploy afforestation and forestry projects in-state. Organizations Anew Climate and Mass Audubon are responsible for registering and receiving credits for the first large scale, verified forestry CDR project in Massachusetts, though Mass Audubon's project has been flagged for questions on additionality.[224 225 226] Massachusetts also does have state programs advancing responsible forestry removals. Agency projects such as Massachusetts' Department of Conservation and Recreation's Greening the Gateway Cities initiative and Boston's Urban Forest Plan provide governmental support for reforestation and afforestation efforts on both private and public land in urban neighborhoods.[227 228]

Co-benefits and potential negative impacts

Social and environmental Co-benefits: Forest-based CDR has the potential to provide significant social and environmental co-benefits including protecting coastal watersheds, expanding urban tree canopy, and biodiversity benefits. Global assessments conclude that improved forest management and restoration deliver climate mitigation alongside biodiversity and water benefits when implemented with local safeguards.[229] In Massachusetts, reforestation and riparian buffers in coastal watersheds could cut nitrogen loads to embayments such as Buzzards Bay and Cape Cod estuaries, improving eelgrass and shellfish habitat and supporting local fisheries.[230] Expanding urban tree canopy could also help reduce extreme heat across southern New England.[231]

Potential risk: Forests have the potential to pose moderate but manageable social and environmental risks, including land-use competition and associated equity and acceptance issues, planting on unsuitable sites, and workforce and supply-chain constraints. Land-use competition could create tensions with agriculture, housing, culture, and heritage. Fairness and social acceptance matters; afforestation should be planned alongside other land needs.[232] Poor site selection could also reduce water yield, harm native open-habitat biodiversity, or underperform ecologically.[233] Capacity limits in seeds, saplings, and skilled labor could slow delivery and raise costs.[234]

Health concerns: Forest-based CDR has the potential to pose moderate but manageable health risks including smoke exposure from prescribed burning, increased exposure to tick-borne diseases, and occupational injuries in forestry operations. Prescribed fire—used in Massachusetts for habitat management and fuel reduction—could affect local air quality and sensitive groups during burn windows.[235] Massachusetts, specifically, experiences persistent tick-borne disease burdens (e.g., Lyme, anaplasmosis, babesiosis), and increased time spent in forested landscapes or edge habitats could elevate exposure risks for residents and field crews.[236] Forestry is also among the most hazardous occupations, with risks from heavy equipment, falling timber, terrain, and extreme weather—relevant where restoration or improved management increases on-the-ground activity.[237]

Rating: Positive

Economic benefit and job creation

Forests have the potential to create up to 1,500 to 5,000 total jobs in Massachusetts across R&D, construction, and operations, if deployed at the maximum potential scale. This estimate was generated using industry-wide estimates for jobs per dollar invested,[238] industry-wide estimates for CDR cost per ton,[239] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Jobs created by forests for CDR will likely be mostly ongoing operations jobs. Forests are likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and forested areas (which are all throughout the state).[240] [241]

Rating: High

Agricultural soils

Table 8-2: Agricultural Soils Overview

Pathway: Agricultural soils	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Medium	
Current cost: \$5-25/tCO_2 **Cost reduction potential:** Low	**Scale potential:** Low (0.01-0.4 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Significant over 100 years **Facility operating lifetime:** 5-130 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 9; deployed at scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Established	**Economic benefit and job creation:** Low
<u>Resource requirements</u> ***Water:*** Low ***Land:*** High ***Energy:*** Low ***Feedstock:*** Low	**Earliest planned start time:** Underway

Table 8-2: Agricultural Soils Overview

Overview

Agricultural soils as a CDR pathway refers to the implementation of agricultural management practices that increase carbon storage in soil and build soil health. This includes methods such as reduced tillage, perennialization, cover cropping, double cropping, crop rotation, managed grazing, and compost application.

Agricultural soils are possibly well-suited to Massachusetts. Limited farmland within the state limits the maximum scale of deployment, which in turn limits the opportunity for job creation from agricultural soils. However, a strong local supply chain and existing agricultural industry within the state provides infrastructure that can help enable deployment. It is important that any deployment of agricultural soils aligns with the state's adoption of additionality requirements.

There is a medium potential for Massachusetts to be a leader in R&D for agricultural soils, due to the existing momentum behind regenerative agricultural practices in the New England region. Massachusetts can leverage the significant research capacity in the state to develop improved soil sampling technologies and to establish soil carbon baselines.

<u>Deployment suitability rating</u>: Medium
<u>R&D leadership potential rating</u>: Medium

Cost

Current cost: The current cost for agricultural soils ranges from \$5 to \$25 per tCO_2,[242] though the cost level will depend on geography, credit type, and quality. The low cost is driven by integration into existing farming practices, limited capital expenses, and inexpensive feedstock needs. Costs for agricultural soil credits produced in Massachusetts will depend on the available suitable land area, e.g., existing or new farmland that can implement agricultural management practices that increase carbon storage in soil and build soil health, Massachusetts has roughly 500,000 acres of farmland,[243] but costs may be on the higher end of this range due to competing uses for this land and limited overall land area within the state.

Range: \$5 to \$25 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

Agricultural soils as a CDR pathway has low design complexity (i.e., a moderate number of components, many of which are mass-produced) and requires moderate customization to each site where it is implemented. Therefore, agricultural soils fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[244] This means that because agricultural soil CDR implementation can easily scale for a given land area but have site specific requirements (i.e., type of feedstock, amount of water), agricultural soils are likely to achieve moderate cost reductions on the basis of scale alone. However, agricultural soil pathways are highly developed and well-established already. Cost reductions due to scale have already occurred and thus costs are unlikely to significantly reduce with future scaling.[245] With increasing scale, costs may actually increase as the best-suited land is increasingly already in use. Competition for land may be increasingly challenging in Massachusetts simply due to its limited land area overall.

Rating: Low

Duration

Risk of reversal: Agricultural soils remove and store carbon with significant risk of reversal over 100 years.[246] Reversal can occur due to changes in soil practices or land use, natural decomposition, and natural disasters including flooding and erosion. Buffer pools, insurance policies, horizontal stacking, and other mechanisms can be used to help account for reversal risk, by putting structures in place to ensure replacement for any removals which are reversed. Mechanisms to replace any reversals require strong and consistent governance which Massachusetts may be well-positioned to implement due to its history of strong climate action. However, Massachusetts can expect a significant risk of reversal on a decadal timescale and must be prepared to address this.

Rating: Significant risk of reversal over 100 years

Operating lifetime of a plant: For agricultural soil carbon removal projects, the operating lifetime is 5 to 130 years. The lifetime depends on the crediting period, which is when the project generates carbon removal credits, and the monitoring period, which is when the project is checked for reversals. The lifetime typically varies by project type and registry requirements. Crediting periods can range from 5-30 years,[247] with ongoing monitoring obligations often extending 100 years.[248] Massachusetts can expect agricultural soil projects to operate on this timeframe due to the maturity of the pathway and the global applicability of the monitoring requirements.

Range: 5 to 130 years

Technology Readiness Level

CDR through agricultural soils is well-established and operates on a commercial scale (TRL 9).[249 250] Farmers have been steadily increasing the use of practices that increase soil carbon such as no-till agriculture and cover cropping.[251] Additionally, newer CDR companies that aim to help farmers increase soil carbon sequestration have started up and are running programs to do so.[252] Although there has been some skepticism about the success of the pathway, large scale credit issuances have built confidence in recent years.[253]

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for agricultural soils is established, although complex. MMRV for agricultural soils is done by comparing changes in soil carbon to a baseline measurement to determine change over a period. A baseline is determined by taking soil samples, conducting analysis on soil organic carbon, and re-sampling. In addition to tracking practices and carbon measurement, remote sending or modeling is often used to scale estimates and reduce sampling burden. While MMRV is established, it is still complex because soil carbon can vary within one field or farm and can reverse depending on practices. MMRV practices can also vary depending on existing measurement mechanisms, farmer and other stakeholder priorities and practices, and other qualities that vary by location.[254] Several relevant methodologies exist, including Verra's Improved Agricultural Land Management methodology and the Gold Standard's Soil-Organic Carbon Framework Methodology.[255,256] Additionally, the USDA has established a conservation practice standard for soil carbon amendment, and the EU CRCF is in the process of establishing a methodology for carbon farming.[257 258]

Rating: Established

Deployment Timelines

Agricultural soils CDR techniques have been deployed at pilot-equivalent scale among small landowners in Massachusetts via initial programs aimed at increasing soil health and soil organic carbon (SOC), and additional small scale deployments are planned in the near future. However, quantification of current deployment and future deployment scale is difficult, as implementations are for wholistic soil health purposes and are not directly measuring for removals, nor registering or selling carbon credits.[259 260 261] Relevant permitting regulations for soil carbon projects are similar to those applied to traditional agricultural practices, including 330 CMR 31.00, standards for application of plant nutrients, and 314 CMR 4, state water quality standards, as well as the state's guidance embedded in the healthy soils initiative.[262 263 264 265] In terms of deployment, typical timelines for soil CDR projects to move from initial planning to first implementation of practices are dependent on landowner and are difficult to quantify. A reasonable estimate considering the variety of planning activities needed for soil CDR projects indicate anywhere from two to six months before to implementation, depending on chosen registry and methodology, growing season, and parcel size. On average, crediting begins two to four years following initial implementation of soil carbon practices, with monitoring and additional credit issuance typically continuing for ten years post-implementation.[266 267 268]

Resource Requirements

The main resource needed for agricultural soils is land area, specifically in the form of farmland. Massachusetts has roughly 500,000 acres of farmland.[269] Estimates suggest that 0.3 to 9 acres of farmland are needed to remove 1 tCO_2 per year.[270] The feedstock, water, and energy requirement will depend on the specific method of implementation of agricultural soils. Reduced tillage, for example, has minimal resource requirements because it is a practice that decreases the energy needed to manage farmland. Cover cropping, however, will require additional feedstock, water, and energy to grow crops in the off-season.[271] Overall, across the suite of methods of implementation, feedstock, water, and energy requirement for agricultural soils are minimal.

Rating (Water): Low
Rating (Land): High
Rating (Energy): Low
Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of agricultural soils in Massachusetts is 11,000 to 375,000 tCO_2e per year, which is rated as low and represents approximately 0.1 to 3% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was arrived at by using the carbon storage potential rate for a range of agricultural soil pathways, as well as an estimate of the amount of farmland available for agricultural soil CDR. [272] The amount of farmland available was calculated by approximating the farmland that could be changed to cover cropping, which was then used as a proxy for all agricultural soil methods. The land available for cover cropping was calculated using the total amount of farmland in Massachusetts,[273] as well as the average US percentage of farmers that are currently cover cropping.[274] Assuming this percentage applies to Massachusetts and that all farmland available for agricultural soil methods implement them, the maximum deployment potential was calculated.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of agricultural soils is 11,000 to 375,000 tCO_2e per year, several factors and risk exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including limited available land, community acceptance, and the developing measurement standards. The risk of land availability is due to the relatively small size of Massachusetts and competing uses for land within the state, which may decrease total farmland over time. Additionally, agricultural soil CDR depends on the farm-owner's acceptance in order to be implemented, and so may require educational outreach to enable scaling within Massachusetts.[275] Finally, the ability to generate widely-accepted credits may also be a risk to growth. Agricultural soils consist of a range of agricultural practices that have existed for a while and are well-developed, but the carbon removal measurement of these practices are still developing. Agricultural soil credits will need to be additional and verified in order to scale.

Rating: Medium

Local supply chain

Agricultural soils CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including nurseries and seed distributors, compost and organic fertilizer providers, farm machinery suppliers, soil practice educators and technical assistance providers, and soil carbon MMRV companies. The state has many nurseries and seed distributors who could provide sourcing of native plants and cover crop species used for increased soil organic carbon (SOC) and reducing erosion.[276 277 278] Massachusetts also has several organic compost and fertilizer producers, which are useful for building and maintaining soil organic matter, reducing traditional fertilizer dependency, and repurposing materials otherwise set to be landfilled.[279 280 281] As soil carbon practices are implemented, tools such as no-till soil drills, roller-crimpers and improved planters, as well as traditional heavy machinery like tractors, will need to be sourced from the variety of in-state suppliers.[282 283 284] The state also hosts several companies dedicated to agronomic technical support, education, and demonstration, which could be important for upskilling landowners on soil carbon practices.[285 286 287] Finally, the state has two soil carbon MMRV companies who could prove critical to quantifying soil carbon and measuring sequestration in SOC, which will be necessary for registry methodologies.[288 289]

Rating: High

Solution providers

Agricultural soils CDR is widely deployed and has many solution providers active across various geographies. Massachusetts does have three solution providers headquartered in state; most notable is Indigo Ag, who is responsible for nearly 1 million tCO_2e in registered credits across 28 US states, though none of these credits were registered in Massachusetts.[290] Momentum Ag is another provider in Massachusetts, though they do not claim to have registered carbon credits.[291] Cibo Technologies is a third provider with a headquarter office based in Massachusetts, and providing farmers with MMRV technology for soil carbon measurement and assisting them with regenerative agricultural practices.[292] Despite both Cibo and Indigo Ag's Massachusetts headquarters, Momentum Ag is the only company conducting work in Massachusetts, having led the state's clover living mulch system project to enhance soil carbon sequestration via the Healthy Soils Challenge Grant Initiative.[293] The state government is also working to advance soil carbon storage via its Healthy Soils Initiative.[294]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Agricultural soils CDR has the potential to provide significant social and environmental co-benefits. Methods such as cover cropping, no-till agriculture, and others increase soil carbon, leading to removals, while they also have positive effects on the environment, including improving the quality of soils so they are more biodiverse, more resistant to degradation, and are able to supply more nutrients.[295] These practices can also reduce erosion, improve water efficiency, and increase soil fertility which can all lead to improved resistance against drought.[296 297] This means that doing CDR through agricultural soils could improve food security, especially in drought-prone areas. Additionally, conducting methods that increase soil carbon could reduce the need for fertilizers, saving farmers money, and potentially increase crop yield over time, creating a more stable revenue stream for farmers.[298]

Social and environmental risks: Agricultural soils CDR has the potential to pose moderate but manageable social and environmental risks, including increasing non-CO_2 emissions such as CH_4 or N_2O and short-term risks to yield or costs. To start, some practices that increase soil carbon may increase other emissions which have adverse impacts on the environment.[299] However, this risk can be managed by ensuring practices are not done in excess and by monitoring emissions. Additionally, although transitioning to these practices may increase crop yields in the long-term, swiftly transitioning methods may reduce crop yields in the near-term while also momentarily costing farmers more as methods and labor shifts.[300]

Health impacts: Agricultural soils CDR has the potential to pose significant health benefits with negligible risks. These practices have the potential to reduce groundwater contamination risks, improving the quality of water, because they can improve soil health and reduce nitrogen and phosphorous run-off.[301] Additionally, these practices can reduce cardiovascular diseases that arise from particulates from tilling.[302] On the other hand, risks are more scattered and depend on how farmers shift practices (e.g., more manure, more herbicides) that could potentially have health risks.

Ranking: Positive

Economic benefit and job creation

Agricultural soils as a CDR pathway has the potential to create between 6 to 400 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by focusing on additional jobs created by agricultural soils and assumes the soil practices are implemented by existing farmers. Therefore, the additional jobs are estimated by assuming the jobs needed for soil sampling and measurement would be similar to terrestrial enhanced weathering (TEW). Because TEW operations jobs also include transportation of delivering mineral to farms,[303] the operations jobs created by agricultural soils were estimated as roughly half of the operations jobs created by TEW. The estimate is also based on the potential scale of deployment in Massachusetts outlined in the Scale and Growth section above, and so the limited scale of deployment limits the job creation potential. Although this estimate does not take it into account, the additional income from the sale of carbon credits could enable existing farmers to stay profitable, helping to keep existing farm occupations. Additionally, agricultural soils are likely to direct economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and farmland throughout Massachusetts.[304] [305]

Ranking: Low

Salt marshes

Table 8-3: Salt Marshes Overview

Pathway: Salt marshes	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Medium	
Current cost: \$25-45/tCO_2 **Cost reduction potential:** Low	**Scale potential:** Low (0.04-0.1 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Significant over 100 years **Facility operating lifetime:** 10-160 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 9; deployed at scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Developing	**Economic benefit and job creation:** Low
<u>Resource requirements</u> ***Water:*** Low ***Land:*** Medium ***Energy:*** Low ***Feedstock:*** Low	**Earliest planned start time:** Underway

Table 8-3: Salt Marshes Overview

Overview

Salt marshes as a CDR pathway refers to conserving and restoring existing salt marshes to maintain and re-establish their ability to act as carbon sinks. Common methods in Massachusetts for salt marsh restoration are ditch remediation, runnels, and marsh habitat mounds.

Salt marshes are possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, because although salt marshes are efficient at removing carbon per square foot, there is limited available salt marsh area within the state. Due to this low scale potential, there is also limited opportunity for job creation from salt marshes. However, low resource requirements, potential co-benefits, and existing momentum in the state on salt marsh restoration increases the likelihood of deployment. It is important that any deployment of CDR using salt marshes aligns with the state's adoption of additionality requirements, because CDR from salt marshes depends on a baseline scenario.

There is a medium potential for Massachusetts to be a leader in R&D for salt marshes. Open questions still exist on the uptake of greenhouse gases, such as methane, by salt marshes. The state can leverage its existing salt marsh research and restoration efforts to advance salt marshes as a CDR pathway.

<u>Deployment suitability rating</u>: Medium

<u>R&D leadership potential rating</u>: Medium

Cost

Current cost: The current cost for salt marshes as a form of CDR ranges from \$25 to \$45 per tCO_2.[306] While the cost of credits from salt marshes will depend on the method employed, the low cost level is driven by the minimal ongoing cost to ensure CO_2 uptake by a salt marsh. However, there will likely be a large upfront cost required if a salt marsh needs to be restored; a feasibility study into a Massachusetts Blue Carbon Incentive Program found that the cost to restore an acre of salt marsh can range from \$7,000 to \$12,000.[307]

Range: \$25 to \$45 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

Salt marshes as a CDR pathway has low design complexity (i.e., a moderate number of components, many of which are mass-produced) and needs moderate customization for each site in which it is implemented, and therefore falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[308] Carbon removal from salt marshes can easily scale for a given marsh area but have site specific requirements and best practices for restoration. Therefore, salt marshes are likely to achieve moderate cost reductions on the basis of scale alone. However, salt marsh pathways are highly developed and well-established; cost reductions due to scale have already occurred and thus costs are unlikely to significantly reduce costs with future scaling.[309] With increasing scale, costs may actually increase as the best-suited salt marsh area is increasingly already in use. Competition for salt marsh area may be increasingly challenging in Massachusetts simply due to its limited salt marsh area overall.

Rating: Low

Duration

Risk of reversal: Salt marshes remove and store carbon with significant risk of reversal over 100 years.[310] Reversal can occur due to natural disasters including sea level rise, land-use change such as from infrastructure build-out, and natural decomposition. Buffer pools, insurance policies, horizontal stacking, and other mechanisms can be used to help account for reversal risk, by putting structures in place to ensure replacement for any removals which are reversed. Mechanisms to replace any reversals require strong and consistent governance which Massachusetts may be well-positioned to implement due to its history of strong climate action. However, Massachusetts can expect a significant risk of reversal on a decadal timescale and must be prepared to address this.

Rating: Significant risk of reversal over 100 years

Operating lifetime of a plant: For salt marsh carbon removal projects, the operating lifetime is 10 to 160 years. The lifetime depends on the crediting period, which is when the project generates carbon removal credits, and the monitoring period, which is when the project is checked for reversals. The lifetime typically varies by project type and registry requirements. Modeling project lifetime based on Massachusetts's Blue Carbon Financial Incentive Program Feasibility Study suggests that projects can generate credits from 10 to 60 years.[311] Ongoing monitoring obligations are likely on the same timeframe as forestry projects, which can extend 100 years.[312] Massachusetts can expect salt marsh projects to operate on this timeframe due to the maturity of the pathway and the global applicability of the monitoring requirements.

Range: 10 to 160 years

Technology Readiness Level

Salt marshes are established and deployed commercially at scale as a method for carbon removal (TRL 9).[313] Projects exist to restore salt marshes in Massachusetts already, such as in Cape Cod.[314] Additionally, significant credits from have been sold on the voluntary carbon market in 2022 and 2023, though the total number of credits issued in 2023 on the voluntary carbon market from peatland and salt marsh restoration was only on the thousands of tCO_2e scale.[315]

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for salt marshes is developing. CO_2 is measured by comparing the carbon stock in the biomass and soil of a salt marsh to a project baseline, and relies on both direct measurement, established rates of carbon uptake, and modeling.[316] Methodologies specific for carbon removal exist by major registries, including Verra's Methodology for Tidal Wetland and Seagrass Restoration.[317] State governments have also developed guidelines for salt marsh conservation and restoration.[318] However, similarly to forests, a challenge to accurately measuring carbon removal is establishing a credible baseline so that all carbon storage is additional.[319] Additionally, quantification methods of the net uptake of greenhouse gases, including methane, of salt marsh restoration projects are still developing. Another challenge is the need for continued monitoring on the order of decades to ensure no reversals occur.

Rating: Developing

Deployment Timelines

Salt marsh CDR deployments have not yet been completed in Massachusetts, though a first-of-a-kind commercial scale project is officially underway in the state as of January 2025. The aforementioned project is being carried out by a consortium of Massachusetts state and federal groups.[320] Early assessments show that the project has potential to remove between 85 thousand to 312 thousand tCO_2e over the next 40 years, though current in-state deployment scale prior to this project's completion is zero tCO_2e removed.[321] While this project is being carried out on NPS land and therefore prevents crediting, government agencies like the US Fish and Wildlife Service (USFWS) are working to develop new policies that enable crediting on federal land. With that said, any future deployments need to adhere to regulations relevant to wetland and tidal zone management and protection; these regulations include the state's MEPA review and a full Environmental Impact Report (EIR) process, Massachusetts' Wetlands Protection Act, MassDEP Section 401 water quality certification guidance, and the state's specific salt marsh restoration guidance.[322] [323] [324] [325] In terms of timelines, deployments are highly dependent on resource availability; the state's only project to-date first began assessing feasibility in 2005, breaking ground in 2023.[326] [327] Once restoration begins, work lasts anywhere from 10 to 20 years, while removals continue for as many as 40 years after the project initially broke ground.[328] Overall, the timescale for salt marsh projects to move from planning to completed implementation can be on the order of decades, and as many as 25 years for the generation of first removals.

Resource Requirements

The main resource needed for salt marshes is land area, specifically in the form of salt marsh. Massachusetts has approximately 47,000 acres of salt marsh.[329] Estimates suggest that 0.4 to 1.25 acres of salt marsh are needed to remove 1 tCO_2 per year.[330] Salt marshes are self-sustaining, and so minimal water, energy, and feedstock resources are needed once a salt marsh is restored.[331] Common methods in Massachusetts for salt marsh restoration are ditch remediation, runnels, and marsh habitat mounds which may involve some energy for construction equipment and some amount of salt marsh hay, though these are minimal compared to land requirements.[332]

Rating (Water): Low
Rating (Land): Medium
Rating (Energy): Low
Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of CDR utilizing salt marshes in Massachusetts is between 35,000 and 120,000 tCO_2 per year, which is rated as low and represents less than 1% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was calculated by leveraging the Massachusetts Blue Carbon feasibility study, completed for the Massachusetts Department of Fish and Game. To calculate the maximum removal potential of Massachusetts salt marshes, the state's total marsh land (approximately 47,000 acres) was multiplied by the range of estimated removal rates of a functional salt marsh ecosystem (0.8-2.5 tCO_2 per year).[333] This removal range assumes that all 47,000 acres of marsh land will be restored and will continue delivering annual removals despite possible disturbances.

Rating: Low

Risks to growth: The estimated maximum potential deployment of salt marsh CDR in MA is between 35,000 and 120,000 tCO_2e per year, and several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including reversal risk from salt marsh degradation post-restoration, funding to scale restoration efforts, and private land holdings that delay or prevent restoration altogether.[334] The Massachusetts Blue Carbon feasibility study identifies the most significant barrier to generating removals from salt marsh restoration as the need for additional science to quantify emissions from degraded salt marshes, the reversal of which underpins the creditable climate benefit.[335] These reversals can occur due to environmental factors such as sea level rise or invasive species proliferation (e.g. Phragmites), which can cause waterlogging, erosion and panne formation, stunting the marsh's ability to remove carbon. Funding also poses a key challenge to scaling restoration efforts; the MA BC study estimates that restoring degraded marshes typically costs $7,000–$12,000 per acre, and although carbon credit revenues can accelerate and support this work by engaging private landowners and sustain long-term monitoring and protection, credits alone are unlikely to cover full project costs.[336] Finally, the mosaic of landholdings that host salt marsh ecosystems can complicate restoration and management rollout; more than 20,000 acres of Massachusetts' salt marshes are currently privately held by landowners, and restoration will require outreach, engagement and educational efforts in these cases.[337]

Rating: Medium

Local supply chain

Salt marsh CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact four sectors in the state's economy, including environmental consultant and engineering firms, wetland plant nurseries and suppliers, monitoring equipment developers, and invasive species management companies.[338 339 340 341 342 343 344 345 346] Several MA-based environmental engineering and consultancies will be crucial for providing coastal modeling, project planning and design, and implementation of restoration efforts, as well as ongoing sampling in restored areas.[347 348 349 350 351] Massachusetts also has at least one specialized nursery that focuses on native wetland plants, which will be needed for restoration projects to establish proper species composition and avoid degradation from erosion.[352] In-state technology developers will be able to provide equipment for continuous water-level and water-quality monitoring, as well as soil sample systems, which will ensure salt marsh condition and carbon fluxes are appropriately monitored.[353] Finally, several national habitat restoration companies with Massachusetts offices could provide invasive-species management that would ensure long-term habitat protection and cultivate conditions that encourage secure sequestration.[354 355]

Rating: Medium

Solution providers

Salt marsh restoration specifically for CDR is not a widely deployed pathway, with no solution providers headquartered in-state. However, one of the few companies focusing on salt marsh restoration specifically for CDR, TerraCarbon, is conducting a project in MA. TerraCarbon is currently assisting the deployment of a Massachusetts-based blue carbon project, alongside collaborators from local municipalities and the NPS. The project is being implemented on the Herring River estuary, a 1,100-acre salt marsh located in Wellfleet and Truro, Massachusetts on the Cape Cod peninsula.[356] While many environmental engineering firms and consultancies specialize in coastal and salt marsh restoration, none of these companies target salt marsh restoration specifically for carbon removal benefit. Massachusetts does have a wide variety of environmental engineering firms who could be considered solution providers if their business proposition shifted away from ecosystem benefits and towards carbon removal.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Salt marshes have the potential to provide significant social and environmental co-benefits including reducing flood damages, improving water quality, and supporting biodiversity. Salt marshes could reduce flood damage and attenuate waves and storm surge as seen during Hurricane Sandy and in systematic reviews of marsh protection functions.[357] Salt marshes could also improve water quality by removing nitrogen through denitrification and burial, with strong evidence from New England systems.[358] Furthermore, salt marshes could create habitats that support fisheries and biodiversity that underpin coastal economies.[359]

Social and environmental risks: Salt marshes have the potential to pose moderate but manageable social and environmental risks including an increase in methane emissions and turbidity. Net greenhouse-gas outcomes are uncertain where methane emissions are elevated—especially in fresher/brackish marshes.[360] Restoration actions like thin-layer placement could cause short-term turbidity and disturb benthic communities.[361]

Health impacts: Salt marsh restoration has the potential to pose moderate but manageable health risks/hazards, including hydrogen sulfide odors and heat stress from working outdoors. Public exposure near marshes may include hydrogen sulfide odors; high concentrations can be hazardous.[362] Construction related to marsh restoration (e.g., turbidity plumes) could effect to water quality.[363] Outdoor crews face heat-stress risks that require hydration and work–rest cycles.[364]

Ranking: Positive

Economic benefit and job creation

Salt marshes have the potential to create between 10 and 300 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by using industry-wide estimates for jobs per dollar invested, [365] industry-wide estimates for CDR cost per ton, [366] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. The relatively low scale of deployment of salt marshes as CDR in Massachusetts limits the potential for job creation. Salt marshes as a CDR pathway are likely to direct economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and salt marshes throughout Massachusetts. [367] [368]

Ranking: Low

Biomass direct storage

Table 8-4: Biomass Direct Storage Overview

Pathway: Biomass direct storage	
Deployment suitability for Massachusetts: High **R&D leadership potential:** Medium	
Current cost: \$10-60/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Medium (0.8-1.2 million tCO_2e/y) **Risks to growth:** Low
Risk of reversal: Significant over 1000 years **Facility operating lifetime:** 20 to 50 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 6-8; pilot to demo scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Developing	**Economic benefit and job creation:** Low
Resource requirements ***Water:*** Low (using biowaste) ***Land:*** Low (using biowaste) ***Energy:*** Low ***Feedstock:*** Medium	**Earliest planned start time:** January 2027

Table 8-4: Biomass Direct Storage Overview

Overview

Biomass direct storage refers to storing terrestrial biomass underground or other environments with conditions to prevent significant decomposition. In practice, biomass direct storage may look like taking forestry residues and storing them in a vault underground.

Biomass direct storage is well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. Massachusetts has available biomass residue in state that leads to a moderate potential scale of deployment with limited risks to growth. Additionally, biomass direct storage has high local supply chain relevance and is already low-cost compared to other CDR pathways.

There is a medium potential for Massachusetts to be a leader in R&D for biomass direct storage. The state can lead on evolving research in storage decomposition modeling and monitoring, due to the synergy between existing research institutions and the potential for large scale deployment for field trials. Additionally, Massachusetts can leverage in-state waste biomass, such as forestry and agricultural residues.

Deployment suitability rating: High

R&D leadership potential rating: Medium

Cost

Current cost: Current cost estimates for biomass direct storage range from \$10–\$60 per tCO_2.[369] Costs will depend on the specific process of biomass storage employed, the location of the storage, and the feedstock used. This low cost level is driven by the simplicity of the process and the lack of large capital expenses. Costs in Massachusetts could be in the middle part of this range due to the state's limited land area overall, reducing transportation distances but potentially increasing feedstock costs due to competing uses.

Range: \$10–\$60 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Biomass direct storage systems has low design complexity (i.e., few components that are mass produced) and requires low customization for each site in which it is implemented, and thus fall in the Type 3 section of the cost reduction potential matrix (see Appendix on potential for cost reduction with scale).[370] This means that because biomass direct storage does not require complex systems that must be customized to each project, biomass direct storage is likely to achieve cost reductions with scaling.[371] Further cost reductions could be driven by increasingly standardized designs and logistics optimization.[372] However, the low cost already biomass direct storage decreases the likelihood of significant future cost reductions.

Rating: Medium

Duration

Risk of reversal. Biomass direct storage can remove and store carbon with significant risk of reversal over 1,000 years.[373] The risk of reversal stems from the possibility of biomass decomposition, which can occur if the biomass is exposed to fire, pests, or human disturbance. This can be mitigated through project design and monitoring.[374] However, although biomass is buried in conditions to prevent decomposition, it is not expected to prevent decomposition on a geologic timescale. Although some environments, like the arctic, can further prevent decomposition, biomass direct storage in Massachusetts would be expected to have this reversal risk.[375]

<u>Rating</u>: Significant risk of reversal over 1000 years

Operating lifetime of a plant. For biomass direct storage, the operating lifetime of a project is 20 to 50 years. Studies have modeled a 30-year operating lifetime, but project lifetime will likely vary depending on feedstock and storage location.[376] Biomass direct storage projects in Massachusetts would likely align with this range of project lifetimes due to the active lifetimes of landfills in the state.[377]

<u>Range</u>: 20 to 50 years

Technology Readiness Level

Biomass direct storage is currently at the pilot to demo scale (TRL 6 to 8).[378] Projects are occurring, such as Mast Reforestation's 5 kt project in Montana, Woodcache's 1 to 100 kt operations in Colorado, and Vaulted Deep's two sites for injection in Kansas and California.[379] Multiple purchase agreements have occurred from the hundred to the tens of thousands of tCO_2 scale.[380] Additional project deployments and process improvements can help advance biomass direct storage's technological maturity.[381]

<u>Range</u>: TRL 6 to 8

Measurement, monitoring, reporting, and verification (MMRV)

Biomass direct storage MMRV is developing. The mass of biomass buried can directly measured and converted to CO_2 equivalent, though this exact measurement technique and the conversion factor will depend on the specific process and feedstock.[382] MMRV protocols from major carbon credit registries exist, such as Puro.earth's Terrestrial Storage of Biomass Standard,[383] and some producers like DuraVault have established their own frameworks.[384] Despite this, challenges in the MMRV process exist in the storage monitoring, which is necessary to ensure that the conditions needed to prevent biomass decomposition stay present. Direct measurement can monitor any CO_2 leakage in real-time, but any accounting for future leakage will likely require modeling.[385] It will be important that as biomass direct storage develops as a technology and more projects are deployed, MMRV protocols will evolve to address these challenges.

<u>Rating</u>: Developing

Deployment Timelines

Biomass direct storage projects have not yet been deployed in Massachusetts and no projects are currently planned in-state. As a result, the scale of deployment to date is zero tCO_2e removed as of November 2025. For deployment in Massachusetts' future, biomass direct storage pathways would fall under the jurisdiction of existing landfill and solid waste management regulations which protect against negative environmental impacts. Massachusetts regulations that would be relevant to biomass direct storage projects would include solid waste management standards under 310 CMR 19.000, MassDEP's solid waste disposal and facility guidance under 310 CMR 19.017 and 310 CMR 19.062, and the Massachusetts Environmental Policy Act.[386] [387] [388] [389] In terms of deployment, companies in the biomass direct storage space have reported a timeline of approximately one year from project planning to the first delivery of credits, assuming a rigorous MMRV process and continued monitoring. The necessary planning for biomass direct storage projects can take approximately six to twelve months, based on existing deployments in other US states, while issuance of credits can occur within 6 months of completing the burial process.[390] Overall, the deployment timeline for biomass direct storage projects is between one and two and a half years from initial planning to first issued credits, depending on project citing, feedstock availability, and local regulations.

Resource Requirements

The main requirement is biomass feedstock. Because the biomass is the source of carbon removal, biomass direct storage projects will scale with the amount of feedstock used. Estimates suggest that approximately 0.5 to 1 t biomass is needed per tCO_2, depending on the carbon content of the feedstock.[391] Otherwise, resource requirements for biomass direct storage are low when using waste biomass, such debris from wildfires.[392] Using biowaste reduces the need to use additional water and land to grow biomass. If growing dedicated crops for biomass direct storage was part of the process, significant water would be required (on the order of 6 Gt of water/tCO_2).[393] Land use for biomass direct storage outside of biomass feedstock production is minimal, since the biomass is buried underground. Energy use is minimal and depends on biomass transportation.[394]

Rating (Water): Low (using biowaste)
Rating (Land): Low (using biowaste)
Rating (Energy): Low
Rating (Feedstock): Medium

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of biomass direct storage in Massachusetts is around 800,000 to 1.2 million tCO_2e per year, which is rated as medium and represents approximately 6 to 8% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leveraged data from the Department of Energy's 2023 Billion-Ton report and ranges of conversion factors for converting biomass to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue, over 20,000 dry tons of agricultural biomass residue, and over 60,000 dry tons of other wet waste (e.g., sludge).[395] Conversion factors range from 1-2 tCO_2e per dry ton across biomass types.[396] [397] By multiplying available biomass residues with relevant conversion factors, and adding the total removals across residue type, the removals range is estimated. This range assumes that all available residual biomass in Massachusetts will be used for biomass direct storage which restricts the available feedstock for other biomass reliant CDR pathways.

Rating: Medium

Risks to growth: While the estimated maximum potential deployment of biomass direct storage is around 800,000 to 1.2 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including project siting and feedstock source co-location, as well as a lack of clarity regarding regulatory requirements. Project siting will be the largest risk to ensuring maximum carbon removal benefits of biomass direct storage deployments. Peer-reviewed life cycle assessments of wood vault pathways show that the net climate benefit is highly sensitive to decay parameters and transport distance. Carbon removal efficiency ranges from as low as 38% (<500km) to as high as 66% (<100km) of total biomass depending on the required distance of haul length from source to storage.[398] Moreover, although the land above the vault can be returned to its previous use, installing a project would pause any operations or use of the land. As for regulatory clarity, it is unclear exactly how Massachusetts regulations would apply to biomass direct storage projects, making forecasted deployment difficult to predict. If wood vault projects trigger aspects of the existing Massachusetts regulatory framework, such as MEPA review, public sentiment and environmental controls could impact project siting.[399] Additionally, if Massachusetts solid-waste rules, which require liners, leachate controls, and operating plans for solid waste disposal projects, apply to biomass direct storage projects, these projects could be subject to regulatory reviews that ensure that groundwater and odor risks are managed prior to deployment.[400] Overall, while these risks pose significant uncertainty, especially for aqueous deployments, they are unlikely to be high barriers to deployment and should not limit scale drastically over time.

Rating: Low

Local supply chain

Biomass direct storage CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including environmental engineering and consulting firms, in-state MMRV equipment providers, construction and demolition waste processors, woody debris processors, and heavy machinery suppliers. Multiple in-state environmental engineering and consulting firms could provide a variety of expertise and services relevant to biomass direct storage projects, including capacity for design and building low-permeability cells and covers that keep wood dry or anoxic, navigating permitting and regulations for subsurface waste storage, and quality control and MMRV for existing projects.[401] [402] [403] [404] [405] [406] Additionally, there is at least one in-state technology supplier who could provide equipment for environmental monitoring for critical components such as groundwater testing and soil-gas exchange.[407] Meanwhile, feedstocks for projects could be sourced from the various existing in-state construction and demolition processors and transfer stations, while feedstocks themselves could be transported and processed by an array of MA-based companies who focus on wood hauling and processing.[408] [409] [410] Finally, in-state suppliers of heavy machinery for digging burial vaults, as well as harvesting, transporting and processing woody biomass and debris, could supply relevant equipment like dump trucks, excavators, and backhoes needed for deployments.[411] [412]

Rating: High

Solution providers

Biomass direct storage is already deployed widely and the sector has several solution providers delivering carbon removal from active projects, most notably companies like Mast Reforestation, WoodCache PBC, and Carbon Lockdown.[413] [414] [415] However, Massachusetts does not have solution providers headquartered domestically. Additionally, there are no solution providers conducting projects in state.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Biomass direct storage has the potential to provide moderate co-benefits, including safer handling of low-value woody residues and urban tree waste and alignment with state climate goals. Using underutilized wood from thinning or storm debris for burial could complement sustainable forest management and reduce pile-burning or open decay.[416 417] Massachusetts' 2050 Clean Energy and Climate Plan and "Forests as Climate Solutions" provide policy context for exploring biomass direct storage alongside conservation and forest management.[418 419]

Social and environmental risks: Biomass direct storage has the potential to pose moderate but manageable risks, including methane generation if burial becomes wet/anaerobic. Technical literature flags methane concerns from improperly managed burial and emphasizes strict moisture exclusion.[420]

Health impacts: Biomass direct storage has the potential to pose moderate but manageable health hazards, including trenching/excavation injuries for burial operations and respiratory risks from wood dust. Trenching cave-ins and confined-space hazards could occur and require protective systems and training.[421] Wood-dust exposure is associated with respiratory symptoms and cancer, necessitating controls and personal protective equipment.[422]

Rating: Positive

Economic benefit and job creation

Biomass direct storage has the potential to create between 400 and 800 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by using CDR supplier interviews of employee numbers and scale, combined with the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. The relatively low scale of deployment of biomass direct storage in Massachusetts limits the potential for job creation. Biomass direct storage may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities, farmland, and forested areas in Massachusetts. [423] [424 425] However, project storage will not necessarily be located near these communities and so these jobs may not be available for community members.

Rating: Low

Timber building products

Table 8-5: Timber Building Products Overview

Pathway: Timber building products	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Medium	
Current cost: \$500-1500/tCO_2 **Cost reduction potential:** Low	**Scale potential:** High (4.5 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Significant over 100 years **Facility operating lifetime:** 20-70 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 9; deployed at scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Established	**Economic benefit and job creation:** High
<u>**Resource requirements**</u> ***Water:*** Medium ***Land:*** Medium ***Energy:*** High ***Feedstock:*** Medium	**Earliest planned start time:** Underway

Table 8-5: Timber Building Products Overview

Overview

Timber building products refers to the use of timber products in long-lived building materials, and can include building houses, offices, and other structures out of lumber or engineered timber. CDR from timber building products can count as occurring in Massachusetts as long as the timber is grown in the state, since this step is when the removal takes place.

Timber building products are possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the high scale potential for deployment in the state, due to the state's available timberland. Additionally, due to this high scale potential, there is a significant opportunity for job creation from timber building products. However, timber building products as a CDR pathway face unanswered questions on additionality, which will be important for the state to address if counting on this pathway for its CDR needs. Timber building products also face a significant risk of reversal over 100 years, which the state will have to consider, and is resource intensive, which leads to an overall rating of medium.

There is a moderate potential for Massachusetts to be a leader in R&D for timber building products. Timber building products are well-established and so there are not significant R&D needs for implementation; however, Massachusetts has the potential to deploy timber building products at scale and innovate in process efficiencies, taking advantage of existing mass timber programs already occurring in-state.

<u>Deployment suitability rating</u>: Medium

R&D leadership potential rating: Medium

Cost

Current cost: Current cost estimates for timber building products are estimated at \$500–\$1500 per tCO_2, depending on size of the production facility and type of timber product (i.e., lumber or cross laminated timber).[426] This cost level represents the cost to produce mass timber and therefore represents the cost to remove carbon as well as to provide a timber building product. In Massachusetts, costs may be at the lower end of the range due to previous support and developed expertise on timber building products in the state, such as Boston's Mass Timber Accelerator.[427]

Range: \$500–\$1500 per tCO_2

Cost reduction potential: The potential for cost reduction is low.

Timber building products have medium design complexity (i.e., many components in manufacturing process, a moderate amount of which are mass-produced) and have a moderate need for customization based on timber source and construction site, and therefore fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[428] Timber building products thus are likely to achieve moderate cost reductions with scale, because the production process can benefit from economies of scale while being limited by the need for timber source customization.[429] However, there is also the potential for timber building products to increase in cost in the future due to competing use for land and biomass.

Rating: Low

Duration

Risk of reversal: Timber building products remove carbon and create storage with significant risk of reversal over 100 years,[430] though could create storage with significant risk of reversal over 1000 years with end-of-life plans to pyrolyze or bury the timber.[431] Reversal risks include fire and building deconstruction, which can accelerate wood decomposition and re-release CO_2. Risk mitigation strategies include building fire protection and clear end-of-life plans for the timber upon building demolition. In Massachusetts, timber building products can be expected to face these same reversal risks, though the state's existing work on mass timber innovation suggests the foundation for implementing timber end-of-life plans to increase the duration of carbon storage.[432]

Rating: Significant risk of reversal over 100 years

Operating lifetime of a plant: For timber building products, the operating lifetime of a project can be estimated at 20 to 70 years. Timber manufacturing facilities have been modeled with a 20-year lifetime.[433] The ultimate lifetime of timber building products will depend on the facility they are integrated into, though buildings on average have a lifetime of 50 years.[434] Timber building products in Massachusetts would be expected to align with this range of project lifetimes due to the standardization of construction processes.

Range: 20 to 70 years

Technology Readiness Level

Timber building products are well established and deployed at scale (TRL 9).[435] The 2021 International Building Code approved mass timber for use in three types of buildings, removing permitting hurdles for deployment.[436] Within Massachusetts, projects emphasizing mass timber in buildings have already occurred and more are planned to start, such as through Boston's Mass Timber Accelerator.[437]

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for timber building products is established. The amount of carbon stored in a timber product can be calculated by mass and the exact timber feedstock, which can then be converted to CO_2 using known ratios.[438] Well-established standards exist, including ISO standard 21930, to guide environmental product declarations for construction products.[439] However, challenges still exist in timber building products MMRV, in accounting for the entire life cycle emissions in timber building products. The decision on where to draw the system boundary can be contested, which is key to calculating the net carbon removal of a timber building product.

Rating: Established

Deployment Timelines

Mass timber building product CDR has been deployed at pilot scale in Massachusetts, with initial projects collectively storing approximately 4,500 tCO_2e in the cross-laminated timber and other timber products utilized during construction; it is worth noting, however, that these removals are not validated credits and no Massachusetts project has registered timber building projects with an accredited registry.[440] [441] [442] Future deployments of timber building product CDR will need to continue to adhere to state building materials standards to ensure building safety, including the 10th Edition of 780 CMR, the current Massachusetts State Building Code, and Massachusetts Comprehensive Fire Safety Code, 527 CMR 1.00.[443] [444] In terms of project timelines, length of deployment varies based on building size and permitting requirements. The largest project conducted in Massachusetts to-date took 18 months to construct following a multi-year planning and permitting process; the first public design was issued 18 months prior to breaking ground.[445] While smaller projects could potentially deploy quicker as shared learnings increase, this project also omitted removal registry and verification. A conservative estimate for the overall process would be approximately 3 to 5 years from planning to first credit issuance for future projects when considering methodologies such as Puro.earth's wooden building elements methodology and other credited projects as guidance.[446]

Resource Requirements

The main resource requirements for timber building products are feedstock, land, water, and energy. Although the exact feedstock requirement will depend on the specific composition of the timber building product, approximately 1 m^3 of timber is needed per tCO_2.[447] While the land requirement for using timber in building products is constrained to the footprint of the building, the land requirement is quite large when accounting for the forestry needed to produce the timber; approximately 0.25 hectares per tCO_2 each year is required.[448] Water and energy use will also depend on the specific timber building product, but public environmental product declarations suggest that 0.2 to 0.5 m^3 of water per tCO_2 is needed in the timber production process and that primary energy requirements are 3 to 7 GJ per tCO_2.[449]

Any resources needed for construction with the timber products would be in addition to those outlined here.

Rating (Water): Medium
Rating (Land): Medium
Rating (Energy): High
Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of timber building products in Massachusetts is around 4.6 million tCO_2e per year in 2050, which is rated as high and represents approximately 33% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This scale potential uses data from the USDA on timberland in Massachusetts, estimated to be over 2.8 million acres,[450] and a medium harvesting intensity of 4 tCO_2 per hectare per year. However, this assumes that all timberland in Massachusetts will be used to create timber building products and that all of this will count as additional, which there are ongoing questions about. A potentially more reasonable estimate of 200,000 to 2 million tCO_2e per year was included in the modeling of Improved Wood Utilization in the Massachusetts Forest Carbon Study.[451] By comparing the Forest Carbon Study's business-as-usual versus improved wood utilization scenarios to one another (tables 18 and 19), the additional carbon stored in wood products, with improved wood utilization, could be estimated. It is important to note that timber and forests act in parallel, and the creation of wood products from timber decreases the amount of sequestration that forests will do.

Rating: High

Risks to growth: While the estimated maximum potential deployment of timber building product CDR is as much as 4.6 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including uncertainty with additionality and how removals will be counted, the need for updated regulations and building codes, and the state's lack of domestic cross-laminated timber product manufacturing. The most immediate operational risk for timber building product CDR is that the rules that determine how to quantify removals (I.e. when, how, and for how long biogenic carbon stored in buildings "counts" as CDR) have not yet been clarified, especially around additionality. Recent technical reviews show inconsistent treatment of biogenic carbon in Environmental Product Declarations (EPDs) and life-cycle assessments, which leads to uncertainty for buyers, credit developers, and policymakers about baselines and double counting across forests and products.[452] Additional issues arise for the deployment of mass timber products when considering product integration into building standards and codes.[453] Outdated building regulations may prevent the use of many mass timber products in construction due to prior concerns around fire safety and structural integrity, and these codes will need to be updated to move forward with scaled deployment. A final consideration for barriers to scaling Massachusetts timber building product CDR is the lack of in-state manufacturing for cross-laminated timber. The New England region lacks an established, large-scale cross-laminated timber (CLT) manufacturing operation, so Massachusetts projects would likely rely on distant suppliers, increasing cost, lead times, and logistical risk.[454] This could be a potentially larger risk, as timber for timber building product CDR projects needs to be sourced from in-state sources in order to be counted towards MA overall removals; If Massachusetts must source CLT from an outside provider, than those removals would belong to the state where they are produced, not where they end up being utilized in construction.

Rating: Medium

Local supply chain

Timber building product CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact three sectors in the state's economy, including domestic wood production, local architectural and engineering firms, and in-state heavy machinery suppliers for material harvest and transport. Companies who source domestic wood products for in-state construction provide the necessary inputs for timber building products, as well as the critical processing components needed prior to construction or fabrication of cross-laminated timber (CLT). Massachusetts has several in-state sawmilling and kiln drying companies that could provide services to support regional wood supply chains already used on Massachusetts projects.[455] [456] [457] Local architectural and engineering firms with experience working with timber building materials and navigating in-state building codes are also prepared to support timber building product CDR and there are a variety of in-state firms with expertise in timber building construction who can support pathway deployment.[458] [459] [460] Finally, heavy machinery critical for harvesting, transporting, and processing wood products prior to implementation will mean local suppliers of equipment can both benefit from and support increased demand as a result of timber building product CDR deployment. There is a wide range of in-state suppliers who stand ready to provide equipment like front loaders and back hoes that will be crucial for rolling out this pathway.[461] [462] [463]

Rating: Medium

Solution providers

Timber building product CDR is widely deployed and has many solution providers, both globally and domestically, who are producing cross-laminated timber (CLT) or glulam products for biogenic sequestration in built structures. However, Massachusetts does not have solution providers headquartered in state, with the existing Massachusetts mass timber projects sourcing their CLT or glulam products from other regional producers.[464] While the state does not have any solution providers who are producing mass timber products in state, Massachusetts does have a series of local contracting, architect and construction agencies conducting mass timber projects in state with the support of government programs; state programs are working to catalyze small scale mass timber projects, having sponsored more than 10 projects in the last 3 years that are all aimed at reducing embodied carbon in new construction projects.[465] [466]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Timber building products have the potential to provide significant co-benefits, including reducing greenhouse gas emissions and protecting water resources. Increased use of engineered wood in mid-rise construction could displace emissions from steel and concrete.[467] The Massachusetts Department of Conservation & Recreation notes that local harvesting under state best practices could reduce transport emissions and maintain water-resource protections.[468]

Social and environmental risks: Timber building products have the potential to pose moderate but manageable risks, including biodiversity and soil-nutrient impacts, land use pressures, and a decrease in water quality. Intensified or poorly managed harvests could lead negative impacts on biodiversity and soil nutrients,[469] as well as potential land-use pressures when wood substitutes other materials at scale.[470] Water-quality and stream-habitat effects could occur if best management practices are not followed.[471]

Health impacts: Timber building products have the potential to pose moderate health risks/hazards, including respiratory and air quality risks. Timber building products could expose workers wood dust (a well-known human carcinogen) and respiratory sensitizers, requiring ventilation and exposure controls.[472] Composite-wood adhesives could emit formaldehyde, but the US Environmental Protection Agency sets emission limits to protect indoor air quality.[473]

Rating: Positive

Economic benefit and job creation

Job creation: Timber building products have the potential to create between 18,000 and 90,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by using technical estimates of CO_2 removed per volume of timber,[474] industry-wide estimates of jobs created per volume of timber,[475] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. The high potential for job creation stems from Massachusetts' high scale potential for timber building products and the large volume of timber material that would need to be produced to reach this scale. Timber building products are likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and timber mills.[476] [477]

Rating: High

Other biomass building products

Table 8-6: Other Biomass Building Products Overview

Pathway: Other biomass building products	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Medium	
Current cost: \$50-10,000/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Low (0.1 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Significant over 100 years **Facility operating lifetime:** 20-70 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 9; commercial scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Established	**Economic benefit and job creation:** Low
Resource requirements ***Water:*** High	**Earliest planned start time:** Underway

Land: Low (using biowaste) ***Energy:*** Medium ***Feedstock:*** Medium	

Table 8-6: Other Biomass Building Products Overview

Overview

Other biomass building products involve integrating biomass, such as agricultural and forestry waste, hemp, and low-quality wood, into construction products, such as insulation and flooring.

Other biomass building products are unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, which is limited by the available biomass residue in the state. Due to this low scale potential, there is also limited opportunity for job creation from other biomass building products. Other biomass building products also face a significant risk of reversal over 100 years, which the state will have to consider if choosing to implement as a CDR pathway.

There is a moderate potential for Massachusetts to be a leader in R&D for other biomass building products, because novel other biomass building products are actively being developed. Although Massachusetts has minimal scale potential for this pathway, the state can integrate R&D efforts into its existing building decarbonization efforts.

Deployment suitability rating: Low
R&D leadership potential rating: Medium

Cost

Current cost: the current cost for other biomass building products ranges from \$50 per tCO_2 to \$10,000 per tCO_2.[478] Many biomass building products have costs comparable to the conventional product types they would replace. For example, hemp fiber batt for cavity insulation is on average \$1.79 per ft^2, while fiberglass batt is average \$1.06 per ft^2.[479] Therefore, biomass building products do not represent much of an additional cost as a building material replacement. However, biomass building products can be expensive per tCO_2 removed depending on the material used. Massachusetts can be on the lower end of this range by making use of waste biomass in the state.

Range: from \$50 to \$10,000 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Biomass building products have medium design complexity (i.e., many components in manufacturing process, a moderate amount of which are mass-produced) and have a moderate need for customization based on biomass source and construction site, but on average fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[480] This means that because biomass building products involve production processes that can be standardized, they are likely to achieve a moderate potential for cost reduction with scale.[481] Because multiple biomass building products are at or near cost parity to conventional building materials,[482] scaling will be key to decreasing costs.

Rating: Medium

Duration

Risk of reversal: Biomass building products are similar to timber building products in that they create storage with significant risk of reversal over 100 years,[483] though could create storage with significant risk of reversal over 1000 years if biomass is buried or pyrolyzed at end-of-life.[484] Reversal risks include fire and building product deconstruction, which can re-release CO_2. Risk mitigation strategies include building fire protection and clear end-of-life plans for the building products upon building demolition. In Massachusetts, other biomass building products can be expected to face these same reversal risks, though the state's existing work on mass timber innovation suggests the foundation for implementing building product end-of-life plans to increase the duration of carbon storage.[485]

Rating: Significant risk of reversal over 100 years

Operating lifetime of a plant: For other biomass building products, the operating lifetime of a project is typically 20 to 70 years. Biomass building product manufacturing facilities can be modeled with a 20 year lifetime after timber manufacturing.[486] The lifetime of biomass building products will depend on the facility they are integrated into, though buildings on average have a lifetime of roughly 50 years.[487] Other biomass building products in Massachusetts would be expected to align with this range of project lifetimes due to the standardization of construction processes.

Range: 20 to 70 years

Technology Readiness Level

Biomass building products are at commercial scale (TRL 9).[488] Biomass building products have been integrated into new construction, such as the Zero House by Endeavour Centre.[489] Companies such as Rare Forms in Massachusetts are creating Accessory Dwelling Units construction kits with straw.[490] However, other biomass building products consist of many different materials; some like straw, hemp, and bamboo are being deployed now while others, like mycelium, are at an earlier stage of development.

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for biomass building products is established. Similarly to timber building products, the amount of carbon stored by biomass can be quantified using known mass ratios. Standards exist, like ISO standard 21930, to help clarify how to create environmental product declarations for construction products.[491] However, also like timber building products, challenges in MMRV still exist, particularly in accurately accounting for the entire lifecycle emissions of a product.[492] The decision on where to draw the system boundary can be contested, which is key to calculating the net carbon removal of a biomass building product.

Rating: Established

Deployment Timelines

Biomass building product CDR has been deployed at pilot scale in a select number of small residential projects in Massachusetts, and continued pilot deployments are planned over the next 2-3 years.[493] [494] [495] However, the current scale of removals is minimal, with the largest completed projects reporting to have removed and stored approximately 12 tCO_2e in construction materials.[496] Future deployments of biomass building product CDR will need to adhere to state building materials standards and building codes to ensure building safety; this includes the 10th Edition of 780 CMR, the current Massachusetts State Building Code, and Massachusetts Comprehensive Fire Safety Code, 527 CMR 1.00.[497] [498] Because of the nascency of biomass building product projects for CDR, deployment timelines from planning to first issued credits are difficult to estimate. The 12 tCO_2e project noted above took over a year from pre-construction and planning to completion, though this project is much smaller than builds that would generate larger removals.[499] [500] However, this project did not register and verify its removal with a registry, and very few registries have a designated methodology for alternative biomass building products, such as hempcrete.[501] Given the uncertainties, an estimate for future large-scale deployments could be similar to mass timber building product projects, with approximately 2 to 3 years from planning to completed construction and 3 to 5 years from project planning to first issued removals.

Resource Requirements

The main resource requirements for other biomass building products are feedstock, water, and energy. Biomass building products consist of many different materials, and so resource requirements will vary by product and feedstock. Using straw insulation as an example, public environmental product declarations suggest that approximately 0.75 t straw is needed per tCO_2, 20 m^3 of water is needed per tCO_2, and 500 MJ of energy is needed per tCO_2 during the production process.[502] Using wheat straw and other waste biomass does not require additional land use, though purpose grown crops may require significant land use change.[503] Otherwise, the land requirement for using biomass in building products is constrained to the footprint of the building. Any resources needed for construction with the biomass products would be in addition to those outlined here.

Rating (Water): High
Rating (Land): Low
Rating (Energy): Medium
Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of other biomass building products in Massachusetts is 115,000 to 130,000 tCO_2e, which is rated as **low** and represents less than 1% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages data from the Department of Energy's 2023 Billion-Ton report and a range of conversion factors for converting biomass to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue and over 20,000 dry tons of agricultural biomass residue.[504] The range excludes other wet waste (e.g., sludge) because, currently, other biomass building products do not utilize other wet waste materials.[505] Conversion factors range from 1.5-2 tCO_2e per dry ton across forest and agricultural residues.[506] [507] By multiplying available residues with relevant conversion factors, and adding the total removals across residue type, the removals range is estimated. This range relies on the assumption that all agricultural and forest residual biomass in Massachusetts will be used for other biomass building products which restricts the available feedstock for other biomass reliant CDR pathways.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of other biomass building products is estimated to be approximately 115,000 to 130,000 tCO_2e per year, there are existing risks that could prevent deployment at this scale or make deployment at this scale inadvisable, including competition with existing biomass sources, lack of familiarity and inclusion in state building codes, difficulty securing insurance due to material nascency, and higher initial costs due to custom and non-mass produced components. Competition from existing industries, such as bioenergy power generation, means that allocating all available eligible waste biomass to biomass building products is unlikely. From an implementation standpoint, adoption of biomass building material CDR can be slowed by limited installer familiarity, insurer caution, and perceived fire/moisture risks for unfamiliar materials.[508] In Massachusetts, the alternate-means path is available under 780 CMR §104.11, but it requires robust test data or research reports, which could add time and transaction costs to utilization, particularly for small manufacturers.[509] Lack of proper insurance coverage for buildings that utilize biomass building products also is a significant barrier to scale; if a project cannot be insured, developers are unlikely to move forward with alternative building materials. Because of the lack of long-term data on products like hempcrete, insurance underwriters may be cautious to approve projects utilizing uncommon materials.[510] Finally, higher initial costs could delay or risk preventing widespread adoption of biomass building product CDR, as developers, particularly at the commercial level, are less inclined to use more expensive materials unless incentivized to do so.[511] A survey of construction experts carried out by an article in the journal of Building Research and Innovation found unanimous agreement that initial costs for bio-materials would be significantly higher than traditional materials, and that this would prevent widespread adoption unless addressed.

Rating: High

Local supply chain

Biomass building product CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least three sectors in the state's economy, including biomass insulation producers, hemp-lime producers and fabricators, and suppliers of machinery necessary for biomass building material production and installation. Massachusetts has at least one in state producer of cellulose insulation, a wood-based product replacement for traditional insulation like fiberglass, which creates a domestic source for biomass CDR projects and an end use for wood-derived products like cardboard or paper.[512] The state also has production and fabrication capacity for hemp-lime building products, which can be used for walls, roofing, and load-bearing structures and offers a biomass-derived replacement to traditional concrete or steel materials.[513] [514] Finally, MA also has a number of suppliers who could support deployment by providing equipment needed for both implementation and production of biomass building products; these include suppliers for cellulose insulation blowing-machinery used in installation, as well as heat-seal machines for producing stable biomass components like insulation panels.[515] [516]

Rating: Medium

Solution providers

Biomass building product CDR is widely deployed and has many active solution providers, both globally and domestically. Massachusetts already has solution providers headquartered in state, including hemp-lime producer HempStone, as well as cellulose insulation company National Fiber, who manufactures cellulose insulation.[517] [518] These in-state solution providers are also conducting initial projects in Massachusetts, including the first hempcrete residential building in the state at Goshen's Hemp House, which will store ~12 tCO_2e, as well as HempStone's Cape Cod Hemp House, which utilizes carbon-storing hempcrete throughout the building.[519] [520]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Other biomass building products have the potential to provide moderate co-benefits, including useful building performance. Mycelium-based panels and foams made from agricultural residues could show strong thermal and acoustic insulation with favorable fire behavior compared with many synthetics.[521] Hemp-lime ("hempcrete") assemblies could help regulate indoor humidity when designed appropriately.[522] Using crop or residue fibers with non-formaldehyde binders (e.g., citric acid or lignocellulosic nanofibrils) could valorize farm by-products and avoid added formaldehyde emissions.[523] [524]

Social and environmental risks: Other biomass building products have the potential to pose significant but manageable risks, including land-use competition and nutrient pollution from purpose-grown crops. Expanding biomass cultivation can displace other land uses including food production.[525] Excess nitrogen from increased crop growth could exacerbate eutrophication and acidification in the already impaired estuaries in Massachusetts, degrading eelgrass and shellfish habitat central to coastal economies.[526] [527] Using waste biomass as feedstock can mitigate these risks.

Health impacts: Other biomass building products have the potential to pose moderate but manageable health hazards, including chemical exposures and dust. Isocyanate-based binders used in some biomass panels could cause occupational asthma during manufacturing and installation.[528] [529]

Rating: Positive

Economic benefit and job creation

Other biomass building products have the potential to create between 200 and 500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by modeling the number of additional jobs that would be created through the harvesting of forestry and agricultural waste residue and the production of building products from this biomass. The estimate of jobs from the harvesting of biowaste was based on CDR supplier interviews of employee numbers and scale. The estimate of jobs from production was generated using industry wide estimates of manufacturing jobs created per biomass building product produced,[530] a range of removal efficiencies of biomass,[531] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. The low potential for job creation stems from Massachusetts' limited scale potential for other biomass building products. Other biomass building products may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities,[532] farmland,[533] and forested areas in Massachusetts.[534] However, manufacturing facilities will not necessarily be located near these communities and so these jobs may not be available for community members.

Rating: Low

Pyrolysis (biochar) and storage

Table 8-7: Pyrolysis (Biochar) and Storage Overview

Pathway: Pyrolysis (biochar) and storage	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Low	
Current cost: $10-350/tCO_2$ **Cost reduction potential:** Medium	**Scale potential:** Low (0.4- 1.1 million tCO_2e/y) **Risks to growth:** Low
Risk of reversal: Significant over 1000 years **Facility operating lifetime:** 1-10 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 7-9; demo to commercial scale	**Co-benefits and potential negative impacts:** Positive
Measurement readiness: Developing	**Economic benefit and job creation:** Medium
Resource requirements ***Water:*** Low (using biowaste) ***Land:*** Medium ***Energy:*** Medium ***Feedstock:*** High	**Earliest planned start time:** June 2026

Table 8-7: Pyrolysis (Biochar) and Storage Overview

Overview

Pyrolysis (biochar) and storage refers to the process of heating biomass in the absence of oxygen to create solid char. In practice, biochar is often added to fields or soils as a soil amendment. Additionally, biochar can be combined with compost, added to concrete, or buried as stable carbon.

Pyrolysis (biochar) and storage is possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, which is limited by the available biomass residue in state. Due to this low scale potential, there is also limited opportunity for job creation from pyrolysis (biochar) and storage. However, minimal risks to growth and potential co-benefits increase the likelihood of deployment, resulting in an overall deployment suitability rating of medium.

There is a low potential for Massachusetts to be a leader in R&D for pyrolysis (biochar) and storage because the pathway is mid-to-late TRL and so has narrowed its R&D needs. Though there are still open research questions on the duration of storage, the relatively developed nature of pyrolysis (biochar) and storage limits the state's R&D leadership potential.

<u>Deployment suitability rating</u>: Medium

<u>R&D leadership potential rating</u>: Low

Cost

Current cost: The current cost for pyrolysis (biochar) and storage ranges from $10–$350/tCO_2$,[535] while a Massachusetts-specific research study estimates a range of $80–$120/tCO_2$ if biochar was at commercial scale in the state.[536] This cost level is driven by the limited capital expenses and inexpensive feedstock needs.

Range: \$10–\$350/tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Biochar has medium design complexity (i.e., moderate number of components, of which a moderate amount of them can be mass-produced) and has moderate need for customization based on the application site, and thus fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[537] This means that because biochar technology can be relatively standardized it can benefit from economies of scale, but its potential is limited by its moderately complex design, especially for novel biochar systems.[538] Therefore, biochar is likely to achieve moderate cost reductions with scale.[539] Costs can also fall through increasing project standardization, as well as through application siting near feedstock. However, costs may also increase with scale due to competition for application sites (often farmland) and for feedstock (such as waste biomass residues).

Rating: Medium

Duration

Risk of reversal. Biochar creates carbon storage with significant risk of reversal over 1,000 years.[540] Pyrolysis converts biomass material into a form that decays more slowly than typical organic material, though the ultimate storage timescale depends on pyrolysis temperature and biomass material.[541] Biochar can also have a lower risk of reversal through integration into durable products.[542] Reversal risk may occur through mineralization or soil leeching.[543] However, the duration of carbon storage from biochar is an active field of research. While many methodologies require 200 years of storage for biochar,[544] recent academic studies suggest that some portion of biochar remains inert for millions of years.[545] Massachusetts should expect biochar to create storage with significant risk of reversal over 1,000 years but should regularly update expectations based on the best available science.

Rating: Significant risk of reversal over 1000 years

Operating lifetime of a plant. For biochar, the operating lifetime of a project is typically 1 to 10 years. Biochar can be used as an agricultural soil amendment and so would be applied on an annual basis, while biochar production equipment is typically modeled with a 10-year lifetime.[546] Biochar projects in Massachusetts would be expected to align with this range due to the general standardization of pyrolysis machinery. However, if used as a soil amendment in Massachusetts, biochar application rates will depend on local agricultural and soil practices.

Range: 1 to 10 years

Technology Readiness Level

Biochar is at the demo to commercial scale (TRL 7-9).[547] Biochar can be produced in multiple technology configurations which are at different levels of maturity (e.g., slow pyrolysis is fully commercial while gasification-derived char and fast-pyrolysis pathways are earlier).[548] Significant biochar offtake agreements have occurred in the past few years, on the order of the tens of thousands to millions of tCO_2 scale.[549] In Massachusetts, active vendors (e.g., New England Biochar systems) indicate deployment is actively occurring.[550]

Range: TRL 7 to 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for biochar is developing. The amount of CO_2 removed is calculated by using quantifiable mass and energy balances through the pyrolysis process.[551] Multiple MMRV methodologies from major carbon credit registries exist for biochar, including Puro.earth and Verra.[552] However, challenges still exist in the MMRV process, particularly due to the uncertainty around the amount of biochar degradation over time, the ultimate storage duration of biochar in soil, and the interactions of biochar with the soil microbiome.[553] Additional research and modeling is needed to quantify these parameters, which is essential to accurately crediting the amount of carbon removal from biochar processes. Moreover, if biochar is used as a soil amendment on agricultural soils, measurement and monitoring after application can be difficult due to the large land area needed for sampling and the extra labor required. Improved modeling can also help with these challenges.

Rating: Developing

Deployment Timelines

Biochar CDR projects have not been deployed in Massachusetts and, while the pathway is already at commercial scale elsewhere, no deployments for Massachusetts -based biochar CDR projects are currently planned. If future projects are planned, however, they will need to follow a host of in-state guidance on combustion and air pollutants, biosolid application, and solid waste conversion facilities.[554] [555] [556] Pyrolysis facilities will need to abide by MassDEP Air Plan application process to ensure danger from air pollutants are minimized.[557] Furthermore, Massachusetts has strict policies on land application of treated byproducts derived from biosolids for environmental safety, especially those produced from sanitary wastewater sludge, drinking water treatment facility sludge, and short paper fiber, potentially restricting biochar feedstocks.[558] Projects will likely also need to adhere to solid waste disposal facility guidance already in place in MA.[559] These are in addition to the standard MEPA review, given that biochar facilities will require emissions permitting from the state.[560] Given the fact biochar is widely deployed outside of MA, drawing on existing project information helps to create a deployment timeline estimate. Commercial biochar facilities take anywhere from three to seven years to go from planning to implementation, and another six to twelve months to verification and issuance of first credits, putting the overall timeline for implementation at approximately four to eight years.[561] [562] At pilot scale, biochar projects could be deployed at a much faster rate, leveraging in-state pyrolysis providers and concentrating on small scale deployments. Verification and credit issuance timelines would remain the same, though pilot biochar deployments could move from planning to operations in as few as six months.[563]

Resource Requirements

The main resource requirements for pyrolysis (biochar) and storage is biomass feedstock, land, and energy. The exact amount of biomass needed will depend on feedstock and process specifics, but estimates range from 1 to 4 t biomass per tCO_2.[564] Biochar can use biowaste, such as woody residues from forestry operations, reducing the need to both grow additional biomass and to use additional water and land to grow the biomass. However, growing dedicated crops for biochar would require significant water on the order of 6 Gt of water per tCO_2, as well as additional land.[565] Land use for biochar application, excluding land for feedstock production, will increase with the scale of project but will generally be large, with a Massachusetts-specific study modeling 18 t biochar applied per acre.[566] Energy use is process dependent but the most energy intensive step is pyrolysis, with estimates suggesting on the order of 10 MJ needed as an input per kg of biochar.[567] Additional energy will be needed for feedstock transportation and application of the biochar.

Rating (Water): Low (using biowaste)
Rating (Land): Medium
Rating (Energy): Medium
Rating (Feedstock): High

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of pyrolysis (biochar) and storage in Massachusetts is 400,000 to 1.1 million tCO_2e, which is rated as low and represents approximately 3-8% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages data from the Department of Energy's 2023 Billion-Ton report and a range of conversion factors that convert biomass to biochar and biochar to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue, over 20,000 dry tons of agricultural biomass residue, and over 600,000 dry tons of other wet waste (e.g., sludge).[568] Conversion factors range from 0.1-0.6 tons of biochar per dry ton across the different residue types,[569] [570] [571] and the conversion factor of biochar to removals ranges from 1.9-2.7 tCO_2e per ton of biochar.[572] By multiplying available residues with relevant conversion factors, adding total biochar across residue type, and converting biochar to tons of removals, the removals range is estimated. This range relies on the assumption that all residual biomass in Massachusetts will be used for biochar creation, which restricts the available feedstock for other biomass reliant CDR pathways. Biochar and bio-liquid are oftentimes produced in the same process, so the production of one does not preclude the other.[573]

Rating: Low

Risks to growth: While the estimated maximum potential deployment of biochar CDR is 400,000 to 1.1 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including environmental risks associated with contaminant production and leaching during pyrolysis, the ability to procure sufficient biomass, regulatory constraints which could delay or hinder large scale projects, and open questions on MMRV. Contaminants are a manageable but non-trivial risk for biochar production; recognized standards set limits for PAHs and metals and prescribe testing/traceability that facilities should adopt or exceed.[574] Ensuring that biochar is lab-tested with high efficacy prior to deployment will help to mitigate risks associated with soil contamination, decomposition, and carbon removal reversals. Additionally, in Massachusetts, new pyrolysis units would likely require MassDEP Plan Approval under 310 CMR 7.02. Recent Cumulative Impact Analysis (CIA) requirements expand the analytical scope for this approval process, which could lengthen schedules and add cost to deployments.[575] From a feedstock perspective, end uses like heat and energy generation, as well as composting for agricultural uses, could create competition for feedstock, particularly for agricultural residues. Massachusetts waste bans and organics rules for recycling and disposal would likely need to be altered to ensure eligible biomass could be prioritized for biochar production, rather than alternative end uses like composting.[576] Finally, challenges still exist in the MMRV process, particularly due to the uncertainty around the amount of biochar degradation over time, the ultimate storage duration of biochar in soil, and the interactions of biochar with the soil microbiome.[577] These questions will need to be answered to enable biochar deployment at scale.

Rating: Low

Local supply chain

Biochar is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact three sectors in the state's economy, including pyrolysis reactor manufactures, biochar retailers, and forestry services focused on disposal and vegetation management. Massachusetts has in-state capacity for reactor sourcing, with at least one company located in state focused on design and installation of pyrolysis retorts, the primary technology for biochar generation and a necessary component for any project deployments.[578] The state also has a variety of local retail distributors who sell biochar to retail and wholesale customers and collaborate with existing in-state and regional solution providers to bring biochar products to market; these businesses could be important for ensuring smaller landowners without financial means for an on-site pyrolysis unit can still implement biochar deployment in practice.[579] Finally, the state has a wide range of forestry service providers who primarily manage tree and vegetation removal and disposal; the deployment of biochar projects could create an alternative revenue stream for these businesses and increase their demand as woody debris sources are identified and prioritized for processing and removal.[580] [581]

Rating: Medium

Solution providers

Biochar is widely deployed and has many active solution providers. Massachusetts has solution providers headquartered in state as well, including New England Biochar and NextChar.[582] [583] These two solution providers are already conducting operations in state but both currently sell biochar and pyrolysis equipment primarily as for soil amendment purposes, with no projects or credits for biochar deployment registered in state according to leading registries;[584] [585] [586] New England biochar offers wholesale and retail supplies of its biochar product, while Nextchar sells biochar produced by its state of the art pyrolysis systems.[587] More notably, Standard Biocarbon, while not based in Massachusetts, is a large biochar company that operates in Massachusetts, and is also already selling its products via Massachusetts-based retailers.[588]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Pyrolysis (biochar) and storage has the potential to provide significant social and environmental co-benefits, including improved soil water retention and nutrient management, and reduced nutrient runoff to sensitive estuaries. Meta-analyses show biochar could increase plant-available water and could reduce runoff/erosion.[589] [590] Reviews also find reduced nitrate leaching when biochar is applied appropriately, which could aid ongoing nitrogen-reduction programs in Cape Cod and South Shore estuaries.[591] [592] Additionally, using biomass to create biochar could potentially reduce other fossil emissions, because the heat generated by biochar facilities can be used for other processes that require heat and creating biochar from wet biomass can reduce methane that would have come from decomposition, though this will depend on many factors.

Social and environmental risks: Pyrolysis (biochar) and storage has the potential to pose moderate but manageable risks including contaminants in biochar. Contaminant risks (PAHs, metals) depend on feedstock, like treated wood, and operating conditions.[593 594]

Health impacts: Pyrolysis (biochar) and storage has the potential to pose moderate but manageable health hazards, including worker exposure to dust and combustion by-products and community exposure to uncontrolled stack emissions. Biochar dust could result in respiratory and eye irritation.[595] Pyrolysis facilities could produce emissions harmful to human health such as particulate matter, criterial air pollutants, and volatile organic compounds.[596]

Rating: Positive

Economic benefit and job creation

Pyrolysis (biochar) and storage has the potential to create between 500 and 3,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment,[597] assuming a similar job creation profile as pyrolysis (bioliquid) and storage, and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Pyrolysis (biochar) and storage may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities,[598] farmland,[599] and forested areas in Massachusetts.[600] However, project pyrolysis facilities will not necessarily be located near these communities and so these jobs may not be available for community members.

Rating: Medium

Pyrolysis (bioliquid) and storage

Table 8-8: Pyrolysis (Bioliquid) and Storage Overview

Pathway: Pyrolysis (bioliquid) and storage	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Medium	
Current cost: \$450-600/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Low (0.4-0.5 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 10-70 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 6-7; pilot to demo scale	**Co-benefits and potential negative impacts:** Positive

Draft, for consideration, not final

Measurement readiness: Developing	Economic benefit and job creation: Low
Resource requirements ***Water:*** Low (using biowaste) ***Land:*** Low (using biowaste) ***Energy:*** Medium ***Feedstock:*** Medium	**Earliest planned start time:** Between December 2026 and January 2028

Table 8-8: Pyrolysis (Bioliquid) and Storage Overview

Overview

Pyrolysis (bioliquid) and storage is the process of heating biomass in the absence of oxygen to produce a bioliquid, sometimes called bio-oil. The bioliquid is then stored, typically underground.

Pyrolysis (bioliquid) and storage is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, which is limited by the available biomass residue in state. Due to this low scale potential, there is also limited opportunity for job creation from pyrolysis (bioliquid) and storage. However, high local supply chain relevance increases the likelihood of deployment, resulting in an overall deployment suitability rating of medium.

There is a moderate potential for Massachusetts to be a leader in R&D for pyrolysis (bioliquid) and storage. The pathway still has open research questions, such as on MMRV, and Massachusetts may be well-suited to lead on bio-liquid injection into Class V wells, which are present in-state.

Deployment suitability rating: Medium
R&D leadership potential rating: Medium

Cost

Current cost: The current cost of pyrolysis (bioliquid) and storage is estimated to be \$450 to \$600 per tCO_2.[601] This cost level is driven by the need, at the moment, for small scale manufacturing of the specialized pyrolysis equipment and for the additional costs of bioliquid injection. In Massachusetts, cost may be at the lower end of the range due to the presence of over 2,500 Class V wells in the state, which are the primary well used for bioliquid injection.[602]

Range: \$450 to \$600 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Bioliquid systems have medium design complexity (i.e., moderate number of components, of which a moderate amount of them can be mass-produced) and have moderate need for customization based on the application site, and thus fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale). This means that because bioliquid systems can benefit from economies of scale due to their ability to be standardized, the potential for cost reduction with scaling is limited by its moderately complex design. Therefore, biochar is likely to achieve moderate cost reductions with scale.[603] Costs may also decline through process logistic improvements, by siting bioliquid systems near feedstock.[604] However, costs may also increase with scaling due to limited available storage sites.

Rating: Medium

Duration

Risk of reversal. Bioliquid creates storage with negligible risk of reversal for greater than 10,000 years.[605] After pyrolysis, bioliquid is stored through injection deep underground into geologic storage. Reversal could occur if the bioliquid resurfaces, but this risk is minimal because bioliquid is dense and has been observed to polymerize into a solid.[606] Additionally, any impact from microbial alteration after storage, which could cause reversal, can be managed through monitoring.[607] Bioliquid projects in Massachusetts can expect the same reversal risk as bioliquid projects in general, due to the geographic-independence of the pyrolysis process and the availability of Class V wells in the state.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant. For bioliquid systems, the operating lifetime of a project is 10 to 70 years. Existing bioliquid production for CDR purposes (such as by the CDR supplier Charm Industrial) uses mobile pyrolizers, which range in lifetime from 10 to 20 years.[608] Assuming regulations similar to other injection wells, bioliquid projects will generally require up to 50 years of post-site monitoring, as well.[609] Bioliquid projects in Massachusetts can be expected to align with this range of project lifetimes due to the federal-level regulation for injection wells.

Range: 10 to 70 years

Technology Readiness Level

Bioliquid is currently at pilot to demonstration scale (TRL 6-7).[610] Bioliquid suppliers are currently developing projects that are growing in scale; CDR supplier Charm Industrial has signed multiple offtake agreements on the 1,000 to 100,000 tCO_2 scale.[611] Suppliers have indicated that they expect their technology to improve as their scale increases, suggesting deployments will be necessary to move bioliquid along the TRL scale.[612] As of November 2025, Charm Industrial has removed 11,000 tCO_2.[613]

Range: TRL 6 to 7

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for bioliquid is developing. The MMRV process is dependent on established measurement technologies and mass-balance calculations to measure biomass transformation into bioliquid and bioliquid injection into geologic storage.[614] Existing bioliquid MMRV protocols exist from major registries (such as Isometric)[615] as well as a protocol published by the CDR supplier Charm Industrial.[616] However, a main source of MMRV uncertainty still remains in the storage monitoring and maintenance step. The long-term dynamics of bioliquid underground is still an area of research, and so MMRV protocols will likely need to continue to develop as the science evolves.[617]

Rating: Developing

Deployment Timelines

Fast pyrolysis for bio-oil injection has not yet been deployed in Massachusetts, and no deployments are currently planned in the near future in the state. As of 2025, only one company is producing and storing fast pyrolysis bio-oil for injection into subsurface formations.[618] If bio-oil production and injection is deployed in Massachusetts, it will need to follow a host of existing regulations that govern subsurface injection, air quality and pollution, and solid waste management. These include the MassDEP Air Plan application process, the Underground Injection control (UIC) framework, MA's 310 CMR 27.00 policy, which regulates underground injection and protects underground sources of drinking water, MA 310 CMR 16.00 for solid waste guidance, and the Massachusetts Environmental policy Act.[619] [620] [621] [622] Overall, deployment timelines for this pathway are constrained by the provider who is deploying the pathway. One company made the decision to move forward with their bio-oil injection pathway in 2020 and had completed initial injection trials within 10 months, with injection at scale completed within the first 2 years.[623] In terms of crediting, monitoring and issuance periods for the current methodology occur on a scale of 4- 12 months.[624] It is feasible that a similar timeline could unfold if deployed in Massachusetts, with projects moving from planning to first credit issuance in approximately 3 years.

Resource Requirements

The main requirement for pyrolysis (bioliquid) and storage is biomass feedstock and energy. The exact amount of biomass needed will depend on feedstock and process specifics but estimates of existing processes suggest roughly 1.2 t biomass are required per tCO_2.[625] Energy input requirements is also process dependent but the most energy intensive step is pyrolysis, with estimates suggesting on the order of 20 MJ needed as an input per kg of bioliquid.[626] If bioliquid uses biowaste as a feedstock, such as woody residues from forestry operations, there is limited need for dedicated crops to be used as feedstock. Land use for bioliquid outside of biomass feedstock production is minimal, as bioliquid is injected underground so only land for the pyrolysis footprint is needed. Water requirements are also low if using biowaste as a feedstock, though growing dedicated crops for biochar would require significant water on the order of 6 Gt of water per tCO_2, as well as additional land.[627]

Rating (Water): Low (using biowaste)
Rating (Land): Low (using biowaste)
Rating (Energy): Medium
Rating (Feedstock): Medium

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of pyrolysis (bioliquid) and storage in Massachusetts is 425,000 to 525,000 tCO_2e, which is rated as low and represents approximately 3-4% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages data from the Department of Energy's 2023 Billion-Ton report and a range of conversion factors that convert biomass to bio-liquid and bio-liquid to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue, over 20,000 dry tons of agricultural biomass residue, and over 600,000 dry tons of other wet waste (e.g., sludge).[628] Conversion factors range from 0.3-0.6 tons of bio-liquid per dry ton across different residue types and the conversion factor of bio-liquid to removals ranges from 1.7-2.1 tCO_2e per ton of bio-liquid.[629] [630] [631] By multiplying available residues with relevant conversion factors, adding total bio-liquid across residue type, and converting bio-liquid to tons of removals, the removals range is estimated. This range relies on the assumption that all residual biomass in Massachusetts will be used for bio-liquid creation, which restricts the available feedstock for other biomass reliant CDR pathways. Biochar and bio-liquid are oftentimes produced in the same process, so the production of one does not preclude the other.[632]

Rating: Low

Risks to growth: While the estimated maximum potential deployment of fast pyrolysis to bioliquid injection CDR is 425,000 to 525,000 tCO2e per year, several factors and risk exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including the bioliquid's chemical instability, pyrolysis process toxicity risks, and lack of environmental permitting and regulatory clarity that could make large scale bio-oil deployment difficult.[633 634 635 636 637 638 639] Bioliquids, particularly those produced during the fast pyrolysis process, are acidic, oxygen-rich, water-laden, and potentially chemically unstable over time; these characteristics mean that transport and conditioning of bio-oils can be complicated.[640] In Massachusetts' deployments, this could make the build out of necessary infrastructure expensive and require routine replacement due to fouling of process components due to the bioliquid composition. Additionally, pyrolysis facilities can emit VOCs, PAHs, and fine particulates without strong controls; this could complicate siting and air-quality risk management.[641] Finally, regulatory risks exist for bio-oil scaling in Massachusetts as well. The lack of deployments in Massachusetts and generally for the pathway mean first-of-a-kind projects would need to engage with a variety of state agencies to determine what policies need to be navigated to reach deployment. When it comes to handling organic feedstocks, many pyrolysis configurations require site assignment under 310 CMR 16.00 and related MassDEP approvals, adding local and state checkpoints to that could delay or prevent scaling.[642] Fast pyrolysis operations might also require air permits under 310 CMR 7.00, requiring additional approval from the Commonwealth prior to operation.[643] When it comes time to store produced bioliquid, injection in Massachusetts is also a potential obstacle. UIC permitting in Massachusetts is regulated under 310 CMR 27.00 and EPA's UIC program, which will require demonstrating that bioliquid injection will not impact or contaminate ground water.[644 645]

Rating: Medium

Local supply chain

Bioliquid pyrolysis CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least five sectors in the state's economy, including engineering firms, fluid pump suppliers, reactor and tankard manufacturers, industrial specialists focused on corrosive processes, and providers of gas analysis technology. Massachusetts has a variety of domestic engineering firms with experience in deep-well injection, hydrogeology, and environmental permitting which could support project deployments in jurisdictions that allow injection.[646 647] Additionally, the state also has suppliers of custom tank components necessary for large scale pyrolysis reactor systems and bio-oil storage; these companies also have expertise in industrial tank assembly and inspection and would be useful in validating project processes.[648] Additionally, Massachusetts has suppliers for process components critical to bio-oil deployment, such as fluid pumps for transport and injection, and projects could leverage this local manufacturing capacity.[649] The state also hosts expertise on corrosive process components, and so Massachusetts could enlist companies who specialize in industrial research for abrasives, construction products, and performance plastics to help scope and implement new deployments.[650] Finally, gas analysis and mass spectrometry technology for MMRV and process control could be contracted to in-state analytic service providers who would help validate removals and monitor operations for leakage or reversal risks.[651]

Rating: High

Solution providers

Pyrolysis to bioliquid injection CDR is not a widely deployed pathway, and Charm Industrial is the only solution provider who has deployed the pathway globally.[652] As a result, Massachusetts does not have a solution provider headquartered in the state, as Charm Industrial is based in San Francisco, California. Charm has no deployments in Massachusetts and, as a result, the state does not have a solution provider in this pathway conducting projects in state.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Pyrolysis (bioliquid) and storage has the potential to provide moderate social and environmental co-benefits including diverting organic waste from landfills. Diverting organic residues from disposal reduces greenhouse gas emissions and supports Massachusetts waste-ban policy (e.g., leaf/yard waste).[653]

Social and environmental risks: Pyrolysis (bioliquid) and storage has the potential to pose moderate but manageable social and environmental risks. Bioliquid is acidic and corrosive; leaks during transfer or storage if materials are not compatible can create environmental risks.[654] Additional risks are associated with health impacts which are described below.

Health impacts: Pyrolysis (bioliquid) and storage has the potential to pose moderate but manageable health risks including harmful air emissions, strong odors, and irritation. Pyrolysis facilities could produce emissions harmful to human health such as particulate matter, criterial air pollutants, and volatile organic compounds.[655]

Rating: Positive

Economic benefit and job creation

Pyrolysis (bioliquid) and storage has the potential to create between 500 and 1,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above.[656] Job creation by bioliquid in Massachusetts is limited by the potential scale of deployment in the state. Pyrolysis (bioliquid) and storage may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities,[657] farmland,[658] and forested areas in Massachusetts.[659] However, project pyrolysis facilities will not necessarily be located near these communities and so these jobs may not be available for community members.

Rating: Low

Microalgae in ponds

Table 8-9: Microalgae in Ponds Overview

Pathway: Microalgae in ponds	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Low	
Current cost: \$250-1200/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** High (1.8-7.8 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Significant over 1000 years **Facility operating lifetime:** 20 to 30 years	**Local Supply Chain Relevance:**
Technology Readiness Level: 7-8; demonstration scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** High
<u>**Resource requirements**</u> ***Water:*** High ***Land:*** Medium ***Energy:*** Medium ***Feedstock:*** Medium	**Earliest planned start time:** September 2027

Table 8-9: Microalgae in Ponds Overview

Overview

Microalgae in ponds refers to the harvest and storage of microalgae biomass grown in land-based systems. This is often done by cultivating microalgae in open, raceway ponds or in greenhouses in photobioreactors. Significant research on microalgae cultivation in ponds has been done for biofuel applications, but microalgae in ponds as a CDR pathway involves drying and burying the algae.

Microalgae in ponds is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. Despite a large theoretical scale of deployment, there are significant risks to growth that would limit deployment, such as competing land use and the likelihood of high costs for deployment in the state.

There is a low potential for Massachusetts to be a leader in R&D for microalgae in ponds. Although the application of microalgae cultivation in ponds for carbon removal is still developing, substantial research on microalgae cultivation in ponds more broadly already exists.

<u>Deployment suitability rating</u>: Low
<u>R&D leadership potential rating</u>: Low

Cost

Current cost: The current cost for microalgae in ponds ranges from \$250 to \$1200 per tCO_2,[660] assuming 1.5 to 2 tCO_2 per ton of biomass.[661] The cost level is driven by the type of microalgae cultivation, with raceway ponds being less expensive than photobioreactors systems.[662] Regardless of the system design, the microalgae cultivation equipment makes up the greatest share of the cost.[663] Costs for microalgae in open ponds produced in Massachusetts may be on the higher end of this range due to the climate of Massachusetts. Raceway ponds will likely freeze in the winter and therefore not be operable the entire year, while photobioreactors are closed systems that can operate year-round but are more expensive.

Range: \$250 to \$1200 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Microalgae in ponds has medium design complexity (i.e., a moderate number of components, some of which are mass-produced) and requires moderate customization to each site's environmental conditions. Therefore, microalgae in ponds fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[664] This means that because microalgae in ponds can easily scale for a given land area but have site specific requirements (i.e., cultivation time, storage site), microalgae in ponds is likely to achieve moderate cost reductions on the basis of scale alone. Cost reductions may also come from process improvements that reduce energy requirements as well as the development of more efficient algal species, though the existing decades of research microalgae cultivation for biofuels suggest that large reductions in cost have already occurred.[665]

Rating: Medium

Duration

Risk of reversal: Microalgae in ponds can remove and store carbon with significant risk of reversal over 1,000 years.[666] The risk of reversal stems from the possibility of biomass decomposition, which can occur if the algae is exposed to fire, pests, or human disturbance. This can be mitigated through project design and monitoring.[667] However, although algae are buried in conditions to prevent decomposition, it is not expected to prevent decomposition on a geologic timescale. Although arid environments can further prevent decomposition,[668] microalgae in ponds in Massachusetts would be expected to have significant risk of reversal over 1,000 years.

Rating: Significant risk of reversal over 1000 years

Operating lifetime of a plant: For microalgae in open ponds facilities, the operating lifetime is 20 to 30 years. Studies have modeled a 30-year operating lifetime for the facility,[669] but equipment may need to be replaced periodically depending on the microalgae cultivation set-up. Raceway ponds typically have a 30-year lifetime, while photobioreactor systems may need to be replaced as often as annually.[670] Microalgae in ponds projects in Massachusetts would likely align with this range of project lifetimes due to the general standardization of project equipment.

Range: 20 to 30 years

Technology Readiness Level

Generally, the cultivation of microalgae in ponds has reached a commercial scale; however, growing microalgae in ponds specifically for the purpose of carbon removal is at a lower TRL, around 7-8.[671] Although commercial companies, such as Euglena, have demonstrated the possibility of growing microalgae for fuel production, there are few companies testing cultivation and storage which would lead to removals. Brilliant Planet has been iterating on and conducting field trials for microalgae cultivation in ponds after which the algae is then buried.[672] The company is now working on its first commercial facility.

Range: 7-8

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for microalgae in ponds is developing. MMRV for microalgae in ponds is done by measuring the microalgae biomass production in ponds (by measuring dry mass or using models), analyzing the carbon content of this biomass, and subtracting lifecycle emissions and leakage. Although measurement of microalgae in ponds used for fuels or other purposes is more established, for the growth of microalgae to be considered a removal, the biomass has to be buried or otherwise stored durably. Methodologies for microalgae in ponds removals are less common. In 2023, EcoEngineers and Brilliant Planet developed a methodology for algal blooms that are then stored in dry tomb landfills that are designed and monitored to ensure 1000-year minimum storage duration.[673]

Rating: Developing

Deployment Timelines

Microalgae in ponds CDR has not been deployed in Massachusetts and no deployments are planned in the near future. If planned, Massachusetts deployments would need to navigate relevant regulations, including those pertaining to wetlands protection, stormwater guidelines, solid waste transport and disposal regulations, and air pollution controls. These regulations could include the many Massachusetts state codes, including 310 CMR 10.00, 310 CMR 7.00, 310 CMR 36.00, 314 CMR 5, 310 CMR 19.000, and 301 CMR 11.00.[674] [675] [676] [677] [678] [679] In terms of estimated timelines for project implementation, deployment timeframes are hard to estimate given available information on the few companies currently conducting microalgae in ponds CDR. Leaders in the microalgae in ponds CDR space have been conducting pilot projects since as early as 2013, with some indications that demonstration scale projects can move from construction to operation in as few as 9 months, with additional upfront planning taking approximately one year, though this information is speculative and based on company projections.[680] [681] The only dedicated methodology for the pathway identifies the credit reporting period to be 12 months post project start, with a ten-year eligibility period following initial review; taking into account all aspects of the project, this could mean between two and half and three years from project planning to first credited removals.[682]

Resource Requirements

The main resource needed for microalgae in ponds is water, specifically in the form of saline water. Estimates suggest that 60 to 780 t of saline water are needed to remove 1 tCO_2.[683] The feedstock requirement is moderate and will ultimately depend on the algae used but estimates suggest 0.5 to 0.7 t algae per tCO_2.[684] Similarly, land requirements will depend on the microalgae cultivation system and the specific algae used but will be non-negligible. Estimates suggest 0.007 to 0.03 ha are needed per tCO_2, with raceway ponds needing more land area than closed photobioreactor systems.[685] The energy requirement is due to water pumping, drying, and storage, and has been estimated at approximately 4 GJ per tCO_2.[686]

Rating (Water): High
Rating (Land): Medium

Rating (Energy): Medium

Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of microalgae in ponds in Massachusetts is 1.8 million to 7.8 million tCO_2e per year, which is rated as high and represents approximately 13 to 55% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was based on the amount of land in the state that could be converted into microalgae in ponds. The amount of available land was taken from Massachusetts Forest Carbon Study's estimate of the available rural land in the state that could be converted to forests, which is additional land in the state that does not include land that is suitable for agricultural use or is developed.[687] It is assumed that this land could be converted into microalgae ponds instead of forests, since it is land identified by the state that could be converted for CDR purposes. The algal production per land area for a range of microalgae cultivation systems and a range of biomass to CO2 conversion efficiencies were used with the available land area to estimate the maximum potential deployment of microalgae in ponds in Massachusetts.[688] [689]

Rating: High

Risks to growth: While the estimated maximum potential deployment of microalgae in ponds is 1.8 million to 7.8 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including land use competition, community acceptance, and cost. Land-use competition is a risk because the scale of microalgae in ponds deployment depends upon the amount of land dedicated to microalgae cultivation.[690] The relatively small size of Massachusetts and competing uses for land within the state would likely decrease the land available for microalgae in ponds. Additionally, because microalgae in ponds has a large land footprint, it has the potential to significantly impact surrounding communities. A lack of community acceptance will limit the scale of deployment. Finally, microalgae in ponds in Massachusetts will likely be expensive, which may limit the scale of its deployment. Due to the state's climate, the closed photobioreactor systems are better suited for year-round operation but the most productive of these systems are also the most expensive.[691]

Rating: High

Local supply chain

Microalgae in ponds is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact three sectors in the state's economy, including suppliers of hydraulic and pumping equipment, liner and containment structure vendors, as well as aquatic monitoring and instrumentation providers. Massachusetts has several companies that could supply microalgae projects with necessary process components, such as mechanical pumps, mixers, and filtration equipment systems to enable transport, dredging, and microalgae capture in pond operations; these process components would also support continuous circulation, mixing, and aeration that could be required for microalgae operations.[692] [693] [694] The state also has at least one provider of pond liners designed for wastewater applications that could be utilized for containment and prevent leaching into groundwater.[695] Ponds for microalgae cultivation will also need monitoring equipment for characteristics like pH, DO, turbidity, as well as flow and control valves for operation, to ensure ideal conditions for microalgae cultivation, and MA has suppliers that could meet these needs and could benefit from large scale deployments.[696 697]

Rating: Medium

Solution providers

Microalgae in ponds is not widely deployed and has only a few solution providers actively pursuing the pathway globally, the most notable companies being BlueGreen Technologies, Brilliant Planet, and Global Algae Innovations.[698 699 700] However, Massachusetts does not have solution providers headquartered in state, nor are there any solution providers conducting projects within Massachusetts borders.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Microalgae in ponds has moderate social and environmental co-benefits, including the use of non-competitive resources and potential integration into wastewater systems. Microalgae in ponds projects can be done on non-arable land and can use non-potable water, reducing competition for food crops or drinking water.[701] Further, microalgae can be integrated into wastewater treatment processes, removing contaminants from industrial or urban effluents.[702]

Social and environmental risks: Microalgae in ponds likely has moderate but manageable social and environmental risks, although there is still uncertainty given this pathway's low TRL. Although this pathway could use a variety of non-competitive water sources, its water use is high, meaning if a project does use freshwater, it could divert necessary resources from communities.[703] If a pond is not constructed safely, it could lead to leaching, the contamination of groundwater, or even algal blooms if a pond leaches into aquatic environments.[704] While these are risks, if a pond is constructed in a way that reduces resource constraints and is monitored, the risks are manageable.

Health impacts: Microalgae in ponds likely has negligible health benefits and moderate but manageable health risks. If microalgae in ponds are used in wastewater treatment, this would improve water quality from baseline but is likely a negligible difference when compared to other wastewater treatment methods. However, if a pond is not constructed safely, leaching happens, and algal blooms or groundwater contamination occur, there are associated health risks.[705] However, as mentioned, these risks are manageable with safe construction and monitoring.

Ranking: Neutral

Economic benefit and job creation

Microalgae in ponds has the potential to create between 600 to 15,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated by using existing modeling on the number of jobs needed for a 5,000-acre raceway pond facility.[706] The algal production per land area for a range of microalgae cultivation systems and a range of biomass to CO_2 conversion efficiencies were used to calculate the number of jobs created per million tCO_2e per year of carbon removal.[707 708] The estimate is also based on the potential scale of deployment in Massachusetts outlined in the Scale and Growth section above. Microalgae in ponds has the potential to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and low-population areas in the state, where deployment is likely to occur due to the large land footprint of microalgae in ponds.[709] [710]

Ranking: High

Microalgae in open water

Table 8-10: Microalgae in Open Water Overview

Pathway: Microalgae in open water	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** High	
Current cost: \$7-1500/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Unknown **Risks to growth:** High
Risk of reversal: Significant over 1000 years **Facility operating lifetime:** 1-10 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 3-4; concept to lab phase	**Co-benefits and potential negative impacts:** Negative
Measurement readiness: Early stage	**Economic benefit and job creation:** Unknown
Resource requirements ***Water:*** Low ***Land (ocean area):*** High ***Energy:*** Low ***Feedstock:*** Medium	**Earliest planned start time:** January 2028

Table 8-10: Microalgae in Open Water Overview

Overview

Microalgae in open water refers to the cultivation and sinking of microalgae in the ocean or other open bodies of water. This can be achieved by using trace nutrients like iron to seed algae blooms, which are then sunk.

Microalgae in open water is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the high degree of uncertainty in microalgae for CDR due to its nascency, as well as the potential unsuitability of Massachusetts coastal waters for this pathway. Significant technical, environmental, and governance questions will need to be answered before microalgae in open water is deployed at scale.

There is a high potential for Massachusetts to be a leader in R&D for microalgae in open water. The pathway is very early-stage and has numerous open research questions that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Massachusetts is specifically well-suited for MMRV and ocean modeling R&D rather than field trials because of potential unsuitability of Massachusetts coastal waters.

Deployment suitability rating: Low

R&D leadership potential rating: High

Cost

Current cost: The current cost for microalgae in open water ranges from $7 to $1500 per tCO_2.[711] This large cost range is due to microalgae in open water being very early-stage and therefore costs being quite uncertain. Some modeling studies predict a smaller cost range of $50 to $125 per tCO_2,[712] but the costs will depend on process specifics, MMRV development, and learnings from real world deployment. Due to the high uncertainty in microalgae in open water costs, where the costs in Massachusetts will fall in this range in unclear; however, Massachusetts' access to the coast may reduce costs.

<u>Range</u>: $7 to $1500 per tCO_2

Potential for cost reduction: The potential for cost reduction medium.

Microalgae in open water systems have medium design complexity (e.g., few components of which a moderate amount can be mass-produced), largely due to MMRV needs, and have a low to moderate need for customization based on the application site, and thus fall in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[713] This means that because microalgae in open water can be standardized and benefit from economies of scale, limited by its moderately complex design, microalgae in open water is likely to achieve moderate cost reductions with scale. Additionally, costs may significantly come down as the technology advances, especially as MMRV develops and becomes more streamlined. However, the efficacy of carbon removal through microalgae in open water is still being understood,[714] so it is possible that costs would increase if it proves less effective than expected or if MMRV is more costly than expected.

<u>Rating</u>: Medium

Duration

Risk of reversal. Microalgae in open water removes and stores carbon with significant risk of reversal over 1,000 years when sunk to a depth of greater than 1,000 meters.[715] Microalgae in open water stores carbon through sinking the algae and therefore the length of storage depends on the depth of algae sinking and the local conditions of the water.[716] Reversal occurs if the algae degrades in the upper levels of the ocean and CO_2 is re-released.[717] Therefore, risk mitigation strategies include any methods to ensure the microalgae sinks to below 1,000 meters.[718] Microalgae in open water projects in Massachusetts would be expected to be the same with respect to reversal risk; ensuring microalgae sinks to a sufficient depth will be very important given the shallower waters of the Gulf of Maine.

<u>Rating</u>: Significant risk of reversal over 1,000 years

Operating lifetime of a plant. For microalgae in open water, the operating lifetime of a project is likely 1 to 10 years. Microalgae would need to be replaced after sinking, while other capital equipment such as lines, buoys, and anchors are often modeled with a 5-10 year lifetime.[719] Due to the early-stage nature of microalgae in open water, the operating lifetime is uncertain. However, microalgae in open water projects in Massachusetts can be expected to align with this range of operating lifetime though will ultimately depend on the specific equipment and microalgae used.

<u>Range</u>: 1 to 10 years

Technology Readiness Level

Microalgae in open water is at the concept to lab phase (TRL 3-4).[720] There are a growing body of literature on microalgae in open water, with limited real-world experiments and deployments.[721] A factor limiting technology development is the uncertainty in the environmental impacts of large scale deployments, especially for the iron fertilization method of applying microalgae in open water.[722]

Range: TRL 3 to 4

Measurement, monitoring, reporting, and verification (MMRV)

Microalgae in open water MMRV is early stage and is a major barrier to address for scaling. Methods for measuring microalgae growth and sinking are still evolving and facing challenges. Microalgae in open water will cover significant ocean area, which suggests using satellite data for measurement—a pathway that is developing but that can only account for surface measurements, not the deep ocean.[723] New approaches to MMRV are being investigated, including innovative approaches like autonomous vehicle with sensors, but need additional testing and development.[724] Puro.earth recently launched a public consultation for their draft Microalgae Carbon Fixation and Sinking Methodology,[725] but no established MMRV methodologies exist.

Rating: Early stage

Deployment Timelines

Microalgae CDR pathways have not been deployed in Massachusetts and no deployments are planned in the near future. Microalgae CDR is an incredibly nascent pathway, and there are only a few companies currently advancing this pathway in 2025, meaning that any future deployments in Massachusetts would likely be limited first to scientific field trials aimed at clarifying science and understanding environmental impacts. With that in mind, any future deployments of microalgae in open water for the purpose of CDR would need to navigate state and federal regulations, and potentially even international / multi-national marine agreements prior to commencement. This could include international pacts, such as the London protocols (though technically the US is not a party to this agreement), and US regulations, such as the Marine Protection, Research and Sanctuaries Act (MPRSA, or the “Ocean Dumping Act”), and the National Environmental Policy Act, as well as the Massachusetts Environmental Policy Act and Coastal Zone Management program.[726] [727] [728] [729] [730] Because of the lack of projects being deployed to date, estimating a deployment timeline for microalgae fertilization and sinking is difficult, especially given the pathway’s uncertainties, such as risk of reversal, safety, multi-layered permits and potential international approvals, as well as the lack of actors pursuing the pathway as a solution. One of the leading companies in the microalgae space was founded in 2022, and by 2024 was operating field trials with plans to expand to operations in 2026 following the approval of their methodology by Puro in 2025.[731] Based on this timeline, and depending on permitting issuance, a theoretical Massachusetts pilot deployment could move from planning to deployment in two years, with an additional six to nine months for crediting based on required methodology activities, though the pathway still has many uncertainties that make this unlikely.

Resource Requirements

The main resources for microalgae in open water are the fertilizer feedstock used to seed the microalgal blooms and the ocean area needed for the algal blooms. The amount of feedstock in the form of ocean fertilizer depends on the nutrient used, but the theoretical potential of common nutrients are 0.05 t nitrogen per tCO_2, 0.09 t silicon per tCO_2, 0.007 t phosphorus per tCO_2, and 0.001 to 0.00001 t iron per tCO_2.[732] Because these are theoretical ratios, a greater amount of feedstock per tCO_2 will likely be needed. The ocean area requirement will depend on the microalgae, but assuming similar requirements to macroalgae means approximately 0.0007 km^2 of ocean area is needed for 1 tCO_2 per year. Water use is minimal because projects use ocean water, and energy use is minimal because projects generally only require energy to transport the fertilizers out into the ocean.[733] Energy use for MMRV may be significant for first-of-a-kind monitoring technologies, though this will likely decrease as the technology develops.

Rating (Water): Low
Rating (Land/Ocean Area): High
Rating (Energy): Low
Rating (Feedstock): Medium

Scale and Growth

Scale possible in Massachusetts: Microalgae cultivation in open water is too early-stage and has too many uncertainties to estimate the maximum potential deployment in Massachusetts. However, this does not mean that Massachusetts should completely rule the CDR pathway out. Instead, Massachusetts could support continued research and exploration of the pathway.

Rating: Unknown

Risks to growth: The current scale estimate for microalgae CDR in Massachusetts is unknown due to several uncertainties and risks that will need to be clarified prior to any meaningful deployments, including impacts of shifting environmental conditions in Massachusetts' coastal waters, lack of clarified science around MMRV, impacts to ecosystems and existing industries, and lack of clarity around national regulations as well as international or mutli-national agreements that have issued guidance on ocean fertilization projects in international waters.[734] [735] [736] [737] [738] [739] [740] [741] First and foremost, Massachusetts' coastal waters lie within the rapidly warming Gulf of Maine. As waters warm, increased stratification and shifting nutrient regimes could make aspects of microalgae CDR, such as growth and deep carbon export, difficult to predict and manage.[742] To that end, initial research has found that only a portion of bloom-fixed carbon is exported to depths that provide century-scale storage, and that MMRV for the net removals that result from the carbon that does reach depth is hard to measure and quantify due to the open system nature of the pathway.[743] Furthermore, durable storage generally requires export below roughly 1,000 meters, and interventions risk ecological side effects such as food-web alteration and deoxygenation, which could cause industry resistance from established sectors like lobster and shellfish farming and cultivation.[744] [745] Finally, international agreements, such as the London Protocol, could play a role in how ocean fertilization is deployed by guiding local and federal legislation. Though the U.S. is not currently party to the London Protocols, the protocols addressed ocean fertilization; a 2013 amendment to regulate ocean fertilization activities was drafted, and while it has not yet entered into force, it recommends that only research related to the pathway move forward, dissuading large scale deployment. This guidance would be relevant for deployments that are examining sites for fertilization that extend more than 200 nautical miles from Massachusetts' coast; the agreement could potentially influence how future policies at a state and federal level treat ocean fertilization pathways, if the US decides to adopt its guidance.[746][747] In U.S. waters off Massachusetts within the 200 nautical mile range, activities that place material for marine CDR or field research could require permits under the Marine Protection, Research, and Sanctuaries Act (MPRSA) administered by EPA, though the permitting of these activities in US jurisdictions has not yet been clarified.[748]

Rating: High

Local supply chain

Microalgae in open water is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact three sectors in the state's economy, including ocean monitoring equipment producers, autonomous marine vehicle developers, and shipyard services. Massachusetts could leverage in-state suppliers of marine monitoring equipment to measure important metrics for microalgae deployment, including dissolved oxygen, tidal conditions water temperature and salinity.[749] Additionally, to improve rate of deployment and lower labor barriers, Massachusetts has a variety of companies that manufacture and provide unmanned surface vehicles (USVs); these USVs could provide seafloor site-mapping via sonar and acoustic technology.[750][751][752] Additionally, domestic companies with capacity to supply infrastructure components like anchors, lines, and frames that hold instruments in place could be useful for accelerating project procurement.[753] To support MMRV and improve monitoring in deep sea environments after algae sinking, Massachusetts hosts a supplier of underwater acoustic releases, which would also permit teams to recover deployment equipment without divers or USVs, reducing risk, cost, and time at sea.[754] Finally, Massachusetts coastal sites host a variety of companies who could manage supportive infrastructure and maintain operational success, including marine railway companies who could support the transport of key inputs for fertilization, while local ship repair could support necessary maintenance for deployment fleets.[755][756]

Rating: Medium

Solution providers

Microalgae is not widely deployed as a pathway and has only a few solution providers currently attempting to deploy the pathway, the most notable being Gigablue, an ocean fertilization company based out of New York who is already piloting its pathway in New Zealand waters.[757] In Massachusetts, a microalgae research trial, led by WHOI, is currently being carried out with the main goals of addressing the effectiveness of ocean iron fertilization for CDR, identifying potential ecological consequences of deployment, and clarifying potential MMRV for the pathway.[758] While Massachusetts does not have solution providers headquartered in state, this trial could pave the way for future work or deployments in Massachusetts state waters.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Microalgae in open water has the potential to provide negligible social and environmental co-benefits including reduced ocean acidification. Microalgae could aid in temporary local buffering of ocean acidity during photosynthetic blooms that raise pH and improve carbonate conditions for calcifying species important to Massachusetts fisheries (e.g., scallops, oysters).[759]

Social and environmental risks: Microalgae in open water has the potential to pose significant risks, including harmful algal blooms (HABs) and deep-water oxygen depletion. Microalgae could contribute to the HABs that already contaminate shellfish and disrupt New England ecosystems, as Massachusetts regularly monitors for paralytic shellfish poisoning linked to *Alexandrium catenella* ("red tide").[760] [761] Sinking algal biomass can drive deep-water oxygen depletion and acidification during decomposition, with uncertain shellfish impacts and biogeochemical side effects (e.g., altered nutrients, potential N_2O).[762] [763]

Health impacts: Microalgae in open water has the potential to pose significant health hazards, including seafood-borne illness and bioaerosol exposure. Seafood-borne illness could include paralytic, diarrhetic, or amnesic shellfish poisoning. There is also risk for occasional aerosol exposure during certain blooms. Massachusetts' shellfish closures and monitoring underscore ongoing public-health risk.[764] [765]

Rating: Negative

Economic benefit and job creation

Due to the nascency of this pathway and lack of scale potential data, job creation estimates have too high a degree of uncertainty to quantity. However, Massachusetts should re-evaluate the potential for microalgae in open water to create jobs as the pathway develops, especially because it may be able to integrate into the existing maritime industry in the state. Additionally, microalgae in open water is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and coastal areas where deployment is likely to occur. [766]

Rating: Unknown

Macroalgae in open water

Table 8-11: Macroalgae in Open Water Overview

Pathway: Macroalgae in open water	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** High	
Current cost: \$480-17,000/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Unknown **Risks to growth:** High
Risk of reversal: Significant over 1000 years **Facility operating lifetime:** 1-10 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 4-6; lab to pilot	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Early stage	**Economic benefit and job creation:** Unknown
<u>**Resource requirements**</u> ***Water:*** Low ***Land (ocean area):*** Medium ***Energy:*** Low ***Feedstock:*** Medium	**Earliest planned start time:** January 2029

Table 8-11: Macroalgae in Open Water Overview

Overview

Macroalgae in open water refers to the process of cultivating macroalgae in algae farms or in the open ocean to then sink the marine biomass into the ocean. This process can be done by harvesting the seaweed before sinking or by using buoys or other structures to sink the seaweed once it has grown.

Macroalgae in open water is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the high uncertainty in the feasibility of deployment in Massachusetts. Due to the shallow waters off the Massachusetts coast, high uncertainty in MMRV and efficacy, and legal feasibility, there are significant risks to growth for macroalgae in open water.

There is a high potential for Massachusetts to be a leader in R&D for macroalgae in open water. The pathway is still early-stage and has open research questions that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean.

<u>Deployment suitability rating</u>: Low

<u>R&D leadership potential rating</u>: High

Note: It is possible to cultivate macroalgae, such as kelp and other seaweeds, to enhance atmospheric carbon removal without sinking or pyrolyzing the biomass. This is generally referred to as **marine permaculture**.

Marine permaculture is an established industry to harvest seaweed for food and other products, but it is not typically used as a method of carbon removal. If marine permaculture is employed as a carbon removal approach, its characteristics would be very similar to those outlined in this section on macroalgae in open water.

The main difference between marine permaculture and macroalgae in open water is that, without the final step of sinking, marine permaculture has a significant risk of reversal over 100 years.

Cost

Current cost: Costs for macroalgae in open water vary greatly depending on the location and macroalgae used. Studies estimate a global average cost of $480 per tCO_2,[767] while a Gulf of Maine specific study estimated a levelized cost of $1,200 to $17,000 per tCO_2.[768] This large cost range is driven by high MMRV uncertainty. Higher costs in Massachusetts are likely to be due to greater transportation costs to bring seaweed to the depth of the ocean needed for sequestration (1,000 meters).[769]

Range: $480 to 17,000 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

Macroalgae in open water systems have medium design complexity (e.g., few components of which a moderate amount can be mass-produced), largely due to MMRV needs, and have a moderate need for customization based on the application site, and thus fall in the Type 2 section of the cost reduction potential matrix (see Appendix on potential for cost reduction with scale).[770] This means that because macroalgae in open water can be standardized and benefit from economies of scale, limited by its moderately complex design, macroalgae in open water is likely to achieve moderate cost reductions with scale. However, MMRV is under development and therefore MMRV costs are highly uncertain; costs may decrease or further increase as MMRV develops.[771] Costs may also decrease with co-location and transport optimization as well as process automation.[772]

Rating: Medium

Duration

Risk of reversal. Macroalgae in open water can create carbon storage with significant risk of reversal over 1,000 years when sunk to a depth of greater than 1,000 meters.[773] The length of secure storage for macroalgae open water depends on the depth of algae sinking, with deeper sinking resulting in longer storage.[774] Reversal can occur if the algae decomposes or is eaten and respired at shallow depths so that the CO_2 is re-released to the atmosphere, or if there is a change in the ecosystem, such as shading, that alters the algae productivity rate compared to its baseline. Therefore, the main risk mitigation strategy is ensuring that macroalgae quickly sinks to sufficient depth (greater than 1,000 meters) to reduce the chance of decomposition. Macroalgae in open water projects in Massachusetts would be expected to be the same with respect to reversal risk; ensuring macroalgae sinks to a sufficient depth will be very important given the shallower waters of the Gulf of Maine.

Rating: Significant risk of reversal over 1000 years

Operating lifetime of a plant. For macroalgae in open water, the operating lifetime of a project is likely 1 to 10 years. Macroalgae would need to be replaced after sinking, while other capital equipment such as lines, buoys, and anchors are often modeled with a 5-10 year lifetime.[775] Macroalgae in open water projects in Massachusetts can be expected to align with this range of operating lifetime though will ultimately depend on the specific equipment and macroalgae used.

Range: 1 to 10 years

Technology Readiness Level

Macroalgae in open water is at the lab to pilot phase (TRL 4-6).[776] There have been real-world experiments and deployments.[777] However, the shutdown of the major macroalgae in open water company, Running Tide, suggests that additional research, testing, and verification are needed before the technology is ready for demonstration and commercial scale.[778]

Range: TRL 4 to 6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for macroalgae in open water is early stage. Some methods of macroalgae in open water implementation include harvesting seaweed before sinking, in which case quantification can be done precisely. However, other methods involve seeding macroalgae in floating buoys which will need to rely on modeling that is still being developed.[779] Moreover, quantifying the amount of macroalgae that does sink to deep enough for long-term storage is difficult and uncertain, and requires both measurement and modeling that is still being developed.[780] MMRV protocols for specific methods of implementing macroalgae in open water do exist, including Puro.earth's Marine Anoxic Carbon Storage Methodology.[781] MMRV protocols will for macroalgae in open water will need to continue to develop as the science evolves.

Rating: Early stage

Deployment Timelines

Macroalgae CDR has not been deployed in Massachusetts and there are currently no deployments planned in the near future. Future deployments of macroalgae sinking in open water for the purpose of CDR would need to navigate state and federal regulations and could potentially be influenced by international multi-national pacts. The regulations would include international pacts, such as the London protocols (though technically the US is not a party to this agreement), the Marine Protection, Research and Sanctuaries Act (MPRSA, or the "Ocean Dumping Act"), the National Environmental Policy Act, as well as the Massachusetts Environmental Policy Act and Coastal Zone Management program.[782] [783] [784] [785] [786] In terms of deployment timelines, no companies have reached commercial scale in macroalgae cultivation and sinking; one company who approached scaled deployment quickly went out of business due to credit integrity concerns and ecosystem impacts.[787] Because of these factors, it is difficult to estimate what a timeline to first-of-a-kind (FOAK) projects and initial removals could be in Massachusetts, though it is clear additional research is needed prior to significant deployment. However, one of the few active companies in the space went from founding in 2021 to 5,000 tCO2e worth of deployment in 2024; while these credits have not yet been registered or verified, a realistic timeline for planning to first removals for macroalgae sinking CDR could be between 3 and 4 years, with credit issuance timelines being dependent on accepted methodologies.[788]

Resource Requirements

The main resource requirements for macroalgae in open water are ocean area and feedstock. Accounting for macroalgae cultivation, 73,000 km^2 of ocean area would be needed to farm the macroalgae needed to remove 100 Mt of CO_2 per year;[789] scaling this down implies about 0.0007 km^2 of ocean area for 1 tCO_2 per year. The amount of macroalgae required depends on the type of macroalgae, but studies estimate 0.4 t to 1 t macroalgae per tCO_2.[790] Water use is minimal because projects use ocean water and energy use is minimal because projects generally only require energy to transport the macroalgae out into the ocean.[791]

Rating (Water): Low
Rating (Land/Ocean Area): High
Rating (Energy): Low
Rating (Feedstock): Medium

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of macroalgae in open water in Massachusetts is too uncertain to quantify. The scale of deployment is highly uncertain due to the question of efficacy in Massachusetts waters (i.e., Massachusetts coastal waters are too shallow for secure storage). However, it is theoretically possible that the state could grow algae in its jurisdictional waters and then transport it to the deep ocean for sinking, but this requires multiple permitting, legal, and governance issues to align to be possible. Because of these uncertainties, the scale is evaluated as unknown.

Rating: Unknown

Risks to growth: The estimated maximum potential deployment of macroalgae cultivation and sinking is unknown, largely due to high uncertainties and risks to growth. Several risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable include lack of clarity around MMRV and logistics for deep sea deposition, potential ecological impacts, competition with other existing marine sectors and uses, as well as challenges with navigating permitting at a national level.[792] [793] [794] [795] [796] [797] [798] [799] [800] [801] [802] Most importantly, the science still needs to be clarified for macroalgae CDR; recent scientific reports have identified potential CDR benefits from sinking macroalgal-derived particulate organic carbon, though these reports have also noted the need for further additional research on organic carbon partitioning and its bioavailability to better understand the effectiveness and impacts of macroalgae sinking as a CDR strategy.[803] Additionally, from a logistics perspective, durable CDR via seaweed sinking typically assumes sinking to deep waters (>~1,000–3,000 meters), which implies that offshore logistics and planning beyond the shallow Massachusetts shelf will be needed for scaling, heightening operational complexity.[804] [805] Existing barriers to implementation exist as well; competition for physical space is significant in the Massachusetts Bay, and existing shipping lanes and growing offshore wind leases could narrow siting options for project siting.[806] [807] There are also concerns about pelagic marine life being harmed by large scale deployments; entanglement and vessel-strike risk to endangered and protected species, such as the North Atlantic right whale, further increase the importance of sensitive site selection for offshore operations.[808] [809] Finally, from a policy perspective, macroalgae CDR projects must navigate layered approvals for open ocean deployment that could lengthen, complicate, or block deployment. These include, but are not limited to municipal site control, DMF aquaculture permits in state waters, potential MEPA review, and federal authorizations, which could delay or altogether prevent large scale deployments needed for meaningful removals.[810] [811] [812]

Rating: High

Local supply chain

Macroalgae CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact four sectors in the state's economy, including aquaculture operations, marine hardware suppliers, autonomous vehicle manufacturers, and port infrastructure operators. The state has local cultivation know-how for species relevant to macroalgae deployments, with at least one local aquaculture company that could support seed acquisition and cultivation guidance for pilots and initial workforce training.[813] Massachusetts also has suppliers of core aquaculture hardware for marine deployments, including longlines, droppers, and rigging, which could be critical for large scale and open ocean deployments.[814] Additionally, the state has port terminals that would support macroalgae deployment via transportation and heavy machinery infrastructure which could allow for the movement of process components, maintain vessels and manage staging prior to deployment.[815] For controlled offshore releases, subsea monitoring and MMRV relevant to macroalgae sinking events, Massachusetts also hosts manufacturers that are well prepared to supply acoustic releases and subsea comms/positioning that can read critical environmental and biotic factors at depth.[816] [817] The Commonwealth also hosts an advanced ocean-tech cluster for monitoring, reporting, and verification, including autonomous gliders, USVs, and integrated metocean buoy systems.[818] [819] Vessel autonomy and remote operations solutions from in-state companies could further reduce labor needs for monitoring of macroalgae projects.[820]

Rating: Medium

Solution providers

Macroalgae cultivation and sinking is not widely deployed and has only a few solution providers globally, most notably the recently defunct operation known as Running Tide and the Sargassum-focused company Seafield Solutions.[821] [822] Because of the pathway's nascent nature, Massachusetts does not have solution providers headquartered in state, nor are there solution providers conducting projects in state. However, in an effort to meet growing biofuel demand, initial research trials have been conducted by WHOI in an attempt bio-engineer sugar kelp such that it grows faster than the species traditional would; this research could be repurposed to focus on growing and sinking this GMO kelp, potentially orienting WHOI as an in-state solution provider or supportive actor in the future.[823]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Macroalgae in open water has the potential to provide moderate co-benefits, including nutrient remediation and habitat provision. Farmed kelp could remove measurable nitrogen and phosphorus loads from coastal waters, improving water quality.[824] [825] Kelp

Draft, for consideration, not final

structures can offer seasonal habitat, though biodiversity gains are context-dependent and evidence remains limited.[826]

Social and environmental risks: Macroalgae in open water has the potential to pose moderate risks, including entanglement, deep-sea ecological impacts, and HABs. Fixed lines and aquaculture gear could add entanglement hazards for the critically endangered North Atlantic right whale present off Massachusetts and regulators flag navigation conflicts.[827 828] Macroalgae sinking could create localized deoxygenation and nutrient imbalances at depth, with uncertain food-web effects.[829 830] It could also exacerbate HABs that already contaminate shellfish and disrupt New England ecosystems.[831 832]

Health impacts: Macroalgae in open water has the potential to pose moderate health risks, including marine-operations injuries, seafood-borne illness, and bioaerosol exposure. Aquaculture work could lead to elevated injury or illness rates including falls, entanglements, and needlestick injuries.[833 834] Seafood-borne illness could occur from shellfish poisoning. There is also risk for occasional aerosol exposure during certain blooms. Massachusetts' shellfish closures and monitoring underscore ongoing public-health risk.[835 836]

Rating: Neutral

Economic benefit and job creation

Due to the nascency of this pathway and lack of scale potential data, job creation estimates have too high a degree of uncertainty to quantity. However, Massachusetts should re-evaluate the potential for macroalgae in open water to create jobs as the pathway develops, especially because it may be able to integrate into the existing maritime industry in the state. Macroalgae in open water is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities and coastal areas where deployment is likely to occur.[837]

Rating: Unknown

Bioenergy with carbon capture and storage (BECCS) to electricity

Table 8-12: BECCS to Electricity Overview

Pathway: BECCS to electricity	
Deployment Suitability for Massachusetts: Low **R&D Leadership Potential:** Medium	
Current cost: $75-300/t$CO_2$ **Cost reduction potential:** Low	**Scale potential:** Low (0.6-1.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20-30 years	**Local Supply Chain Relevance:**
Technology Readiness Level: 6-8; pilot to demo scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** Medium
<u>**Resource requirements**</u> ***Water:*** Low (using biowaste) ***Land:*** Low (using biowaste) ***Energy:*** Medium ***Feedstock:*** Medium	**Earliest planned start time:** Retrofit of existing plant: January 2027 New Facility: January 2034

Table 8-12: BECCS to Electricity Overview

Overview

BECCS to electricity refers to the thermal conversion of biomass (either dedicated feedstock or waste) to generate electricity and produce CO_2 that is captured with CCS technology. There are multiple methods of converting the biomass, such as direct combustion or gasification and then combustion. BECCS to electricity is a CDR pathway because it captures biogenic CO_2, which came from the atmosphere.

BECCS to electricity is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, which is limited by the available biomass residue in state. There are also significant risks to growth for BECCS to electricity in Massachusetts. The state's lack of in-state geologic storage means that any CO_2 captured from BECCS to electricity will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges.

There is a moderate potential for Massachusetts to be a leader in R&D for BECCS to electricity. The state's existing facilities that handle biomass, such as paper and pulp mills, could offer key opportunities to pioneer BECCS integration into existing industries.

<u>Deployment Suitability rating</u>: Low
<u>R&D Potential rating</u>: Medium

Cost

Current cost: The current cost for BECCS to electricity ranges from $75 to $300 per tCO_2.[838] This cost level is driven by the type of biomass used, the transportation distances needed, and the efficiency of the BECCS plant, and so can vary depending on these parameters for a specific BECCS facility. Given Massachusetts' relatively high industrial electricity prices,[839] in-state projects may be towards the upper end of this range.

Range: $75 to $300 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

BECCS to electricity has high design complexity (i.e., many number of components, some of which are mass-produced) and requires high customization to each site and each feedstock used in the process. Therefore, BECCS to electricity falls in the Type 3 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[840] This means that because BECCS to electricity requires substantial customization each time it is deployed, BECCS to electricity is unlikely to achieve cost reductions on the basis of scale alone. Cost reductions may also come from process improvements that reduce energy requirements or reduce feedstock transportation requirements. However, costs may also increase with scale due to competition for feedstock (such as waste biomass residues).

Rating: Low

Duration

Risk of reversal: BECCS to electricity can remove and store carbon with negligible risk of reversal over 10,000 years.[841] This assumes that the CO_2 is placed in geologic storage. Assuming BECCS to electricity uses conventional CO_2 storage or in-situ mineralization, reversal occurs if CO_2 leaks from the storage reservoir due to permeable faults or fractures in the storage site, but this can be mitigated through site selection.[842] Assuming BECCS to electricity uses ex-situ mineralization, reversals could occur if there is strong acid weathering at the site of carbonate mineral storage, but this can be mitigated through site selection and monitoring.[843] If the CO_2 removed by BECCS is used in a consumable product, such as a low-carbon fuel, BECCS to electricity creates storage with significant risk of reversal over 100 years because the storage is released upon combustion.[844] BECCS plants in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For BECCS to electricity, the operating lifetime of a plant is typically 20 to 30 years. Studies have modeled BECCS with a plant lifetime of 20 years.[845] BECCS plants are large industrial facilities and so can be treated analogously in planning. BECCS plants operating in Massachusetts can expect a similar plant lifetime due to the geographic independence of BECCS plant components.

Range: 20 to 30 years

Technology Readiness Level

Across the globe, only a few BECCS to electricity projects are operating at a large scale. Additionally, there are still several questions and uncertainties around net-negativity and sustainable resource use; further, more existing BECCS plants produce fuels than electricity. Because of this, it's important that BECCS to electricity continue refining and demonstrating success while being net-negative, placing the technology between pilot and demonstration phases, or TRL 6-8.[846] Some companies are pursuing large scale demonstration projects, such as Drax.[847]

Range: 6-8

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for BECCS to electricity is established, although there is some level of uncertainty. MMRV for BECCS to electricity is done by measuring the amount of CO_2 emitted during biomass combustion, the amount of CO_2 captured using flow meters, and the amount of CO_2 stored. BECCS MMRV also relies on accounting for other lifecycle emissions like biomass sourcing and transport. With these measurements, BECCS removals are calculated by subtracting the lifecycle emissions, including CO2 lost during the combustion process, from the CO_2 stored. Unlike DAC, which also has established MMRV, BECCS has uncertainty in its MMRV because of market impacts such as the diversion of land for BECCS purpose-grown crops from other uses, like forested lands or agricultural lands.[848] There are about 10 methodologies either active or under review for BECCS.[849]

Rating: Established

Deployment Timelines

BECCS to electricity has not been deployed in MA and no deployments are planned in the near future. Future deployments of BECCS to electricity projects in MA would be required to navigate relevant permitting and regulations, including energy facility siting and public zoning laws, air pollution controls and continuous operating permits, beneficial use of solid waste guidance, renewable power standards, and CO_2 transport and pipeline regulations. The legislation that these projects would need to adhere to could include M.G.L Chapter 164 Section 69J, 301 CMR 11.00, 310 CMR 19.060, 310 CMR 7.00, MassDEP Title V Operating Permit, 225 CMR 14.00, and USDOTs PHMSA guidance.[850] [851] [852] [853] [854] [855] [856] [857] [858] In terms of deployment, initial projects could move from planning to start of commercial operations at a similar rate to other MA energy generation facilities. The permitting process from MA's Energy Facilities Siting Board has historically taken between one and four years, with some projects taking as much as a decade to complete.[859] Methodologies for credit issuance indicate first issuance can coincide with project validation, though project validation requires significant review from verification bodies and document submission from projects prior to operation.[860] Overall, the timescale for BECCS to electricity projects could be on the order of a decade from planning to first credits issued. However, this timeline could potentially be accelerated if existing biomass to electricity projects were retrofit, allowing deployments to take advantage of built facilities and issued permits.[861] [862] One company with pilot and demonstration scale experience in the BECCS space moved its first pilot from completed retrofitting to captured carbon in little over a year, though this deployment took place in the UK under different regulations and did not register credits.[863]

Resource Requirements

The main requirement for BECCS to electricity is biomass feedstock and energy. The exact amount of biomass needed will depend on feedstock and process specifics but estimates suggest roughly 0.6 to 0.8 t biomass are required per tCO_2.[864] Energy use is also process dependent but is moderate due to the need to combust the biomass and capture the emitted CO_2, and has been estimated at 2.5 GJ per tCO_2.[865] If BECCS to electricity uses biowaste as a feedstock, such as woody residues from forestry operations, there is no need to use land to grow dedicated crops and therefore the land use for BECCS to electricity is minimal. Water requirements are also low if using biowaste as a feedstock, though growing dedicated crops for BECCS would require significant water on the order of 6 Gt of water per tCO_2, as well as additional land.[866]

Rating (Water): Low (using biowaste)
Rating (Land): Low (using biowaste)
Rating (Energy): Medium
Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of BECCS to electricity in Massachusetts is 550,000 to 1.0 million tCO_2e per year, which is rated as low and represents approximately 4 to 7% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages data from the Department of Energy's 2023 Billion-Ton report and a range of conversion factors that convert biomass to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue, over 20,000 dry tons of agricultural biomass residue, and over 600,000 dry tons of other wet waste (e.g., sludge).[867] Waste biomass produced from other processes in the state, such as paper and pulp production or from municipal solid waste, could also be feedstock for BECCS. However, for the removals to count as conducted in Massachusetts, the biomass would have to be grown in-state; quantifying what fraction of biomass used in these facilities are grown in Massachusetts is out of scope for this estimate. A range of carbon contents for biomass type and conversion efficiencies in BECCS to electricity (70% to 90%) was used to estimate the scale.[868] [869] This scale range relies on the assumption that all residual biomass in Massachusetts will be used for BECCS to electricity, which restricts the available feedstock for other biomass reliant CDR pathways. While BECCS to electricity could be limited by electricity offtake, Massachusetts electricity demand in 2024 was two orders of magnitude greater than what BECCS would produce,[870] which is why the scale is determined by the biomass feedstock availability.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of BECCS to electricity is 550,000 to 1.0 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including competing uses for biomass feedstock, access to secure CO_2 storage, and lifecycle accounting consistency. Even if BECCS to electricity only uses biomass residues and waste within the state, there are competing uses for the biomass just within CDR pathways; it is reasonable to assume that the amount of available biomass feedstock will limit the scale of deployment in Massachusetts. Additionally, a risk to growth for BECCS to electricity in Massachusetts is access to secure storage of the captured CO_2. Due to the limited onshore geologic storage in the state,[871] any CO_2 captured from BECCS to electricity will have to either be stored by ex-situ mineralization or transported out of state. Each of these options comes with associated costs and process logistics which pose a risk to growth. Finally, there is inconsistency in BECCS LCAs on project boundaries which can lead to different amounts of net removals. Uncertainty in quantification methods may hinder growth.

Rating: High

Local supply chain

BECCS to electricity is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least five sectors in the state's economy, including forest management companies, organic biomass management companies, power plant equipment and services provider, environmental engineering and EPC firms, and industrial gas and CO_2 pipeline companies. MA's variety of forestry management companies could provide forest residues for BECCS to electricity operations, valorizing woody debris and waste that would otherwise be disposed of or decompose, offering a consistent feedstock source for BECCS companies.[872] [873] [874] Existing in-state organic biomass disposal companies could also supply feedstocks for BECCS operations, while the select few operations that already convert solid waste into electricity could be retrofit with CCS technology to accelerate BECCS to electricity deployment.[875] [876] [877] Power plant heavy equipment and service providers in MA could be important for BECCS to electricity deployments by assisting with key process components such as steam generators and industrial boils.[878] [879] Additionally, Massachusetts hosts a variety of environmental engineering firms and EPC providers who could help navigate permitting, planning, material sourcing, and facility design for new BECCS generation sites.[880] [881] [882] [883] Finally, MA has at least one in-state providers of gas transport and pipeline equipment that could help supply the needed process components for onsite CO2 transport and storage.[884]

Rating: High

Solution providers

BECCS to electricity is not widely deployed and has only a few solution providers globally, with the most notable companies being Drax and Stockholm Exergi.[885] [886] As a result, Massachusetts does not have solution providers headquartered in state, though the state does have several biomass-to-electricity facilities, such as those operated by ReWorld.[887] However, there are not solution providers conducting projects in state, and recent biomass combustion energy plants that did not incorporate CCS have received push back during initial proposal stages; The most recent planned projects both had their permits revoked before construction, citing health and emissions concerns.[888] [889]

Co-benefits and potential negative impacts

Social and environmental co-benefits: BECCS to electricity has moderate to significant co-benefits, primarily through the creation of low-carbon electricity. Increasing low-carbon electricity production not only reduces reliance on other fossil fuel production; it also gives Massachusetts the opportunity to produce more electricity within the state. In 2023, Massachusetts consumed twice as much electricity as it produced, relying on electricity from out of state.[890] BECCS to electricity may give the state an opportunity to reduce its reliance on out of state generation. Additionally, if a BECCS to electricity plant uses municipal solid waste or other residue biomass, it could have co-benefits such as waste mitigation.[891]

Social and environmental risks: The environmental and social risks of BECCS to electricity are also moderate to significant and depend on the feedstock use and other qualities of a BECCS plant. If a BECCS plant utilizes purpose-grown crops, then this increases competition for land which could increase cost of land, displace communities, and increase food costs (if agricultural land is being diverted). If purpose-grown crops are used, this could also increase water and fertilizer use which diverts water resources from communities and could lead to run-off and leaching.[892] However, if a BECCS plant relies on biomass residues, then these risks are likely mitigated. There are also risks associated with pipeline and geologic storage infrastructure, and these risks are further explored in the storage pathways.

Health impacts: Health benefits from BECCS to electricity, separate to the core benefits related to climate mitigation, are indirect and result from the displacement of other types of electricity production; however, health risks are moderate. For example, biomass combustion could lead to increased air pollution like particulate matter.[893] Additionally, if BECCS uses purpose-grown crops and diverts land and water from communities, this could lead to associated health risks like dietary quality and water security.

Ranking: Neutral

Economic benefit and job creation

BECCS to electricity has the potential to create between 750 and 2,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[894] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. BECCS to electricity may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities,[895] farmland,[896] and forested areas in Massachusetts.[897] However, BECCS to electricity facilities will not necessarily be located near these communities and so these jobs may not be available for community members.

Ranking: Medium

Bioenergy with carbon capture and storage (BECCS) to fuels

Table 8-13: BECCS to Fuels Overview

Pathway: BECCS to fuels	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Low	
Current cost: \$75-300/tCO_2 **Cost reduction potential:** Low	**Scale potential:** Low (0.1-1.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20-30 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 9; commerical scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** Medium
Resource requirements ***Water:*** Low (using biowaste) ***Land:*** Low (using biowaste) ***Energy:*** Medium ***Feedstock:*** Medium	**Earliest planned start time:** January 2034

Table 8-13: BECCS to Fuels Overview

Overview

BECCS to fuels refers to thermal or biochemical conversion of biomass (either dedicated feedstock or waste) to generate fuels and produce CO_2 that is captured with CCS technology. The biomass can be converted into multiple fuels, such as ethanol or hydrogen. BECCS to fuels is a CDR pathway because it captures biogenic CO_2, which came from the atmosphere.

BECCS to fuels is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, which is limited by the available biomass residue in state. There are also significant risks to growth for BECCS to fuels in Massachusetts. The state's lack of in-state geologic storage means that any CO_2 captured from BECCS to fuels will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges.

There is a low potential for Massachusetts to be a leader in R&D for BECCS to fuels, since BECCS to fuels technologies are established. Although there is additional research needed for the creation of fuels like hydrogen, existing research hubs for bio-fuel productions, such as those in the Midwest, are better-suited to lead on these questions.

Deployment suitability rating: Low
R&D leadership potential rating: Low

Cost

Current cost: The current cost for BECCS to fuels ranges from \$75 to \$300 per tCO_2.[898] This cost level is driven by the type of biomass used, the transportation distances needed, and the efficiency of the BECCS plant, and so can vary depending on these parameters for a specific BECCS facility. Given

Draft, for consideration, not final

Massachusetts' relatively high industrial electricity prices,[899] in-state projects may be towards the upper end of this range.

Range: \$75 to \$300 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

BECCS to fuels has high design complexity (i.e., many number of components, some of which are mass-produced) and requires high customization to each site and each feedstock used in the process. Therefore, BECCS to fuels falls in the Type 3 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[900] This means that because BECCS to fuels requires substantial customization each time it is deployed, BECCS to fuels is unlikely to achieve cost reductions on the basis of scale alone. Cost reductions may also come from process improvements that reduce energy requirements or reduce feedstock transportation requirements. However, costs may also increase with scale due to competition for feedstock (such as waste biomass residues).

Rating: Low

Duration

Risk of reversal: BECCS to fuels can remove and store carbon with negligible risk of reversal over 10,000 years.[901] This assumes that the CO_2 is placed in geologic storage. Assuming BECCS to fuels uses conventional CO_2 storage or in-situ mineralization, reversal occurs if CO_2 leaks from the storage reservoir due to permeable faults or fractures in the storage site, but this can be mitigated through site selection.[902] Assuming BECCS to fuels uses ex-situ mineralization, reversals could occur if there is strong acid weathering at the site of carbonate mineral storage, but this can be mitigated through site selection and monitoring.[903] If the CO_2 removed by BECCS is used in a consumable product, such as a low-carbon fuel, BECCS to fuels creates storage with significant risk of reversal over 100 years because the storage is released upon combustion.[904] BECCS plants in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For BECCS to fuels, the operating lifetime of a plant is typically 20 to 30 years. Studies have modeled BECCS with a plant lifetime of 20 years.[905] BECCS plants are large industrial facilities and so can be treated analogously in planning. BECCS plants operating in Massachusetts can expect a similar plant lifetime due to the geographic independence of BECCS plant components.

Range: 20 to 30 years

Technology Readiness Level

BECCS to fuels is operating on a commercial scale; several plants around the world produce fuels using BECCS and have been operating for several years, making this a TRL 9.[906] There is still uncertainty around net-negativity and sustainable resource use that should be further researched. Although BECCS plants that produce fuels like ethanol are operating commercially, there are other fuels that are in earlier stages. For example, Mote Hydrogen has a plant planned to convert woody biomass to hydrogen using BECCS processes and this process is at a lower TRL than BECCS to fuels overall.[907]

Range: 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for BECCS to fuels is established, although there is some level of uncertainty. MMRV for BECCS to fuels is done by measuring the amount of CO_2 emitted during biomass combustion, the amount of CO_2 captured using flow meters, and the amount of CO_2 stored. BECCS MMRV also relies on accounting for other lifecycle emissions like biomass sourcing and transport. With these measurements, BECCS removals are calculated by subtracting the lifecycle emissions, including CO2 lost during the combustion process, from the CO_2 stored. Unlike DAC, which also has established MMRV, BECCS has uncertainty in its MMRV because of market impacts such as the diversion of land for BECCS purpose-grown crops from other uses, like forested lands or agricultural lands.[908] There are about 10 methodologies either active or under review for BECCS.[909]

Rating: Established

Deployment Timelines

BECCS to fuels has not been deployed in MA and no deployments are planned in the near future. Future deployments of BECCS to fuels projects in MA would be required to navigate relevant permitting and regulations, including industrial facility siting and public zoning laws, air pollution controls and continuous operating permits, beneficial use of solid waste guidance, ethanol protocols, and CO_2 transport and pipeline regulations. The legislation that these projects would need to adhere to could include EPA UIC CO_2 injection guidance 301 CMR 11.00, 310 CMR 19.060, 310 CMR 7.00, MassDEP Title V operating permit, state ethanol guidance, Mass. General Laws c.40A, and USDOTs PHMSA guidance.[910 911 912 913 914 915 916 917]In terms of deployment, initial MA projects could move from planning to start of commercial operations at a rate analogous to other US-based deployments of the BECCS to fuel pathway.[918] Active BECCS to ethanol plants have required as many as four years of site analysis and operational experimentation prior to construction, with half of that time dedicated solely to regional geologic basin studies.[919] It is important to note that timelines are also dependent on production facilities for fuels, such as ethanol, and timelines would vary depending on if entirely new facilities for fuel and CO_2 production would need to be constructed in MA. Additionally, deployments would likely require subsurface storage near production plants to maintain favorable LCAs, potentially limiting deployment potential due to the absence of appropriate geology in MA and the lengthy process for UIC permitting. FOAK credits for ethanol-production BECCS to Fuels CDR were verified in 2024, and first credits were issued after 14 months of operations.[920] Based on that information, an optimistic timeline from planning and initial conceptual design to implementation and injection could be as much as eight to ten years all told, while first credits could be achieved approximately one to two years after operations.

Resource Requirements

The main requirement for BECCS to fuels is biomass feedstock and energy. The exact amount of biomass needed will depend on feedstock and process specifics but estimates suggest roughly 0.6 to 4 t biomass are required per tCO_2.[921] Energy use is also process dependent but is moderate due to the need to combust the biomass and capture the emitted CO_2, and has been estimated at 2.5 GJ per tCO_2.[922] If BECCS to fuels uses biowaste as a feedstock, such as woody residues from forestry operations, there is no need to use land to grow dedicated crops and therefore the land use for BECCS to fuels is minimal. Water requirements are also low if using biowaste as a feedstock, though growing dedicated crops for BECCS would require significant water on the order of 6 Gt of water per tCO_2, as well as additional land.[923]

Rating (Water): Low (using biowaste)
Rating (Land): Low (using biowaste)
Rating (Energy): Medium
Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of BECCS to fuels in Massachusetts is 100,000 to 1.0 million tCO_2e per year, which is rated as low and represents approximately 1 to 8% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages data from the Department of Energy's 2023 Billion-Ton report and a range of conversion factors that convert biomass to removals. It is estimated that Massachusetts will have over 40,000 dry tons of forest biomass residue, over 20,000 dry tons of agricultural biomass residue, and over 600,000 dry tons of other wet waste (e.g., sludge).[924] Waste biomass produced from other processes in the state, such as paper and pulp production or from municipal solid waste, could also be feedstock for BECCS. However, for the removals to count as conducted in Massachusetts, the biomass would have to be grown in-state; quantifying what fraction of biomass used in these facilities are grown in Massachusetts is out of scope for this estimate. A range of carbon contents for biomass type[925] and conversion efficiencies in BECCS to fuels (14% to 90%)[926] was used to estimate the scale, which reflects the wide range of conversion efficiencies of BECCS to fuels depending on process and feedstock. This scale range relies on the assumption that all residual biomass in Massachusetts will be used for BECCS to fuels, which restricts the available feedstock for other biomass reliant CDR pathways. While BECCS to fuels could be limited by fuel offtake, Massachusetts gasoline consumption in 2025 was two orders of magnitude greater than the number of gallons BECCS could produce,[927] which is why the scale is determined by the biomass feedstock availability.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of BECCS to fuels is 100,000 to 1.0 million tCO_2e per year, several factors and risks exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including competing uses for biomass feedstock, access to secure CO_2 storage, and lifecycle accounting consistency. Even if BECCS to fuels only uses biomass residues and waste within the state, there are competing uses for the biomass just within CDR pathways; it is reasonable to assume that the amount of available biomass feedstock will limit the scale of deployment in Massachusetts. Additionally, a risk to growth for BECCS to fuels in Massachusetts is access to secure storage of the captured CO_2. Due to the limited onshore geologic storage in the state,[928] any CO_2 captured from BECCS will have to either be stored by ex-situ mineralization or transported out of state. Each of these options comes with associated costs and process logistics which pose a risk to growth. Finally, there is inconsistency in BECCS LCAs on project boundaries which can lead to different amounts of net removals. Uncertainty in quantification methods may hinder growth.

Rating: High

Local supply chain

BECCS to fuels is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least four sectors in the state's economy, including waste biomass providers, thermal conversion technology providers, environmental engineering and EPC firms, and industrial gas and CO_2 pipeline companies. Massachusetts has a variety of companies that could source agricultural and forestry wastes as biomass feedstocks for BECCS to fuels operations.[929] [930] [931] The state also host technology providers who could provide process components key to the thermal conversion of biomass during the BECCS to fuels process.[932] [933] [934] Additionally, Massachusetts hosts a variety of environmental engineering firms and EPC providers who could help navigate permitting, planning, material sourcing, and facility design for new BECCS generation sites.[935] [936] [937] [938] Finally, MA has at least one in-state providers of gas transport and pipeline equipment that could help supply the needed process components for onsite CO2 transport and storage.[939]

Rating: Medium

Solution providers

BECCS to fuels CDR is not widely deployed and has only a few solution providers deploying the pathway to-date, with the most notable companies being Archer Daniels Midland, who opened the first commercial ethanol BECCS plant in Decatur, IL in 2024, and Mote, whose BECCS to H_2 approach is set for deployment in 2027.[940] [941] Unfortunately, Massachusetts does not have any solution providers headquartered in state, nor are there any solution providers currently conducting or planning projects within the state's borders.

Co-benefits and potential negative impacts

Social and environmental co-benefits: BECCS to fuels has moderate co-benefits, primarily through the creation of low-carbon fuels which could divert the use of more carbon-intensive fuels (e.g., the use of BECCS to make sustainable aviation fuel).[942] This leads to the production of and burning of cleaner fuels which could lead not only to economic opportunity but also to a reduction in pollutants. Additionally, if a BECCS to electricity plant uses municipal solid waste or other residue biomass, it could have co-benefits such as waste mitigation.[943]

Social and environmental risks: The environmental and social risks of BECCS to fuels are similar to those for BECCS to electricity, are moderate to significant, and depend on the feedstock use and other qualities of a BECCS plant. If a BECCS plant utilizes purpose-grown crops, then this increases competition for land which could increase cost of land, displace communities, and increase food costs (if agricultural land is being diverted). If purpose-grown crops are used, this could also increase water and fertilizer use which diverts water resources from communities and could lead to run-off and leaching.[944] However, if a BECCS plant relies on biomass residues, then these risks are likely mitigated. There are also risks associated with pipeline and geologic storage infrastructure, and these risks are further explored in the storage pathways.

Health impacts: Health benefits from BECCS to fuels, separate to the core benefits related to climate mitigation, are indirect and result from the displacement of other types of fuel production (like jet fuels); however, health risks are moderate. For example, biomass combustion could lead to increased air pollution like particulate matter.[945] Additionally, if BECCS uses purpose-grown crops and diverts land and water from communities, this could lead to associated health risks like dietary quality and water security.

Ranking: Neutral

Economic benefit and job creation

BECCS to fuels has the potential to create between 150 and 2,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[946] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. BECCS to fuels may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. Harvesting forestry and agricultural residues may create jobs for these communities due to the overlap in geography between disadvantaged communities,[947] farmland,[948] and forested areas in Massachusetts.[949] However, BECCS to fuels facilities will not necessarily be located near these communities and so jobs may not be available for community members.

Ranking: Medium

Geochemical CDR

Geochemical CDR (gCDR) pathways use naturally-occurring neutralization reactions between acidic forms of carbon and alkaline minerals to convert CO_2 from the atmosphere into solid carbonate minerals or dissolved bicarbonates.

Surficial mineralization

Table 8-14: Surficial Mineralization Overview

Pathway: Surficial Mineralization	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Low	
Current cost: \$55-500/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Low (0.6-1.2 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 5 to 70 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 5-6; lab to pilot	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** Medium
<u>**Resource requirements**</u> ***Water:*** Low ***Land:*** High ***Energy:*** Medium ***Feedstock:*** High	**Earliest planned start time:** January 2029

Table 8-14: Surficial Mineralization Overview

Overview

Surficial mineralization enhances the natural reaction between alkaline materials and air to turn CO_2 into solid carbonates (as opposed to weathering pathways where the CO_2 ends up as dissolved bicarbonate). In practice, this means exposing reactive tailings or excavated rock, and, in Massachusetts, also recycled concrete fines and some ashes, to air, potentially after processing steps like crushing and spreading.

Surficial mineralization is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential of the pathway, due to the lack of available in-state alkaline minerals. The limited feedstock availability and open MMRV questions pose a high risk to growth as well.

There is a low potential for Massachusetts to be a leader in R&D for surficial mineralization. The pathway is still developing and has open research questions, such as on MMRV. However, regions with greater current or historical mining, such as Canada, have already begun to lead on R&D. Massachusetts has limited suitable feedstock for surficial mineralization and so is better suited to lead in R&D for other pathways that can be deployed at greater scale in-state.

<u>Deployment suitability rating</u>: Low
<u>R&D leadership potential rating</u>: Low

Cost

Current cost: The current cost for surficial mineralization ranges from \$55 to \$500 per tCO_2.[950] The cost level will vary depending on the feedstock reactivity and operational activity (e.g., surface agitation to prevent passivation). Costs in Massachusetts would be in the higher end of this range. In

Massachusetts, limited historical ultramafic mining means few large in-state tailings piles,[951] so the opportunity for lower cost implementation is limited. If surficial mineralization was done in the state at a large scale, implementing would cost more due to the need and cost of importing relevant feedstocks, though this is not reasonable for the state.

Range: \$55 to 500 per tCO_2

Cost reduction potential: The potential for cost reduction is high.

Surficial mineralization has medium design complexity (e.g., few components, but many are not mass-produced) and a moderate need to be customized at each project site and thus falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[952] This means that because surficial mineralization requires site-specification but can benefit from economies of scale as more equipment is mass-produced, surficial mineralization is likely to achieve a moderation cost reduction with scale. Cost reductions may also come from process innovation, including increasing reactivity through grain-size control and moisture management.[953] However, MMRV for surficial mineralization still faces uncertainty due to the open system nature of projects, which may cause costs to increase as MMRV protocols develop.

Rating: Medium

Duration

Risk of reversal: Surficial mineralization removes and stores carbon with negligible risk of reversal over time periods greater than 10,000 years,[954] by storing CO_2 as solid carbonates (e.g., calcite, magnesite. Under normal temperature and pressure conditions, properly managed carbonate products are effectively permanent.[955] The main risk of reversal would be strong acid weathering, which can be mitigated through site monitoring.[956]

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For surficial mineralization, the operating lifetime of a project is typically 5 to 70 years, modeled after average lifetimes for mines.[957] Modeling studies treat project lifetime on multi-decade horizons.[958] Project lifetime will ultimately be determined by feedstock reactivity and availability, though conventional materials-handling and mineral-processing equipment may need periodic replacement during the overall project lifetime.

Range: 5 to 70 years

Technology Readiness Level

Surficial mineralization ranges from lab development to pilot scale (TRL 5-6).[959] Arca's Mt. Keith Mineral Carbonation Project in Australia is a notable pilot in which surficial mineralization was integrated at a small scale into mining operations, for an 18-month project in 2023.[960] Additionally, Arca currently operates a testing site in Canada to evaluate their MMRV technologies in relevant environmental conditions.[961]

Range: TRL 5 to 6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for surficial mineralization is developing. MMRV is based on the mass of CO_2 stored in carbonates and can be quantified through the decrease of CO_2 in the air using eddy covariance flux towers or dynamic closed chambers; the change in carbonate chemistry, such as by measuring pH; or the change in mineral content.[962] Methodologies have been developed for surficial mineralization MMRV, including Isometric's Open System Ex-situ Mineralization protocol,[963] However, challenges to MMRV include the accurately accounting for the heterogeneity present in open systems and creating an accurate baseline to ensure credited removal is additional.[964] Additionally, MMRV is currently labor-intensive, though autonomous measurement is being piloted by companies,[965] which could decrease labor requirements.

Rating: Developing

Deployment timelines

Surficial mineralization has not been deployed in MA and no deployments are currently planned as of 2025. If project developers do plan to deploy surficial mineralization in MA, they will have to navigate regulations for land application of industrial residuals, groundwater management, and air permitting for pre-processing and application of feedstocks.[966] [967] [968] These regulations include 310 CMR 32.00, 314 CMR 4 and 310 CMR 7.00.[969] [970] [971] In terms of deployment, companies operating in the surficial mineralization space has demonstrated timelines for moving projects from planning to completed, moving from founding to completion of a pilot scale project in approximately three and a half years. One company's pilot project for surficial mineralization took approximately 18 months to complete initial planning and site selection, as well as operational agreements with feedstock suppliers, and an additional 18 months to complete pilot projects.[972] [973] [974] The first standard methodology for accreditation of the company's surficial mineralization pathway was validated in June of 2025, so verified credits have yet to be issued, though this process could reasonably be expected to take between six and twelve months.[975] While this may vary at commercial scale, MA deployments could move from planning to first credit issuance in approximately three and half to five years, given the available data for the pathway.

Resource Requirements

The main resource requirement for surficial mineralization is feedstock, land, and energy. The amount of alkaline mineral feedstock needed per tCO_2 removed ultimately depends on the feedstock's composition. Assuming full conversion of common alkaline mineral feedstock means about 1.6 t mineral per tCO_2 is needed for olivine, 1.3 t mineral per tCO_2 for brucite, and 2.0–2.5 t mineral per tCO_2 for serpentine and wollastonite.[976] In field-relevant conditions, only a small fraction is readily reactive,[977] which will increase the feedstock requirement relative to the full conversion assumption. Energy use is dominated by materials handling and any feedstock pre-treatment. One method of pre-treatment is grinding, which could increase the energy requirement by 0.03 to 0.9 GJ per tCO_2. Land needs are large to allow passive feedstock reaction with atmospheric CO_2; although dependent on the thickness of the alkaline mineral layer, at least 0.5 km^2 per tCO_2 can be expected with passive uptake of CO_2 only.[978] The water requirement is low because ambient moisture/precipitation suffice.[979]

Rating (Water): Low

Rating (Land): High

Rating (Energy): Medium
Rating (Feedstock): High

Scale and growth

The estimated maximum potential deployment of surficial mineralization in Massachusetts is between 600,000 to 1.2 million tCO_2, which is rated as low and represents approximately 4-9% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was arrived at by using data on ultramafic mine tailings, steel slag, coal ash, and construction and demolition (C&D) waste produced in Massachusetts.[980] [981] [982] Massachusetts does not have significant ultramafic mine tailings or steel slag; the available coal ash in Massachusetts, around 300 tons per year, was estimated using historical coal ash volumes from the Mt. Tom facility,[983] assuming to be used from now until 2050. C&D waste was by far the highest feedstock value with over 1.6 million tons produced in a year.[984] Once all available feedstocks were combined, the final scale potential was calculated by leveraging mineralization rates for Wollastonite and Brucite, 2.5 and 1.3 tonnes per tCO_2 respectively.[985] This estimate relies on the assumption that all C&D materials in Massachusetts could be used for surficial mineralization; however, the C&D category also includes materials like rubber, brick, and wood which cannot undergo carbonation, meaning this scale potential is an overestimate. Because surficial mineralization typically relies on alkaline waste as a feedstock, available feedstock is used as the constraining factor in this estimate rather than land area. It is unlikely that waste feedstock, such as ultramafic mine tailings, would be transported into Massachusetts due to environmental and hazardous material regulations.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of surficial mineralization CDR is 600,000 to 1.2 million tCO_2, there are risks that could prevent deployment at this scale, including the lack of suitable in-state feedstocks and the development of MMRV processes suitable for scaled deployment.[986] [987] [988] [989]Primarily, the scale of surficial mineralization CDR in Massachusetts is dependent on the availability of excavated and processed alkaline feedstocks; Surficial mineralization integrates well with existing mining operations as well as other industrial processes by using mine tailings and industrial waste streams as feedstock, though scale is then limited by these operations.[990] In the context of Massachusetts, where no alumina refineries, steelmaking operations, or active metallic mining locations are operational, feedstocks such as mine tailings will be limited to legacy waste residues and residuals from decommissioned operations and would not factor into meaningful scaled deployment.[991] [992] [993] An additional risk is to scaling surficial mineralization is scaling MMRV.[994] As project size increases, the area and time needed for MMRV will similarly increase unless autonomous sampling and/or modeling improves.[995]

Rating: High

Local supply chain

Surficial mineralization CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least three sectors in the state's economy, including concrete producers, quarry operators, and suppliers of gas measurement equipment. Massachusetts has several companies prepared to assist in sourcing feedstock for surficial mineralization projects; these companies could monetize materials like quarry fines and recycled-concrete fines while also providing a reliable source of alkaline materials for spreading and carbonation[996,997]. The state also has capacity for the necessary pre-processing capacity, including crushing and grinding operations, that would improve reaction kinetics at deployment sites; These services could again be outsourced to state-based quarry mills and associated crushing facilities that are already in the business of grain size reduction and processing [998]. Finally, technology needed for surficial mineralization MMRV can also be procured with the assistance of Massachusetts-based innovators; a local company has developed thermogravimetric analyzers to quantify carbonate formation and CO_2 uptake, while other in-state suppliers of gas analysis technology could support lab analysis via mass spectrometer and CO_2 measurement equipment.[999] [1000]

Rating: Medium

Solution providers

Surficial mineralization CDR is not widely deployed and has only a few notable solution providers pursuing the pathway; Vancouver-based Arca, who focuses on surficial mineralization of mine tailings, and Karbonetiq, a California-based company with Canadian projects, are two field leaders with active deployments.[1001] In MA, Anvil, a company recently founded and now based out of Somerville, MA, is aiming to utilize highly reactive alkaline minerals to capture atmospheric CO_2 in a proprietary low-energy system which intends to speed up the rate of mineralization.[1002] The company hopes to create solid carbonate minerals that would then be stored durably at the site of mineralization, which could mean new surficial mineralization deployments are announced in MA in the near future. With that said, the commonwealth does not currently have any solution providers conducting projects domestically, largely due to lack of ultra-mafic mining and a subsequent absence of mine tailings; however, if suitable mineral-rich feedstock streams are identified at MA construction and industrial sites, projects could move forward in Massachusetts.[1003]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Surficial mineralization has the potential to provide significant social and environmental co-benefits, including diverting industrial waste. Solid carbonate could convert alkaline industrial byproducts (e.g., steel slag, recycled concrete fines) into stable carbonates and usable aggregates, reducing waste liabilities and supporting low-carbon construction markets.[1004] [1005]

Social and environmental risks: Surficial mineralization has the potential to pose moderate but manageable social and environmental risks, including mobilizing trace metals. Operations that weather ultramafic/alkaline solids outdoors could release highly alkaline runoff and mobilize trace metals which could contaminate receiving waters and harm fisheries.[1006] [1007]

Health impacts: Surficial mineralization has the potential to pose moderate health hazards including respiratory illnesses. Crushing, handling, and stockpiling industrial alkaline solids could generate respirable crystalline silica which could lead to lung damage and cancer.[1008] [1009]

Rating: Neutral

Economic benefit and job creation

Surficial mineralization has the potential to create between 800 and 3,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment,[1010] assuming a similar job creation profile as terrestrial enhanced weathering. Making this assumption implies that the surficial mineralization process will include operators using industrial equipment to spread out alkaline minerals and to measure and monitor CO_2 uptake. Methods of implementing surficial mineralization that include autonomous surface agitation and measurement would create fewer jobs. This job creation estimate is also calculated using the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Surficial mineralization may direct a portion of total economic benefits in the form of jobs to disadvantaged communities within the state. If coal ash from the Mt. Tom facility jobs may be directed to the disadvantaged communities within the area.[1011] However, there are waste facilities all over the state that have C&D waste and so jobs from surficial mineralization using C&D waste as a feedstock may not be available for these community members.

Rating: Medium

Terrestrial enhanced weathering

Table 8-15: Terrestrial Enhanced Weathering Overview

Pathway: Terrestrial enhanced weathering	
Deployment suitability for Massachusetts: High **R&D leadership potential:** Medium	
Current cost: $50-500/t$CO_2$ **Cost reduction potential:** Medium	**Scale potential:** High (3.1-11.7 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 1 to 70 year	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 6-7; pilot to demo scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** High
Resource requirements ***Water:*** Low ***Land:*** High ***Energy:*** Medium ***Feedstock:*** High	**Earliest planned start time:** September 2026

Table 8-15: Terrestrial Enhanced Weathering Overview

Overview

Terrestrial enhanced weathering (TEW) is the acceleration of the natural geologic weathering process through the spreading of finely ground alkaline materials in agricultural, urban, or forest soils, where it reacts with CO_2 and water to produce dissolved inorganic carbon.

Terrestrial enhanced weathering is likely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the high scale potential of the pathway, which stems from the availability of farmland and forest area for alkaline mineral application, as well as the potential to be integrated into state pH management programs.

There is a moderate potential for Massachusetts to be a leader in R&D for terrestrial enhanced weathering. The pathway is still developing and has open research questions, such as on MMRV, for which the state can lead on developing technology. Additionally, although significant research on terrestrial enhanced weathering on croplands is already occurring, the large-scale potential on forested land in the state creates a key opportunity to lead on research.

Deployment suitability rating: High
R&D leadership potential rating: Medium

Cost

Current cost: The current costs for TEW on U.S. cropland are estimated at \$50 to \$500 per tCO_2.[1012] This cost level will vary based on the reactivity of the rock type, the amount of grinding needed for the mineral feedstock, and the transport of feedstock to the application site. In Massachusetts, TEW costs may be on the higher end of this range due to likelihood of needing transport of feedstock to application sites, such as farmland, throughout the state. This cost range refers to the gross cost of the TEW process; using alkaline minerals to replace soil management materials in agricultural practice would reduce the marginal cost of carbon removal.

Range: \$50 to \$500 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

TEW has low design complexity (e.g., few components, and many are mass-produced) and a moderate need to be customized at each project site and with each feedstock. Therefore, TEW falls in the Type 2 section of the cost reduction potential matrix (see Appendix on potential for cost reduction with scale). This means that because TEW is simple in its design but has a requires customization at each application site, TEW is likely to achieve moderate cost reduction with scale. Cost decreases may also come from lower-energy feedstock pre-treatment processes, shorter supply chains by siting near quarries, and standardized MMRV that spreads fixed costs at scale.[1013] However, MMRV for TEW still faces uncertainty due to the open system nature of projects, which may cause costs to increase as MMRV protocols develop.

Range: Medium

Duration

Risk of reversal: TEW removes and stores carbon removal with negligible risk of reversal for greater than 10,000 years.[1014] The process converts atmospheric CO_2 into bicarbonate, of which 90% is delivered to the ocean and can be stored for millennia.[1015] Reversal risks are primarily during transportation through watersheds to the ocean, where a small fraction of carbon may be released due to local pH.[1016] In Massachusetts, TEW projects can expect the same level of reversal risk due to its proximity to the ocean for storage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: The operating lifetime of a TEW project is typically 1 to 70 years, depending on whether the project is integrated into existing agricultural practices or into mining sites. TEW can integrate into existing agricultural practices to manage soil pH, which typically require at least annual application,[1017] while mines can operate for decades.[1018] Ultimately, the operating lifetime will depend on feedstock and application site availability, which will determine the operating lifetime for TEW projects in Massachusetts.

Range: 1 to 70 years

Technology Readiness Level

TEW is at the pilot to demonstration scale (TRL 6-7), reflecting increasingly larger projects under relevant environmental conditions.[1019] There are multiple TEW companies such as Lithos and UNDO, that are securing offtake agreements with major corporate buyers, including Microsoft and Frontier.[1020] In Massachusetts, small basalt rock-dust field trials have occurred, demonstrating that operational conditions can exist in-state.[1021] Improving MMRV will be key in allowing TEW to increase in scale and move along the TRL scale.[1022]

Range: TRL 6 to 7

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for TEW is developing. MMRV is done by directly measuring the mass mineral applied to a site, which then can be converted to CO_2 removal through a variety of measurement techniques and modeling. Critically, MMRV for TEW needs to reduce carbon removal quantification uncertainty in both mineral weathering (which increases net carbon removal) and any solid carbonate precipitation (which decreases net carbon removal).[1023] However, there has been significant progress in TEW MMRV, including a TEW-specific methodology public consultation by the carbon credit registry Puro.earth,[1024] an Enhanced Weathering in Agriculture protocol by the carbon credit registry Isometric,[1025] and quantification guidance by Cascade Climate.[1026] Credits have already been certified by these registries. MMRV will likely require improvements in modeling as TEW scales to decrease labor needs.[1027]

Rating: Developing

Deployment Timelines

Terrestrial enhanced weathering has not yet been deployed in MA and no deployments are planned as of 2025. If project developers do plan to deploy terrestrial enhanced weathering in MA, they will have to navigate regulations for land application of industrial residuals, groundwater management, and air permitting for pre-processing and application of feedstocks.[1028] [1029] [1030] The state of Massachusetts has strict regulations on the application of treated residuals derived from industrial facilities, potentially restricting eligible feedstocks produced from manufacturing operations, such as concrete fines.[1031] Additionally, because of the potential risk of feedstocks causing the leaching of metals or unwanted contaminants into soils during rainfall events, TEW projects will need to navigate state surface and storm water quality standards, as well as EPA Clean Water Act guidelines, to ensure that deployments do not impact groundwater sources.[1032] Finally, given the rock dust generated from feedstock pre-processing and in-situ application for TEW deployment, projects will also have to navigate air quality guidelines, including pollution control standards and permit requirements, and will require air plan approvals prior to project siting and deployment.[1033] The first company to receive verified TEW removal credits, which were issued in January of 2025, was founded in mid-2022; by the end of 2022, the company had deployed their first pilot project, and, by 2024, they had spread more than 50 kt of rock dust across several projects.[1034] [1035] [1036] While this is a specific example for a particular company's approach, a reasonable deployment timeline from planning to credit issuance for a large scale project could take between three and four years for future MA deployments of TEW, while a pilot scale project could potentially be move from planning to deployment in as few as six to nine months.

Resource Requirements

The main resources required for TEW are mineral feedstock and land for application. Alkaline minerals are typically silicate or carbonate minerals and requirements will depend on specific chemistry and particle size. Studies estimate that between 0.8 to 3 t mineral per tCO_2 are needed, though actual feedstock needs may be higher when applied in open systems like farmland.[1037] TEW can integrate into agricultural practices and therefore not require significant land conversion, though the scale of carbon removal is then limited by farmland in Massachusetts.[1038] Regardless, substantial land will be needed for TEW to scale; although dependent on feedstock type and application rate, some estimates suggest 3 hectare are needed per tCO_2.[1039] Energy demand will depend on the comminution needs (which can be significant and on the order of 0.02 to 1.2 GJ per tCO_2)[1040] and transportation needs (which depends on transportation distance). Water use is minimal because precipitation is sufficient for TEW.[1041]

Rating (Water): Low
Rating (Land): High
Rating (Energy): Medium
Rating (Feedstock): High

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of terrestrial enhanced weathering in Massachusetts is between 3.1 million and 11.7 million tCO_2e, which is rated as high and represents approximately 20-80% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was arrived at by leveraging the amount of farmland and forested land in Massachusetts, an application rate, and a range of removal rates. Application and removal rates will vary depending on the specific feedstock, application site, and climate. This scale estimate assumes that 7 tons of alkaline mineral can be added per hectare of farmland, based on a field trial in Massachusetts, and that the removal rate ranges from 0.8 - 3 tons per tCO_2e, based on scientific literature.[1042] This means that the removal rate for one hectare is 2 - 8 tCO_2e. Massachusetts has over 180,000 hectares of farmland and 1.2 million hectares of forested land, resulting in the mentioned range of removals.[1043] This estimate assumes that terrestrial enhanced weathering would occur on all farmland and all forested land. It also assumes the applied alkaline mineral would remove CO_2 per hectare within the range calculated here, which will depend on application rates and feedstock composition but does align with a range of literature values for different TEW implementations.[1044]

Rating: High

Risks to growth: While the estimated maximum potential deployment of terrestrial enhanced weathering CDR is between 3.1 million and 11.7 million tCO_2e per year, challenges exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including local climate impacts on weathering rates, community concerns from widespread application, MMRV and temporal concerns over time to mineralization, and competing uses for land. Because of its generally cool, seasonal climate, Massachusetts-based TEW deployments could experience slower dissolution and wider year-to-year variability relative to deployments in warmer regions.[1045] Empirical temperate-cropland results (~3.4 tCO_2/ha/yr with basalt) are promising, but these results should be applied cautiously in the context of Massachusetts, as removal rates may be lower.[1046] Additionally, rock dust from large scale deployments could pose a potential threat to population health in communities that host large-scale deployments.[1047] New TEW deployments must balance health concerns with state environmental regulations and soil application guidelines to achieve successful deployment as well. Land-applied rock dust is governed by Massachusetts fertilizer/soil-conditioner law and nutrient-application rules, requiring product registration, labeling, and safeguards, which could delay deployments due to concerns of metal leaching and create legal issues depending on community sentiment.[1048] [1049] Additionally, the use of quarry fines or other secondary materials will require a MassDEP Beneficial Use Determination, leaving the state to decide whether or not various feedstocks can be utilized in TEW projects, potentially limiting feedstock availability.[1050] On top of these issues, there are also concerns that stem from the extended timeline for MMRV and mineralization in TEW deployments; The reaction time of minerals used in TEW applications with atmospheric CO_2 is slow and occurs on the order of years to decades.[1051] Over the course of this time, portions of alkaline feedstocks could escape from the initial area of application, making it difficult to measure what percentage of the alkali reacts with atmospheric CO_2. In some cases, select feedstocks have even been shown to release GHGs, potentially negating the CDR benefit from application.[1052] As a result, there is uncertainty in how enhanced weathering will operate or be measured at scale, especially because a significant amount of data on the pathway has been sourced from lab or small pilots. Finally, more specific to MA context, the above scale estimate assumes that all farmland and forested land in MA is allocated to TEW; competitive and existing commercial uses will prevent this level of utilization, meaning only a percentage of state land could be used by TEW developers.

Rating: Medium

Local supply chain

Terrestrial enhanced weathering CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact three sectors in the state's economy, including local quarry operators, milling and rock processing companies, and fertilization operations currently focused on spreading lime. In terms of mineral feedstock, Massachusetts quarry operators could supply initial rock and fines for TEW project feedstock streams, enabling consistent deployment while monetizing waste rock.[1053] [1054] Additionally, basalt fines/stone dust and carbonates are already sold in-state by at least one other company, though additional micronization to maximize reaction surface area would likely be required.[1055] [1056] [1057] To address that need, Massachusetts has at least one company whose jet mills and classifiers could be utilized to produce controlled fine particles to improve sequestration rates and reaction kinetics.[1058] MA projects could also leverage the many conventional lime-spreading companies that are already established or operating domestically, utilizing their spreading machinery to deploy mineral feedstock at scale without significant additional CAPEX, as well as the companies applying sand to roads.[1059]

Rating: Medium

Solution providers

Terrestrial enhanced weathering CDR is widely deployed and has many active solution providers globally. However, Massachusetts does not have solution providers headquartered in state, nor are there any out-of-state solution providers conducting projects in the commonwealth. With that said, Yale conducted a trial in NY in 2023-24 utilizing 160 tons of crushed basalt feedstock sourced from MA quarries, demonstrating the state's capacity to leverage local resources to begin trial deployments on a reduced timescale and initial field trials have been conducted by UMASS and UVA in MA to understand basalt rock dust impacts on soil health and inorganic nutrients.[1060] [1061] However, neither UMASS, Yale, nor UVA can be considered solution providers as these experiments were either focused on CDR benefits from basalt application or did not occur in-state.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Terrestrial enhanced weathering has the potential to provide significant social and environmental co-benefits, including soil health gains. Finely ground silicates could raise soil pH and supply Magnesium, Calcium, and Potassium, with field and mesocosm studies reporting improved fertility and, in some cases, yield increases—relevant to MA's acidic northeastern soils.[1062][1063][1064][1065] TEW can also decrease fertilizer use, reducing N_2O emissions and eutrophication, as well as reducing the need for fertilizer procurement by farms.[1066] Massachusetts' has approximately 7,000 farms across 180,000 hectares which could provide practical testbeds to validate benefits and operational practices before broader use.[1067]

Social and environmental risks: Terrestrial enhanced weathering has the potential to pose moderate but manageable social and environmental risks, including mobilizing trace metals. Operations that weather ultramafic/alkaline solids outdoors could release highly alkaline runoff and mobilize trace metals which could contaminate receiving waters and harm fisheries.[1068] [1069]

Health impacts: Terrestrial enhanced weathering has the potential to pose moderate but manageable health hazards including respiratory illnesses. Crushing, handling, and stockpiling industrial alkaline solids could generate respirable crystalline silica which could lead to lung damage and cancer.[1070] [1071]

Rating: Neutral

Economic benefit and job creation

Terrestrial enhanced weathering has the potential to create between 4,000 and 27,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above.[1072] Job creation by terrestrial enhanced weathering will likely be mostly in ongoing operations jobs, based on the need to regularly spread alkaline minerals and sample for MMRV. MMRV. The large potential for job creation stems from the large scale potential of deployment. Terrestrial enhanced weathering is likely to direct economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities[1073] and farmland throughout Massachusetts.[1074]

Rating: High

Coastal enhanced weathering

Table 8-16: Coastal Enhanced Weathering Overview

Pathway: Coastal enhanced weathering	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** High	
Current cost: \$55-225/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Low (0.04-0.1 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 1-70 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 5-6; lab to pilot	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** Low
Resource requirements ***Water:*** Low ***Land (coastal):*** High ***Energy:*** Medium ***Feedstock:*** High	**Earliest planned start time:** June 2028

Table 8-16: Coastal Enhanced Weathering Overview

Overview

Coastal enhanced weathering (CEW) is the process of spreading crushed alkaline minerals onto the beach and coastal areas to react with the dissolved CO_2 in ocean water to form bicarbonates that can be stored for millennia. This process can be integrated with beach nourishment activities.

Coastal enhanced weathering is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the State's total need for CDR. The potential scale for deployment is low within the State due to limited suitable coastal area. Although Massachusetts has significant access to the coast, many of the beaches are broken into smaller sections by various aquaculture and wetland resources, which limit application area, and the medium to coarse grained nature of the State's beaches pose a mismatch with the fine-grained alkaline minerals typically applied in CEW. Open MMRV questions will also need to be answered before large-scale deployment, which pose a risk to growth.

However, there is a high potential for Massachusetts to be a leader in R&D for coastal enhanced weathering. The pathway is still developing and has open research questions, such as on MMRV, that the State can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the coast. Additionally, research institutions in the State are actively investigating the effectiveness and safety of applying CEW to tidal wetlands, positioning Massachusetts well to lead on innovation in this early stage area of research as well.

Deployment suitability rating: Low
R&D leadership potential rating: High

Note: An active area of research is **wetland enhanced weathering**, in which alkaline minerals are spread onto wetlands as opposed to beaches. One potential application site are salt marshes, which could be particularly relevant to Massachusetts due to the State's 47,000 acres of salt marsh.

However, there is still significant uncertainty with alkaline mineral application to salt marshes, since deployment so far has only been at the research trial scale. In Massachusetts, enhanced weathering on salt marshes may face additional barriers to implementation due to geographic proximity to tidal restrictions.

Due to these uncertainties, the potential scale of enhanced weathering on salt marshes is not included in the total coastal enhanced weathering scale estimate later in this section. However, for additional context, if Massachusetts were to deploy enhanced weathering on all of its 47,000 acres of salt marsh, using the methodology describes in the Scale and Growth section below, approximately 90,000 to 200,000 tCO_2e per year could be deployed. This represents 0.5 to 1.5% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target and so enhanced weathering on salt marshes is unlikely to substantially aid the State in meeting its total need for CDR.

At the same time, Massachusetts may be especially well-poised to lead on R&D for salt marsh enhanced weathering. Research institutions in the State are actively investigating the effectiveness and safety of this process, positioning Massachusetts well to lead on innovation.

Potential benefits from the integration of wetland enhanced weathering with salt marsh projects include minimizing incremental project logistics and costs, as well as the further coupling of CDR with salt marsh restoration efforts. Additionally, measurement of CO_2 uptake by the salt marsh may be able to be directly measured prior to export to the ocean, which would decrease MMRV complexity. Massachusetts can continue to develop the understanding of these co-benefits through research and development.

Cost

Current cost: The current cost for CEW ranges from \$55 to \$225 per tCO_2. This cost level will vary based on the reactivity of the rock type, the amount of grinding needed for the mineral feedstock, and the transport of feedstock to the application site. Costs for CEW have some uncertainty due to MMRV requirements. Estimates suggest a cost of approximately \$55 to \$150 per tCO_2, without specifying MMRV costs.[1075] However, a recent study found that MMRV costs for CEW could be up to 50% of the total cost,[1076] which increased the upper range presented here. Costs in Massachusetts may be on the lower end of this range due to potential integration with the state's beach nourishment and coastal resilience projects. ⍰

Range: \$55 to \$225 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

CEW has low design complexity (e.g., few components, and many are mass-produced) and a moderate need to be customized at each project site and with each feedstock. Therefore, CEW falls in the Type 2 section of the cost reduction potential matrix (see Appendix on potential for cost reduction with scale). This means that because CEW is simple in its design but has a requires customization at each application site, CEW is likely to achieve moderate cost reduction with scale. Costs can also decrease due to lower-energy feedstock grinding, shorter transport distances, and standardized MMRV that spreads fixed costs at scale.[1077] However, MMRV for CEW still faces uncertainty due to the open system nature of projects, which may cause costs to increase as MMRV protocols develop if quantification proves difficult. Alternatively, MMRV costs could significantly decrease with scale as large scale ocean modeling develops and data collection methods are simplified.

Rating: Medium

Duration

Risk of reversal: CEW provides storage with negligible risk of reversal for greater than 10,000 years.[1078] Throughout the process, alkaline minerals react with the dissolved CO_2 in ocean water to form bicarbonates that can be stored for millennia.[1079] The main risk of reversal is if, due to local pH, secondary precipitation occurs that re-releases CO_2.[1080] CEW projects in Massachusetts can expect a slightly lower reversal risk due to the relatively low temperature, low pH, and low alkalinity in New England waters which decreases the likelihood of carbonate precipitation.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: The operating lifetime of a CEW project is typically 1 to 70 years, depending on whether the project lifetime is determined by the application timeline and is integrated into existing coastal restoration practices, occurring on the year to decade scale,[1081] or if the project lifetime is determined by the mining site, which can operate for multiple decades.[1082] Ultimately, the operating lifetime will depend on feedstock and application site availability, as well as the requirement for monitoring, which will determine the operating lifetime for CEW projects in Massachusetts.

Range: 1 to 70 years

Technology Readiness Level

CEW is currently at the lab to pilot scale (TRL 5 to 6).[1083] Pilots are actively occurring by the supplier Vesta, including a pilot in Southampton, NY in which olivine was integrated into the area's beach nourishment activities and a pilot with olivine in Duck, NC.[1084] MMRV will have to develop to allow CEW projects to scale and the technology to move along the TRL scale.[1085]

Range: TRL 5 to 6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for CEW is developing. The amount of CO_2 removed is measured based on the amount of alkaline mineral applied, which can be directly measured by mass, and the amount of mineral that reaches the ocean and reacts to form bicarbonates, which is based on modeling.[1086] The level of uncertainty in measuring the degree of secondary precipitation is a challenge for MMRV and will likely require additional research and development in measurement and modeling techniques.[1087] Better oceanographic models are also needed understand how long alkalinity-enhanced water stays at the ocean's surface because this will affect the amount of atmospheric CO_2 the ocean water will absorb.[1088]

Isometric has developed a protocol, Ocean Alkalinity Enhancement from Coastal Outfalls,[1089] that is relevant but broader than just CEW.

Rating: Developing

Deployment Timelines

Coastal enhanced weathering has not been deployed in MA and no deployments are planned in the state as of 2025. Future projects leveraging this foundational research will need to navigate a myriad of regulations to reach meaningful deployment, including guidance utilized in beach nourishment projects, marine dumping policy, and wetland and tidal zone management.[1090] [1091] [1092] At selected sites, CEW project developers will need to characterize the physical and chemical properties of near-shore sediments prior to deployment to ensure minimal ecosystem and habitat disturbance, as well as maximum reaction efficiency.[1093] Projects will also need to negotiate marine dumping regulations, primarily managed via the Marine Protection, Research and Sanctuaries Act (MPRSA) and will need to secure an MPRSA permit to authorize the deposition of feedstocks.[1094] Additionally, projects will need to adhere to permitting processes for MA coastal management zones, which consider impacts on water quality, habitats, protected species, and managed marine areas.[1095] MA CEW deployments could take between three and four years from planning to first credit issuance, with approximately two and half to three of those years accounting for planning and implementation; this information is based on operational data from the only supplier to have completed a pilot project for CEW to-date, a project which took 40 months from inception to completion. [1096] Deployment timelines will likely will change as new companies enter the field, permitting and feedstock sourcing are streamlined, and credit issuance is clarified for the pathway.[1097]

Resource Requirements

The main resources required for CEW are mineral feedstock and coastal area for application. Alkaline minerals for CEW are commonly olivine and limestone. Theoretical alkaline mineral requirements are between 0.8 to 3 t mineral per tCO_2, depending on specific chemistry and particle size.[1098] CEW can use existing coastal areas without causing land use change,[1099] though scale is then limited by coastline. Regardless, substantial coastal area will be needed for CEW to scale, Although dependent on feedstock type and application rate, some estimates suggest up to 2 acres are needed per tCO_2 for coastal application, but it could be much lower depending on the application site.[1100] The amount of energy required will depend on whether the alkaline minerals require grinding before application, which could increase energy needs by 0.02 to 1.2 GJ per tCO_2,[1101] as well as on how far feedstock needs to be transported. Similarly, water use will depend on feedstock processing but will generally be low because CEW uses ocean water.[1102]

Rating (Water): Low
Rating (Land): High
Rating (Energy): Medium
Rating (Feedstock): High

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of coastal enhanced weathering in Massachusetts is between 40,000 and 100,000 tCO_2e per year, which is rated as low and represents less than 1% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in

2050 to achieve its net zero target. This estimate was arrived at by leveraging the size of beaches and shallow shoreline in Massachusetts, an application rate, and a range of removal rates. It is estimated that between 0.6-1.4 kg of olivine can safely be added per square meter of sea floor and that the removal rate of olivine is 1.25 tonnes per tCO_2e.[1103 1104] Massachusetts has approximately 575 miles of shoreline and it was assumed, on average, that the width of beaches and shorelines shallow enough to conduct coastal enhanced weathering is 0.06 miles which resulted in an estimate of over 35 square miles of relevant shore. [1105] The final estimate assumes that coastal enhanced weathering would occur on the whole shoreline. It also assumes olivine is the only mineral being added which influences the scale estimate because application and removal rates can vary for other minerals.

Rating: Low

Risks to growth: While the estimated maximum potential deployment of coastal enhanced weathering CDR is 40,000 and 100,000 tCO_2e per year, several factors exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including the risk of secondary carbonate precipitation or stimulated calcification, the need for more developed MMRV at scale, the effects of potential heavy metal leaching on marine ecosystems, as well as the temporal uncertainty of feedstock reactions and the complications it will cause for MMRV, and challenges with existing permitting frameworks.[1106 1107 1108 1109 1110 1111 1112] Most notably, for CEW in particular, the addition of alkalinity to ocean water that results from mineral feedstock deposition in coastal environments can sometimes cause secondary carbonate precipitation, where limestone (CaCO3) spontaneously forms; this process can reduce net removals and confound MMRV.[1113] With MMRV in mind, another major near-term barrier for maximizing CEW removals is further clarifying the MMRV process; CEW is extremely difficult to measure due to weathering timeline inconsistencies, the nature of open system deployment, and the uncertainties of uncontrollable environmental conditions.[1114] These factors need to be clarified before deployments at scale. From a feedstock perspective, risks to pathway growth include consistency in grain size and potential toxicity associated with feedstock choice. When deployed minerals are smothered by natural sediments due to currents and turbidity, removal efficiency decreases, particularly if grain size is mismatched with the natural sand present at deployment sites, and potential Ni/Cr release from some feedstocks like olivine could prolong deployments due to concerns around environmental impacts and risks to local fisheries and / or aquaculture operations.[1115] On top of these issues, there are also concerns that stem from the extended timeline for MMRV and mineralization in CEW deployments; The reaction time of some minerals used in CEW applications, such as olivine, with dissolved CO_2 is slow and can occur on the order of years to decades.[1116] Over the course of this time, portions of alkali feedstocks could escape from the initial area of application or be washed away by tides if deposited in coastal water, making it difficult to measure what percentage of the alkali reacts with atmospheric CO_2. In some cases, olivine feedstocks have even been shown to release GHGs, potentially negating the CDR benefit of depositing these minerals in coastal environments.[1117] As a result, there is uncertainty in how coastal enhanced weathering will operate or be measured at scale, especially because a significant amount of data on the pathway has been sourced from lab or small pilots. Finally, policy and permitting uncertainty also risk delaying or preventing scaled deployment for CEW. CEW feedstock deployed in intertidal/subtidal zones generally require a local Orders of Conditions under the Wetlands Protection Act to approve work, and deployments may trigger MEPA review depending on thresholds and agency action.[1118 1119] Additionally, because CEW involves placing minerals in coastal water, projects could require USACE authorization under CWA §404/RHA §10, which is often administered via the Massachusetts General Permits.[1120] Feedstock sourcing would not be a risk for CEW, as feedstocks could be procured from outside of the state without significant additional cost or emissions.

Rating: High

Local supply chain

Coastal enhanced weathering CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including quarry operators, rock processing companies, dredging and engineering firms, marine equipment suppliers, and port operations. Massachusetts has multiple companies quarrying minerals relevant for CEW, which could serve as a local alkaline mineral replacement if olivine feedstocks cannot be procured from out of state sources.[1121] Additionally, the state has several companies with in-state rock processing capacity for potential CEW feedstock adoption.[1122] MA's several operating marine terminals could provide heavy machinery and bulk transport capacity, as well as storage for key pathway inputs; these services could simplify the process of receiving, staging, and deploying mineral feedstocks.[1123] Furthermore, MA-based marine contractors could provide in-state dredging fleets and nearshore construction experience, and at least one in-state contractor could lead on feedstock deposition given their prior experience with Project Vesta's 8 kt pilot in Duck, NC.[1124] MA also hosts several marine technology manufacturers, who could provide moored samplers, sediment traps, and acoustic releases used in MMRV deployments.[1125] These technology providers could supply alkalinity/pH instrumentation, as well as lab services for alkalinity and dissolution analyses.[1126] Finally, domestic engineering firms could assist in site selection and coastal process modeling for CEW projects, ensuring careful adherence to MA and federal frameworks that guide deployments. [1127]

Rating: High

Solution providers

Coastal enhanced weathering is not widely deployed and has only a few active solution providers, most notably Project Vesta, who is the first company to run a real-world CEW beach pilot by blending olivine into a Southampton, NY beach nourishment project.[1128] Massachusetts does not have solution providers headquartered domestically, but there are solution providers conducting projects in state; Project Vesta recently entered into a collaborative project with WHOI, USGS, and NOAA to examine CEW efficacy in Massachusetts tidal wetlands.[1129] The project will culminate in a large-scale demonstration where the project team will deploy olivine sand in a portion of the Herring River Restoration area in Cape Cod, MA and will be the first of its kind in MA.[1130]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Coastal enhanced weathering has the potential to provide significant social and environmental co-benefits, including a reduction in local ocean acidification where deployments occur and creation of favorable environmental conditions for sensitive marine species that are critical to MA's massive commercial fisheries, as well as supporting coastal restoration efforts.[1131] By offsetting the acidic conditions in Massachusetts coastal water that threaten shellfish aquaculture and wild fisheries, CEW could directly address risks flagged by Massachusetts' Ocean

Acidification Commission. These benefits will also help to prevent decline in the MA commercial fishing industry; MA's New Bedford port remains the nation's top commercial fishing port by value, and any measures that stabilize conditions for calcifiers like sea scallops and oysters would have economic, employment, and cultural benefits for one of MA's oldest industries.[1132] Finally, co-integration with MA's beach-nourishment projects, which already move and manage sediment under established state best-practice guidance, could minimize incremental logistics and ensure that deployments also couple CDR with coastal restoration efforts, protecting shorelines from storms that cause coastal flooding and erosion.[1133]

Social and environmental risks: Coastal enhanced weathering has the potential to pose moderate but manageable social and environmental risks, including leaching and release of heavy metals from some alkaline feedstocks, the creation of alkaline hotspots due to over-concentration of deployment in a single site, and the risks of secondary carbonate precipitation (which can dramatically reduce removal capacity and ecosystem benefits altogether). The CEW feedstocks olivine pose some environmental risks when deployed; this alkaline materias has been known to can release nickel and chromium when deployed, potentially harming local biota and damaging ecosystem stability; Lab and in-situ studies report species-specific responses, particularly for food chain anchors like plankton, which support strict feedstock specifications and conservative exposure limits for Massachusetts water.[1134] Careful site monitoring as well as the use of other CEW feedstocks like limestone can help address this risk. Finally, secondary carbonate precipitation is notable risk for CEW. If too much alkaline feedstock is added (or very reactive minerals are dissolved too quickly), seawater can become so saturated that it spontaneously forms tiny $CaCO_3$ crystals (abiotic "chalk"/aragonite); That process uses up the alkalinity that was previously added, meaning less CO_2 stays as dissolved bicarbonate, leading to higher costs and the need to deploy more material to create removal benefits.[1135]

Health impacts: Coastal enhanced weathering poses moderate but manageable health risks, namely respiratory hazards associated with processing and handling of alkaline feedstocks. Onshore handling of crushed alkaline minerals, such as the grinding and preprocessing needed for deployment, can generate respirable dust, including crystalline silica.[1136] Inhalation of rock dusts create a recognized occupational hazard and, if this processing happens at a large scale near populations, it could potentially pose risks to local air quality and community health.

Rating: Neutral

Economic benefit and job creation

Job creation: Coastal enhanced weathering has the potential to create between 50 and 250 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment,[1137] assuming a similar job creation profile as terrestrial enhanced weathering, and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Job creation by coastal enhanced weathering will likely be mostly in ongoing operations jobs, based on the need to regularly spread alkaline minerals and sample for MMRV. Coastal enhanced weathering is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities[1138] and coastal areas where deployment is likely to occur.

Rating: Low

Mineral alkalinity enhancement

Table 8-17: Mineral Alkalinity Enhancement Overview

Pathway: Mineral alkalinity enhancement	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** High	
Current cost: \$55-225/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Medium (1.5-2.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 1 to 70 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 4-6; lab to pilot scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** Medium
Resource requirements ***Water:*** Low ***Land:*** Low ***Energy:*** Medium ***Feedstock:*** High	**Earliest planned start time:** January 2028

Table 8-17: Mineral Alkalinity Enhancement Overview

Overview

Mineral alkalinity enhancement refers to the addition of alkaline minerals to the ocean or other bodies of water, which increases the alkalinity of the water and therefore its capacity to absorb CO_2. In practice, mineral alkalinity enhancement can include adding alkaline minerals to the open ocean or to wastewater treatment facilities.

Mineral alkalinity enhancement is possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the moderate scale potential of the pathway, which depends on the rate of alkalinity that can be added to the oceanwater without causing secondary precipitation. Open MMRV questions and questions around ocean health impacts will also need to be answered before large-scale deployment, which pose a high risk to growth. Community engagement will also be essential before any deployment, to ensure any potential impacts on surrounding communities such as fishers are minimized.

There is a high potential for Massachusetts to be a leader in R&D for mineral alkalinity enhancement. The pathway is still early-stage and has open research questions, such as on MMRV and governance, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Additionally, the state could lead on the integration of this pathway with wastewater treatment processes.

Deployment suitability rating: Medium

R&D leadership potential rating: High

Cost

Current cost: The current costs for MAE ranges from \$55 to \$225 per tCO_2. This cost level will vary based on the feedstock, any necessary mineral feedstock pre-processing steps, and any transportation needed. Costs for MAE have some uncertainty due to MMRV requirements. Estimates suggest a cost of approximately \$55 to \$150 per tCO_2, without specifying MMRV costs.[1139] However, a recent study found that MMRV costs for MAE could be up to 50% of the total cost,[1140] which increased the upper range presented here. Costs in Massachusetts may be on the lower end of this range due its significant coastline, which may reduce transportation distances and overall costs.

Range: \$55 to \$225 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

MAE has low moderate design complexity (e.g., moderate components, not all of which are mass-produced) and a moderate need to be customized at each project site and with each feedstock. Therefore, MAE falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale). This means that because MAE is simple enough in its design to benefit from economies of scale but requires customization at each application site, MAE is likely to achieve moderate cost reduction with scale. Costs can also decrease through improved process logistics and increased reactivity of feedstock However, MMRV for MAE still faces uncertainty due to the open system nature of projects, which may cause costs to increase as MMRV protocols develop if quantification proves difficult. Alternatively, MMRV costs could significantly decrease with scale as large scale ocean modeling develops and data collection methods are simplified.

Rating: Medium

Duration

Risk of reversal: MAE creates storage with negligible risk of reversal over time periods greater than 10,000 years.[1141] The alkaline minerals added to the ocean or to wastewater react with the dissolved CO_2 in the water to form bicarbonates that can be stored for millennia.[1142] The main risk of reversal would be due to a supersaturation of alkalinity in a concentrated area, which could lead to carbonate precipitation and a decrease in net CO_2 removal.[1143] Reversal risks can be mitigated through intentional application timelines and ongoing monitoring. MAE projects in Massachusetts can expect this same level of reversal risk due to the known chemistry and mitigation strategies for MAE.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: The operating lifetime of a MAE project is typically 1 to 70 years, depending on whether the project lifetime is determined by the application of alkaline minerals, which could occur multiple times a year, or if the project lifetime is determined by the mining site, which can operate for multiple decades. [1144] If integrated into a wastewater facility, an MAE project would likely be operating for 20 to 30 years based on the lifetime of the wastewater facility.[1145] Ultimately, the operating lifetime will depend on the available sites for application, which will determine the operating lifetime for MAE projects in Massachusetts.

Range: 1 to 70 years

Technology Readiness Level

MAE is currently at the lab to pilot scale (TRL 4 to 6).[1146] Projects are occurring outside of the lab at small scales, including Planetary's active project in Nova Scotia.[1147] There is significant uncertainty in measurement at scale for MAE, which has hindered deployments of larger sizes.

Range: TRL 4 to 6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for MAE is developing. The MMRV process is very similar to CEW; the amount of CO_2 removed is measured based on the amount of alkaline mineral added to the ocean, which can be directly measured by mass, and the amount of mineral that reacts to form bicarbonates, which is based on modeling.[1148] The level of uncertainty in measuring the degree of secondary precipitation is a challenge for MMRV and will likely require additional research and development in measurement and modeling techniques.[1149] Better oceanographic models are also needed understand how long alkalinity-enhanced water stays at the ocean's surface because this will affect the amount of atmospheric CO_2 the ocean water will absorb.[1150] Isometric has developed a protocol, Ocean Alkalinity Enhancement from Coastal Outfalls,[1151] that is relevant but broader than just MAE, and the supplier Planetary has created their own open-source MMRV protocol.[1152]

Rating: Developing

Deployment Timelines

Mineral alkalinity enhancement CDR has not been deployed in MA and no deployments are planned as of 2025. For the pathway to deploy in earnest and begin generating removals for the state, several regulatory frameworks, as well as state and federal policies, will need to be considered, including multi-national agreements for international waters, federal marine dumping policy, and Massachusetts' coastal management zone regulations. These regulations could include international agreements, such as the London protocols, though technically the US is not a party to this agreement, as well as the Marine Protection, Research and Sanctuaries Act (MPRSA, or the "Ocean Dumping Act"), MA's Ocean Sanctuaries designation, both the National and Massachusetts Environmental Policy Act, and the MA Coastal Zone Management permit process.[1153] In terms of deployment, operations of active companies in the MAE space indicate that projects can move from planning phase to credit issuance in three to four years; During this process, planning and permitting can take approximately one year, deployment of operations consumes approximately one year, and the registration and verification processes can account for one to two years.[1154] These timelines could decrease as new projects are deployed and new learnings for accelerated permitting, construction and monitoring are leveraged.

Resource Requirements

MAE primarily requires mineral feedstock and energy. Theoretical alkaline mineral requirements are between 0.8 to 3 t mineral per tCO_2, depending on specific chemistry and particle size.[1155] The amount of energy required will depend on whether the alkaline minerals require grinding before application, which could increase energy needs by 002 to 1.2 GJ per tCO_2,[1156] as well as on how far feedstock needs to be transported. Similarly, water use will depend on feedstock processing but will generally be low because MAE uses ocean water if applied to the open ocean or wastewater is integrated into existing facilities.[1157] MAE does not directly require land.

Rating (Water): Low
Rating (Land): Low
Rating (Energy): Medium
Rating (Feedstock): High

Scale and growth

The estimated maximum potential deployment of mineral alkalinity enhancement in MA is 1.5 million to 2 million tCO_2, which is rated as medium and represents approximately 11-14% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate was arrived at by multiplying the coastal and territorial sea water area off Massachusetts, around 5800 square kilometers, by an application rate, 10 mol per meter squared per year, and by a range of conversion rates, 0.6-0.8 mol CO2 per mol alkalinity.[1158] This scale potential bounds the application rate to the territorial and coastal water area of Massachusetts, including protected zones. It also relies on a study that indicates that the application rate of 10 mol per squared meter per year for a sustained period of time would not lead to a pH change of more than 0.1 and would not lead to precipitation.[1159] It is important to note that, the scale potential assumes that minerals are added to the Massachusetts territorial and coastal area but spread beyond that bound to result in removals.

Rating: Medium

Risks to growth: While the estimated maximum potential deployment of mineral alkalinity enhancement is 1.5 to 2 million $tCO_{2,}$ a variety of factors exist that could prevent deployment at this scale or make deployment at this scale inadvisable, including uncertainty around MMRV at scale, feedstock constraints, and challenging permitting pathways. MMRV at scale will necessitate site-specific baselines for deployment locations, and will require conservative, careful accounting that has not been fully clarified due to pathway nascency.[1160] Additionally, the scaling of MAE requires not only safe, but abundant, mineral feedstocks that suit coastal deposition, and state-based CDR analyses have noted that feedstock availability could be a major constraint to MAE deployment in Massachusetts.[1161] That said, while in-state feedstock availability could be limited, feedstocks could still be imported from outside of Massachusetts, leveraging low emission maritime transport to maintain net-negative carbon balances for projects. Finally, from a permitting and policy perspective, introducing alkalinity to marine waters likely could trigger review under the Marine Protection, Research, and Sanctuaries Act and EPA research permits; If dosing aims to utilize wastewater outfalls, projects would need approval and permitting from EPA Region 1, and additional in-state reviews can include MEPA, CZM federal consistency with the Massachusetts Ocean Management Plan, and Chapter 91 where waterways licensing applies.[1162] The observance of these pieces of legislation and their processes present opportunities for deployment delay or project denial.

Rating: High

Local supply chain

Mineral alkalinity enhancement CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including lab analysis services, marine monitoring technology, environmental engineering firms, chemical suppliers, and tankard and dosing process component providers. Massachusetts has several in-state chemical suppliers who could support the procurement of MAE inputs like alkaline reagents (E.g. Magnesium Hydroxide) that are needed for several MAE pathways.[1163] The state also hosts manufacturers of process components important to MAE deployment, such as tankards for storage, blending, and handling of feedstocks or alkaline slurries; additional in-state suppliers could also provide dosing pumps and fluid-path equipment suited to alkaline slurry solutions.[1164] To address siting, design, and permitting aspects of deployment, Massachusetts has a variety of domestic engineering firms who could bring coastal engineering and modeling capacity needed for evaluating MAE project feasibility and navigating the state's environmental regulations.[1165] Massachusetts deployments could also leverage equipment from a variety of local technology developers, such as autonomous piloting systems for safe, repeatable open-water deployment, and marine monitoring technology to track currents, dispersion, and in-situ conditions.[1166] Finally, MMRV and lab QA/QC equipment and services could be sourced from at least one in-state supplier who designs Orion titrators capable of quantifying water alkalinity.[1167]

Rating: High

Solution providers

Mineral alkalinity enhancement is not widely deployed and has only a few active solution providers, including the Halifax-based company Planetary Technologies, who have been running field trials in Halifax harbor since December 2024, and CREW Carbon, who are implementing mineral feedstocks to wastewaters.[1168] As a result of the few companies deploying the pathway, Massachusetts does not have solution providers headquartered in state, nor are there any public projects deployed in the state as of yet.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Mineral alkalinity enhancement has the potential to provide significant social and environmental co-benefits, including a reduction in local ocean acidification where deployments occur and creation of favorable environmental conditions for sensitive marine species that are critical to MA's massive commercial fisheries. The primary co-benefit for mineral alkalinity enhancement is the impact the pathway could have on ocean conditions where deployed; by adding alkaline feedstocks to ocean waters, not only does MAE create the conditions for additional CO_2 uptake potential in MA ocean area, but it increases the pH locally as well.[1169] Thus, by aiding in coastal water's ability to resist acidification, the pathway offers a host of co-benefits to MA local industry and marine life. By increasing local pH, MAE creates more favorable conditions for shell calcination in marine species like lobster, shellfish, and bivalves.[1170] By offsetting the acidic conditions in Massachusetts coastal water that threaten shellfish aquaculture and wild fisheries, MAE could directly address risks flagged by Massachusetts' Ocean Acidification Commission. Additionally, by increasing pH, MAE could also increase seawater buffering capacity and aragonite saturation state, which provides shell-forming species the proper chemical conditions needed to build and maintain calcium-carbonate shells.[1171] These benefits will also help to prevent decline in the MA commercial fishing industry; MA's New Bedford port remains the nation's top commercial fishing port by value, and any measures that stabilize conditions for calcifiers like sea scallops and oysters would have economic, employment, and cultural benefits for one of MA's oldest industries.[1172] Moreover, integration with wastewater treatment facilities could minimize incremental logistics of MAE projects and maximize the impact of these facilities by coupling CDR with wastewater processing.

Social and environmental risks: Mineral alkalinity enhancement has the potential to pose moderate but manageable social and environmental risks, including the creation of alkaline hotspots due to over-concentration of deployment in a single site, and the risks of secondary carbonate precipitation, which can dramatically reduce removal capacity and ecosystem benefits altogether. Deployments risk creating unintended consequences where alkaline feedstocks are overly concentrated; Over-alkalinization that causes localized shifts in water chemistry can damage marine ecosystems if dosing or placement is not carefully considered during project design, reinforcing the need for site-specific modeling and adaptive management.[1173] Finally, secondary carbonate precipitation is notable risk for MAE. If too much alkalinity is added (or very reactive minerals are dissolved too quickly), seawater can become so saturated that it spontaneously forms tiny $CaCO_3$ crystals (abiotic “chalk”/aragonite); That process uses up the alkalinity that was previously added, meaning less CO_2 stays as dissolved bicarbonate, leading to higher costs and the need to deploy more material to create removal benefits.[1174]

Health impacts: Mineral alkalinity enhancement has the potential to create moderate but manageable health risks, namely respiratory hazards associated with processing and handling of alkaline feedstocks. Onshore handling of crushed alkaline minerals, such as the grinding and preprocessing needed for deployment, can generate respirable dust, including crystalline silica.[1175] Inhalation of rock dusts create a recognized occupational hazard which will require controls such as respirators under OSHA/NIOSH guidance.[1176] Furthermore, if this processing happens at a large scale near populations, it could potentially pose risks to local air quality and community health. For workers handling these feedstocks, specifically caustics and lime, contact hazards could include burns and eye injury; this will require proper precautions such as ventilation and PPE would be needed for sage operation standard controls.[1177]

Rating: Neutral

Economic benefit and job creation

Mineral alkalinity enhancement has the potential to create between 1,000 and 3,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[1178] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Job creation by mineral alkalinity enhancement, once the technology develops, will likely be mostly in ongoing operations jobs, based on the need to regularly spread alkaline minerals and sample for MMRV. However, MAE currently has numerous open research questions, which provides a near-term opportunity for R&D jobs. MAE is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities[1179] and coastal areas where deployment is likely to occur.

Rating: Medium

Synthetic CDR

Synthetic CDR (sCDR) pathways use engineered systems powered by low carbon energy to directly separate CO_2 from the air and capture it or to alter water chemistry to indirectly remove CO_2 from the air.

Draft, for consideration, not final

CO_2 stripping

Table 8-18: CO2 Stripping Overview

Pathway: CO_2 stripping	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** High	
Current cost: $400-2,400/tCO_2$ **Cost reduction potential:** Medium	**Scale potential:** Medium (1.5-2.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20-40 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 5-6; lab to pilot scale	**Co-benefits and potential negative impacts:** Negative
Measurement readiness: Developing	**Economic benefit and job creation:** Medium
<u>Resource requirements</u> ***Water:*** Low ***Land:*** Low ***Energy:*** High ***Feedstock:*** Low	**Earliest planned start time:** January 2028

Table 8-18: CO2 Stripping Overview

Overview

CO_2 stripping refers to electrochemical processes that split water from oceans, lakes, or other bodies of water, into acid and base streams, then use the acid stream to push dissolved CO_2 out of the water to be captured, and finally, recombine the acid and base streams to re-neutralize the water and return it to the source.

CO_2 stripping is possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the moderate scale potential of the pathway, which depends on the rate of alkalinity that can be added to the oceanwater without causing secondary precipitation. Additionally, the state's lack of in-state geologic storage means that any CO_2 captured from CO_2 stripping will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges. The high energy requirements of CO_2 stripping will need to be met with clean energy to ensure net overall carbon removal.

There is a high potential for Massachusetts to be a leader in R&D for CO_2 stripping. The pathway is still developing and has open research questions, including ones related to energy efficiency and ocean modeling, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean.

<u>Deployment suitability rating</u>: Medium

<u>R&D leadership potential rating</u>: High

Cost

Current cost: The current cost for CO_2 stripping ranges from \$400 to \$2,400 per tCO_2.[1180] This high cost level is driven by the need for a large industrial facility and high electricity requirement. Given Massachusetts' relatively high industrial electricity prices,[1181] in-state projects may be towards the upper end of this range. However, co-locating CO_2 stripping projects with existing facilities, such as desalination plants, can reduce costs and represent the low end of this range.

Range: \$400 to \$2,400 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

CO_2 stripping has medium design complexity (e.g., many components, a moderate amount of which are mass-produced) and a moderate need to be customized at each plant site due to local water conditions. Therefore, CO_2 stripping falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[1182] This means that because CO_2 stripping will likely become more standardized with scale even though it will have complex components, CO_2 stripping is likely to achieve moderate cost reduction with scale. Cost reductions may also come from process or technology improvements that reduce energy requirements and capital costs.

Rating: Medium

Duration

Risk of reversal: CO_2 stripping can remove and store carbon with negligible risk of reversal over 10,000 years.[1183] This assumes that the CO_2 is placed in geologic storage. Assuming CO_2 stripping uses conventional CO_2 storage or in-situ mineralization, reversal occurs if CO_2 leaks from the storage reservoir due to permeable faults or fractures in the storage site, but this can be mitigated through site selection.[1184] Assuming CO_2 stripping uses ex-situ mineralization, reversals could occur if there is strong acid weathering at the site of carbonate mineral storage, but this can be mitigated through site selection and monitoring.[1185] If the CO_2 removed by CO_2 stripping is used in a consumable product, such as a low-carbon fuel, CO_2 stripping creates storage with significant risk of reversal over 100 years because the storage is released upon combustion.[1186] CO_2 stripping plants in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For CO_2 stripping, the operating lifetime of a plant is typically 20 to 40 years. Studies have modeled CO_2 stripping with a plant lifetime of 25 years.[1187] Plants will likely have the same typical lifetime as electrolysis plants, though some components will need to be replaced throughout the operating lifetime, e.g., electrolyzers need replacement every 7 to 10 years.[1188] Massachusetts can expect a similar plant lifetime due to the geographic independence of CO_2 stripping plant components.

Range: 20 to 40 years

Technology Readiness Level

CO2 stripping is an early-stage CDR pathway ranging from lab to pilot stage, or TRL 5-6.[1189] Companies and labs have raised money to conduct research on electrochemical processes used in CO_2 stripping, and one company, Captura, is operating pilot projects. In 2025, Captura opened its third pilot project in Hawaii, operating at 1000 tons/year.[1190] This pathway still needs to undergo additional field testing in a variety of settings to prove the technology at a demonstration scale.

Range: 5-6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for CO_2 stripping is developing. MMRV for CO_2 stripping is done by measuring the amount of CO_2 absorbed from the atmosphere into the upper surface ocean through Air-Sea Gas exchange and subtracting from it the emissions from the process and leakage.[1191] The amount of CO_2 absorbed from the atmosphere is a proportion of carbon removed from the ocean and will be modeled. Captura is partnering with others to establish modeling for this pathway and has a methodology in development.[1192] Uncertainty exists in modeling and, because this is an open system pathway, direct measurement of removals, rather than modeling, is very challenging.

Rating: Developing

Deployment Timelines

CO_2 stripping CDR has not been deployed in Massachusetts, and no deployments are planned as of 2025. Project developers deploying CO_2 stripping in Massachusetts would need to navigate state and federal regulations akin to those followed by desalination plants, such as marine dumping policies and coastal management permitting, as well as water quality and marine habitat protections. Any project that discharges effluent, such as an alkaline solution, CO_2-depleted water, or brines, into ocean or coastal waters would need to navigate the following regulations at a federal and state level; the federal Marine Protection, Research and Sanctuaries Act, the National Environmental Policy Act (NEPA), MEPA and MA's Coastal Zone Management program, the Rivers and Harbors act, and MA's Ocean Sanctuary designation.[1193] In terms of deployment, the timeline for CO_2 stripping projects to move from planning to first credit issued is dependent on the company; one company in the sector was founded in 2021 and deployed their first 1tCO_2e / year pilot project by end-of-year 2022, with a 1000 tCO_2e / year pilot project deployed by 2025.[1194] Credit issuance for this pathway depends on methodology, though initial crediting can occur within a year of operations, with monitoring periods typically taking between one and three years after operation until full credit issuance occurs.[1195] Overall, timelines from planning to pilot to first credit delivery could take anywhere from two to seven years depending on facility scale.

Resource Requirements

The main resource requirement for CO_2 stripping is energy. The exact requirement will depend on the process but estimates suggest 5 to 11 GJ are needed per tCO_2.[1196] To maximize net CO_2 removal, low-carbon energy should be used to power CO_2 stripping. Otherwise, resource requirements for CO_2 stripping are low. Neither water nor mineral feedstock is consumed in the process. The land footprint is minimal and can be further reduced by co-locating with existing coastal infrastructure or offshore deployment.[1197]

Rating (Water): Low

Rating (Land): Low

Rating (Energy): High

Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of CO_2 stripping in Massachusetts is 1.5 million to 2 million tCO_2e per year, which is rated as medium and represents approximately 11-14% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages the same pathway as mineral alkalinity enhancement and was arrived at by multiplying the coastal and territorial sea water area off Massachusetts, around 5800 square kilometers, by an application rate, 10 mol per squared meter per year, and by a range of conversion rates, 0.6-0.8 mol CO2 per mol alkalinity.[1198] This scale potential bounds the application rate to the territorial and coastal water area of Massachusetts, including protected zones. It also relies on a study that indicates that the application rate of 10 mol per squared meter per year for a sustained period of time would not lead to a pH change of more than 0.1 and would not lead to precipitation.[1199] It is important to note that the scale potential assumes that minerals are added to the Massachusetts territorial and coastal area but spread beyond that bound to result in removals. If, rather than alkalinity being used as a constraint in this calculation, access to electricity was used, the estimated maximum potential deployment of CO_2 stripping in Massachusetts would be between 6.7 million and 13.8 million tCO_2e per year, using the same methodology as in DAC and CO_2 stripping-specific electricity requirements.[1200]

Rating: Medium

Risks to growth: While the estimated maximum potential deployment of CO_2 stripping is between 1.5 to 2 million tCO_2e per year, several factors exist that could prevent deployment at this scale and make deployment at this scale inadvisable, including competing uses for energy, environmental risks, and permitting uncertainty. Energy needs for CO_2 stripping are high,[1201] and should be powered by clean electricity in order to maximize net carbon removal. However, Massachusetts already has significant energy demands that are projected to grow by 2050,[1202] and so the availability of clean energy for CO_2 stripping may limit its deployment. Additionally, because CO_2 stripping involves intaking and discharging large volumes of water with a different pH, CO_2 stripping will impact the local ecosystem.[1203] Additional research will be needed to understand environmental impact, which may limit deployment scale.[1204] Finally, because CO_2 stripping involves discharging a modified stream of water back into the ocean or other body of water, it is possible that a project could be subject to a substantial permitting process which has the potential to create significant hurdles to scale and lengthen deployment timelines.

Rating: High

Local supply chain

CO_2 stripping CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact four sectors in the state's economy, including public utility holding companies, desalination operations, port terminal operators, and marine monitoring equipment suppliers. On the grid side, the state hosts a public utility company who specializes in interconnection tools and grid capacity analysis to identify feasible distribution sites for flexible behind-the-meter or distribution-connected loads from CO_2 stripping's high electricity demand.[1205] Additionally, Massachusetts has several port terminals that offer heavy machinery and infrastructure for anchoring the transportation and maintenance of CO_2 stripping equipment, reagent handling, and MMRV deployments.[1206] The state also hosts a desalination plant where the pathway could leverage existing permits for smooth integration.[1207] Massachusetts marine technology suppliers are also prepared to assist with MMRV; MA has an in-state marine tech company who has developed solar USVs that could be utilized for continuous ocean and environmental monitoring that suits CO_2 stripping MMRV.[1208] Finally, Massachusetts also hosts desalination facilities which offer potential intake/brine processing integration to accelerate deployment permitting.[1209]

Rating: Medium

Solution providers

CO_2 stripping is not a widely deployed pathway and has only a select number of solution providers globally, most notably Captura, who has deployed several pilot projects and has planned commercial scale up.[1210] As a result, Massachusetts does not have solution providers headquartered in the state, nor does MA host any CO_2 stripping projects conducted by active solution providers.

Co-benefits and potential negative impacts

Social and environmental co-benefits: CO_2 stripping is likely to have negligible social and environmental co-benefits, outside of the inherent climate benefits associated with CDR. One possible co-benefit is that CO_2 stripping, because facilities will be sited near oceans or other bodies of water, may not compete for arable land and could be co-located with low-carbon offshore energy or water infrastructure, like desalination plants.[1211] However, this is not a guarantee and is more related to reducing risks than providing new, tangible co-benefits.

Social and environmental risks: On the other hand, CO2 stripping has moderate social and environmental risks, including energy competition and localized ocean impacts. CO2 stripping, like other synthetic pathways, requires a large amount of energy, which places a burden on other energy consumers.[1212] Additionally, although CO2 stripping aims to re-neutralize water by the end of its process, discharge from the facilities can lead to changes in water temperature, flow, and other qualities that may influence ocean chemistry and nearby ocean ecosystems.[1213] These localized impacts combined with other stressors like overfishing or pollution could have adverse impacts on ecosystem health.

Health impacts: There are also moderate but manageable health risks associated with CO_2 stripping. These facilities deal with large amounts of concentrated acids and bases and other hazardous materials used in electrochemical processes. There are occupational hazards associated with working with these processes and materials; however, if safety precautions are taken, these risks should be mitigated.[1214] Further, if hazardous materials are mishandled and discharged into the ecosystem inappropriately, they could have negative impacts not only on ocean health but also be a public health concern.

Ranking: Negative

Draft, for consideration, not final

Economic benefit and job creation

CO_2 stripping has the potential to create between 900 and 2,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[1215] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. CO_2 stripping is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities[1216] and coastal areas where deployment is likely to occur.

Rating: Medium

Electrochemical alkalinity production

Table 8-19: Electrochemical Alkalinity Production Overview

Pathway: Electrochemical alkalinity production	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** High	
Current cost: \$400-2400/tCO_2 **Cost reduction potential:** High	**Scale potential:** Medium (1.5-2.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20-40 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 5-6; lab to pilot scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Developing	**Economic benefit and job creation:** Medium
Resource requirements ***Water:*** Low ***Land:*** Low ***Energy:*** High ***Feedstock:*** Low	**Earliest planned start time:** January 2028

Table 8-19: Electrochemical Alkalinity Production Overview

Overview

Electrochemical alkalinity production as a pathway is the use of electrochemistry to create alkalinity that is added to the ocean or another body of water, enabling it to absorb additional carbon dioxide. This is traditionally performed via either changing the pH of a stream of water with electricity in a wastewater treatment facility to enable the water to uptake additional CO_2, or splitting ocean water into acid and base streams with electricity, then using the base stream to raise the pH of seawater locally while the acid stream is removed or disposed of elsewhere.

Electrochemical alkalinity production is possibly well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the moderate scale potential of the pathway, which depends on the rate of alkalinity that can be added to the oceanwater without causing secondary precipitation. Open MMRV questions will also need to be answered before large-scale deployment, which pose a high risk to growth. Additionally, the high energy requirements will need to be met with clean energy to ensure net overall carbon removal.

There is a high potential for Massachusetts to be a leader in R&D for electrochemical alkalinity enhancement. The pathway is still developing and has open research questions, including ones related to energy efficiency and co-product creation, that the state can lead on, due to its intellectual and physical resources including existing oceanographic research institutes and access to the ocean. Additionally, the state could lead on the integration of this pathway with wastewater treatment processes.

Deployment suitability rating: Medium

R&D leadership potential rating: High

Cost

Current cost: The current cost of EAP ranges from \$400 to \$2400 per tCO_2.[1217] This cost level is driven by large capital expenses and significant electricity needs because EAP has high energy needs. Given Massachusetts' relatively high industrial electricity prices,[1218] in-state projects are likely toward the upper end of these ranges.

Range: \$400 to \$2400 per tCO_2

Potential for cost reduction: The potential for cost reduction is high.

EAP has medium design complexity (e.g., many components, a moderate amount of which are mass-produced) and a moderate need to be customized at each plant site and thus EAP falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[1219] This means that because EAP will likely become more standardized with scale even though it will have complex components, EAP is likely to achieve moderate cost reduction with scale. Costs could also decrease through technology improvements that reduce energy needs and through the production of co-products that can add additional revenue streams.[1220]

Rating: High

Duration

Risk of reversal. EAP removes and stores carbon with negligible risk of reversal for greater than 10,000 years.[1221] EAP stores CO_2 by converting it into bicarbonates and carbonates, which can be stable for millennia. The main risk of reversal is from adding excessively large amount of alkalinity without dispersion, as this could cause a reverse in the chemical reaction and release CO_2 back to the atmosphere,[1222] but this can be mitigated by process design and monitoring. EAP plants in Massachusetts can expect this same level of reversal risk due to the known chemistry and mitigation strategies for EAP.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant. For EAP, the operating lifetime of a plant is typically 20 to 40 years. Project lifetime can be modeled after electrolysis plants, which have the same typical lifetime.[1223] Some components will need to be replaced throughout the operating lifetime, e.g., electrolyzers need replacement every 7 to 10 years.[1224] Massachusetts can expect a similar plant lifetime due to the geographic independence of EAP plant components.

Range: 20 to 40 years

Technology Readiness Level

EAP is currently at the lab to pilot scale (TRL 5-6).[1225] Pilot projects include Ebb Carbon's 100 ton per year project with U.S. Department of Energy's Pacific Northwest National Laboratory in Sequim, Washington,[1226] as well as Equatic's proposed 365 ton per year facility in Sarawak, Malaysia, in partnership with Boeing and SECD Energy.[1227] Pilots and pre-commercial projects will be necessary to get EAP ready for broad deployment.

Range: TRL 5 to 6

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for EAP is developing. Certain elements can be directly measured with low uncertainty, such as the amount of alkalinity dispersed into the ocean, though other parts of the process pose a challenge for measurement, such as the gas exchange between the ocean and the atmosphere.[1228] MMRV protocols exist for EAP, including Isometric's Electrolytic Seawater Mineralization protocol.[1229] MMRV will likely have to depend on some level of modeling that needs additional research as EAP develops.[1230]

Rating: Developing

Deployment Timelines

Electrochemical alkalinity production has not been deployed in MA and no deployments are planned as of 2025. Project developers deploying EAP in MA would need to navigate state and federal regulations akin to those followed by desalination plants, such as marine dumping policies and coastal management permitting, as well as water quality and marine habitat protections. Any project that discharges effluent, such as an alkaline solution, CO_2-depleted water, or brines, into ocean or coastal waters would need to navigate the following regulations at a federal and state level; the federal Marine Protection, Research and Sanctuaries Act, the National Environmental Policy Act (NEPA), MEPA and MA's Coastal Zone Management program, the Rivers and Harbors act, and MA's Ocean Sanctuary designation.[1231] In terms of deployment, the timeline for EAP projects to move from planning to first credit issued is dependent on the company; One company in the space moved from founding in 2021 to first operational pilot plant in 2023.[1232] Leaders in the EAP space have publicized the ability to move from planning to first removals in 2 to 3 years, even for commercial operations removing more than 100kt CO_2e per annum. [1233] With that said, this information is based on company projections and actual deployment timelines could extend past this estimate.

Resource Requirements

The main resource requirement for EAP is energy in the form of electricity. The exact requirement will depend on the process but estimates suggest 2 to 4 MWh are needed per tCO_2.[1234] To maximize net CO_2 removal, low-carbon electricity should be used to power EAP. Otherwise, resource requirements for EAP are low. Neither water nor mineral feedstock is consumed in the process. The land footprint is minimal and can be further reduced by co-locating with existing coastal infrastructure or offshore deployment.[1235]

Rating (Water): Low

Rating (Land): Low

Rating (Energy): High

Rating (Feedstock): Low

Scale and Growth

Scale possible in Massachusetts: The estimated maximum potential deployment of electrochemical alkalinity production in Massachusetts is 1.5 million to 2 million tCO_2, which is rated as medium and represents approximately 11-14% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate leverages the same pathway as mineral alkalinity enhancement and was arrived at by multiplying the coastal and territorial sea water area off Massachusetts, around 5800 square kilometers, by an application rate, 10 mol per squared meter per year, and by a range of conversion rates, 0.6-0.8 mol CO2 per mol alkalinity.[1236] This scale potential bounds the application rate to the territorial and coastal water area of Massachusetts, including protected zones. It also relies on a study that indicates that the application rate of 10 mol per squared meter per year for a sustained period of time would not lead to a pH change of more than 0.1 and would not lead to precipitation.[1237] It is important to note that the scale potential assumes that minerals are added to the Massachusetts territorial and coastal area but spread beyond that bound to result in removals. If, rather than alkalinity being used as a constraint in this calculation, access to electricity was used, the estimated maximum potential deployment of electrochemical alkalinity production in Massachusetts would be between 4.7 million and 10.4 million tCO_2e per year, using the same methodology as in DAC and EAP-specific electricity requirements.[1238]

Rating: Medium

Risks to growth: While the estimated maximum potential deployment of electrochemical alkalinity enhancement is between 1.5 to 2 million tCO_2e per year, several factors exist that could prevent deployment at this scale and make deployment at this scale inadvisable, including overall electricity intensity and in-state availability, permitting uncertainty, the need to clarify scaled MMRV, and unintended ecological consequences at scale. A large barrier to scale for EAP is energy availability. Considering current EAP technologies require 2–4 MWh per tCO_2, continuous access to low-carbon electricity will be a major constraint for EAP scale.[1239] With MA energy demand in 2050 set to hit more than 138 TWh, the above scale estimate using electricity as the limiting constraint assumes that the state will 1) reach the 2050 energy production target , 2) be able to do so through only clean or low-carbon energy, and 3) be able to allocate as much as 15% of that energy (more than 20Twh) to EAP, an unlikely feat.[1240] Currently, while clean-power additions are expanding, projects like Massachusetts' multi-GW offshore wind pipeline are subject to uncertainty due to funding cuts from the federal government.[1241] Environmental risks exist for EAP as well; concerns around localized pH "hot spots" and a lack of adequate currents to dissipate high pH concentrations risk narrowing potential deployment zones and drawing backlash from existing marine industries.[1242] Furthermore, MMRV in dynamic currents and turbid waters, like those off of MA's coast, remains challenging; dilution, equilibration, and background variability can force extensive monitoring and create uncertainties around removals due to the open system nature of EAP.[1243] Finally, EAP projects could encounter delays or denied approval for deployment because the permitting regime has yet to be clarified in MA. Any EAP discharge to coastal waters could require an EPA-issued NPDES permit in Massachusetts, depending on discharge location, process, and amount, and MA has limited desalination/brine resources for co-location today, with only 3 operational plants, so early deployments are likelier at existing seawater intakes/outfalls, which could potentially narrow siting options.[1244] With that said, projects that use or modify existing outfalls (e.g., MWRA's Massachusetts Bay diffuser) may trigger permit modifications and monitoring, while coastal discharges might also undergo MEPA review and, when federal actions are involved, CZM federal consistency.[1245] The navigation and process of clarifying these permitting pathways could put financial and administrative strain on first-of-a-kind deployments.

Rating: High

Local supply chain

Electrochemical alkalinity production is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including electrolyzer suppliers, public utility holding companies, desalination operations, port terminal operators, and marine monitoring equipment suppliers. On the hardware side, MA has several in-state suppliers of electrolyzer cells and stacks, which allow for electricity to split saltwater into basic and acid components; the companies could help to shorten procurement and integration timelines for MA deployment.[1246] On the grid side, the state also hosts a public utility company who specializes in interconnection tools and grid capacity analysis to identify feasible distribution sites for flexible behind-the-meter or distribution-connected loads from EAP's high electricity demand.[1247] Additionally, Massachusetts has several port terminals that offer heavy machinery and infrastructure for anchoring the transportation and maintenance of EAP equipment, reagent handling, and MMRV deployments.[1248] The state also hosts a desalination plant where EAP could leverage existing permits for smooth integration.[1249] Massachusetts marine technology suppliers are also prepared to assist with MMRV; MA has an in-state marine tech company who has developed solar USVs that could be utilized for continuous ocean and environmental monitoring that suits EAP MMRV.[1250] Finally, Massachusetts also hosts desalination facilities which offer potential intake/brine processing integration to accelerate deployment permitting.[1251]

Rating: High

Solution providers

Electrochemical alkalinity production is a widely deployed pathway and has several active solution providers, most notably Equatic and Ebb Carbon.[1252] However, Massachusetts does not have solution providers headquartered in the state. With that said, MA has hosted one of the first open ocean research trials related to EAP; In Massachusetts, the Woods Hole Oceanographic Institution completed a small-scale research trial, the LOC-NESS project, in August 2025 that deposited traceable sodium hydroxide off the Gulf of Maine, monitoring dissolution and environmental impacts.[1253] Sodium hydroxide is a chemical compound produced as an end product during the EAP process. In terms of solution providers dedicated solely to EAP, Massachusetts is home to BlueShift, a company formerly focused on EAP, though the company has recently pivoted away from CDR towards critical mineral processing, and no longer is considered a solution provider for EAP technology.[1254]

Co-benefits and potential negative impacts

Social and environmental co-benefits: Electrochemical alkalinity production has the potential to deliver significant social and environmental co-benefits in MA, including a reduction in local ocean acidification, creation of favorable environmental conditions for sensitive marine species that are critical to MA's massive commercial fisheries, and motivation for additional build out of coastal infrastructure such as desalination plants. The primary co-benefit for EAP is the impact it will have on local ocean conditions where deployed; by adding alkaline solutions produced during EAP's acid/base separation process to coastal waters, not only does EAP create the conditions for additional CO2 uptake potential in MA ocean area, but it increases the pH locally as well.[1255] By aiding in coastal water's ability to resist acidification, the pathway offers a host of co-benefits to MA local industry and marine life. By increasing local pH, Electrochemical Alkalinity Production creates more favorable conditions for shell calcination in marine species like lobster, shellfish, and bivalves.[1256] By addressing the acidic conditions in Massachusetts coastal water that threaten shellfish aquaculture and wild fisheries, EAP could directly counter the risks flagged by the state's Ocean Acidification Commission. More specifically, EAP additions could increase seawater buffering capacity and aragonite saturation state, which provides the chemical "headroom" shell-forming marine life needs to build and maintain calcium-carbonate shells.[1257] These benefits will also help to aid in the longevity of the MA commercial fishing industry; MA's New Bedford port remains the nation's top commercial fishing port by value, and any measures that stabilize conditions for calcifiers like sea scallops and oysters create meaningful benefits for both aquaculture and fisheries.[1258] Finally, the deployment of EAP at scale can help encourage the build out of critical marine infrastructure, particularly operations like desalination plants that EAP operations can integrate with to accelerate joint permitting.[1259] This will allow MA to double down on its valuable coastal infrastructure and create valuable freshwater resources that will be crucial for mitigating climate events (e.g. drought).

Social and environmental risks: However, Electrochemical alkalinity enhancement also has the potential to pose moderate social and environmental risks where deployed in MA, including risks associated with reactive acid and base handling, risks associated with secondary carbonate precipitation, the creation of localized pH hotspots that could threaten marine life, land use change and disturbance of critical coastal habitats if siting is not carefully carried out, and the ability for demand increases on local electricity to drive up prices for communities if EAP deployments are not accompanied by added clean energy generation. Because EAP involves returning elevated alkaline streams back to ocean environments, deployment will need to be extremely sensitive to created concentrated areas of heightened pH.[1260] In MA, alkaline plumes returned by EAP operations could threaten local ecosystems and create unbalanced local impacts if plume dispersion is not closely monitored.[1261] Conversely, the acid streams that represent the secondary byproduct of EAP processes, will need to be neutralized prior to disposal to avoid issues of local contamination or negative environmental impacts that can result from low pH solutions.[1262] Furthermore, similar to direct air capture, EAP is heavily reliant on adequate low-carbon or clean energy to operate; if new EAP deployments are not co-located with or planned using energy sources like offshore wind, operations risk not only increasing energy prices in nearby communities, but could cause additional emission concerns if Massachusetts' gas-dominant grid is used to power operations.[1263] Finally, secondary carbonate precipitation is notable risk for EAP. If too much alkalinity is added, seawater can become so saturated that it spontaneously forms tiny $CaCO_3$ crystals (abiotic "chalk"/aragonite); That process uses up the alkalinity that was previously added, meaning less CO_2 stays as dissolved bicarbonate, leading to higher costs and the need to deploy more alkaline streams to create removal benefits.[1264]

Health impacts: Electrochemical alkalinity production has the potential to pose moderate health risks that will need to be planned for during deployment, including chlorine gas production from seawater electrolysis, labor safety considerations for handling of strong acid and base compounds, and the need to mitigate and carefully dispose of strong acid stream byproducts. Leading producers have identified that processes associated with EAP have the potential to generate toxic chlorine gas as a byproduct; as a result, any deployments in MA will need to be sure to utilize innovative processes (E.g. Equatic) to avoid unintended health hazards, both to labor working in EAP facilities and ecosystems where deployment occurs.[1265] Additionally, the acid streams that are a byproduct of EAP pathways will also require careful planning and thoughtful disposal to avoid having impacts on local ecosystems, human health, or groundwater.[1266] Finally, because EAP systems intentionally generate and handle corrosive acid and base streams, they must put worker-safety safeguards in place to protect labor from handling high and low pH solutions.[1267]

Rating: Neutral

Economic benefit and job creation

Job creation: Electrochemical alkalinity production has the potential to create between 1,000 and 3,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[1268] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Because the impact of adding alkalinity to open waters still has numerous open research questions, EAP provides a near-term opportunity for R&D jobs. EAP is likely to direct some of these economic benefits in the form of jobs to disadvantaged communities within the state, due to the overlap in geography between disadvantaged communities[1269] and coastal areas where deployment is likely to occur.

Rating: Medium

Direct Air Capture

Table 8-20: Direct Air Capture Overview

Pathway: Direct air capture	
Deployment suitability for Massachusetts: Medium **R&D leadership potential:** Medium	
Current cost: \$500-2000/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** High (1.8-4.1 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20 to 30 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 2-9; concept to commercial depending on specific technology	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** High
<u>Resource requirements</u> ***Water:*** Medium ***Land:*** Low ***Energy:*** High ***Feedstock:*** Low	**Earliest planned start time:** January 2030

Table 8-20: Direct Air Capture Overview

Overview

Direct air capture as a pathway is the process of using clean energy to power machinery that captures CO_2 from the atmosphere in a concentrated stream. DAC pathways vary, though most use either liquid solvents, solid sorbents, membrane gradients (pressure, electrochemical, etc.), or cryogenic phase separation to sequester carbon.

DAC is possibly well-suited for deployment in Massachusetts to meet a substantial fraction of the state's total need for CDR. Although DAC has a high scale rating and there is significant opportunity for job creation, DAC is energy intensive and energy in Massachusetts is expensive, in high demand, and will likely increase in demand as decarbonization efforts progress. The high energy requirements will also need to be met with clean energy to ensure net overall carbon removal. Additionally, the state's lack of in-state geologic storage means that any CO_2 captured from DAC will have to either be stored by ex-situ mineralization or transported out of state or offshore, which adds costs and transportation challenges. As a result, it is possible that DAC could be well-suited for deployment in Massachusetts, but there is still uncertainty preventing the pathway from getting a high rating.

There is a moderate potential for Massachusetts to be a leader in R&D for direct air capture. Novel materials and methods are still being developed on DAC. Though there are already existing geographic areas, such as in the US Southeast and Northwest, that are leading in deployment, Massachusetts may be well-suited to lead on lab-scale and pilot-scale research on sorbents, solvents, and electrochemical processes.

<u>Deployment suitability rating</u>: Medium

<u>R&D leadership potential rating</u>: Medium

Cost

Current cost: The current costs for DAC range from \$500 to \$2,000 per tCO_2, [1270] with suppliers citing current costs of \$600 per tCO_2.[1271] DAC requires significant capital expenses, which drives this cost level, as well as the large energy required as an input. Given Massachusetts' relatively high industrial electricity prices,[1272] in-state projects are likely toward the upper end of this range.

<u>Range</u>: \$500 to \$2,000 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

DAC technology varies based on the specific pathway deployed (e.g., liquid solvent versus solid sorbent). In general, however, DAC has medium to high design complexity (e.g., many components of which a moderate number can be mass-produced) and requires moderate customization to the ambient conditions of every site. Therefore DAC falls in the Type 2 to 3 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale). [1273] This means that because DAC has many complex components, DAC is likely to achieve low to moderate cost reduction with scale. Costs could also decrease through the development of more efficient capture materials, more low-carbon energy sources, and the development of shared CO_2 storage infrastructure.

<u>Rating</u>: Medium

Duration

Risk of reversal: DAC can remove and store carbon with negligible risk of reversal over 10,000 years.[1274] This assumes that the CO_2 is placed in geologic storage. Assuming DAC uses conventional CO_2 storage or in-situ mineralization, reversal occurs if CO_2 leaks from the storage reservoir due to permeable faults or fractures in the storage site, but this can be mitigated through site selection.[1275] Assuming DAC uses ex-situ mineralization, reversals could occur if there is strong acid weathering at the site of carbonate mineral storage, but this can be mitigated through site selection and monitoring.[1276] If the CO_2 removed by DAC is used in a consumable product, such as a low-carbon fuel, DAC creates storage with significant risk of reversal over 100 years because the storage is released upon combustion.[1277] DAC plants in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

<u>Rating</u>: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For DAC, the operating lifetime of a plant is typically 20 to 30 years. Studies have modeled DAC with a plant lifetime of 25 years.[1278] DAC plants are large industrial facilities and so can be treated analogously in planning. DAC plants operating in Massachusetts can expect a similar plant lifetime due to the geographic independence of DAC plant components.

<u>Range</u>: 20 to 30 years

Technology Readiness Level

The TRL of DAC depends on the specific technology used and ranges from the concept to commercial scale (TRL 2 to 9).[1279] The supplier Climeworks uses the well-developed pathway of a solid sorbent and low-grade heat for regeneration[1280] and is at commercial deployment; their Mammoth project is ramping up to capture 36,000 tCO_2 per year.[1281] More novel technological pathways to DAC are at an earlier level of development. For example, RepAir's electrochemical approach to DAC has pilot and demonstration projects in the pipeline.[1282]

Range: TRL 2 to 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for DAC is established. The amount of CO_2 captured by a DAC plant can be directly measured at the plant with low uncertainty, as can the amount of CO_2 injected into geologic storage through sensors and flow meters.[1283] MMRV protocols exist for DAC by major carbon credit registries, including Isometric's Direct Air Capture protocol[1284] and Puro.earth's Geologically Stored Carbon methodology.[1285] Challenges to address in DAC MMRV is accurately measuring leakage during any transport of CO_2,[1286] as well as long-term monitoring of wells if the CO_2 is stored in conventional CO_2 storage.

Rating: Established

Deployment Timelines

Direct air capture CDR has not been deployed in MA and current MA DAC removals are zero tCO_2e as of 2025. Future DAC projects deploying in Massachusetts will need to follow regulations that apply to industrial emitters, as well as pipeline safety protocols, including air pollution controls, industrial facility siting rules, and hazardous material guidance due to CO_2 transport. These regulations include MA air & climate regulations, the Massachusetts Environmental Policy Act, Chapter 40A of the state's zoning regulations, as well as state building and mechanical codes for high-pressure gas transport and OSHA regulations to protect workers in the event of CO_2 leakage.[1287] In terms of deployment, timelines for DAC projects vary greatly dependent on the type of the DAC pathway being deployed; A realistic deployment timeline for demonstration scale DAC projects in MA based on industry leaders is approximately 18 months from construction to operation and 18 months from operation to first credit issuance.[1288] Planning processes can range depending on pathway and varies based on local regulations, but a realistic estimate for the site selection and planning phase of a DAC project is an additional 12 to 18 months; An end-to-end estimate for DAC operations to roll out in MA could be four to five years, with removals occurring immediately when capture CO2 streams are injected or utilized in permanent products (E.g. via ESM), though this process could be extended further if offtake or storage of CO_2 is not clarified in-state or if UIC permitting is delayed.

Resource Requirements

The main resource requirement for DAC is low-carbon energy. Some DAC pathways require electricity only while others require both electricity and heat, and estimates range from 5 to 11 GJ of energy per tCO_2.[1289] Energy used for DAC must be low carbon to maximize the amount of CO_2 removed. The land requirements for DAC are minimal and limited to the footprint of the system and any on-site energy generation. A DAC facility under construction today is estimated to require 0.3 to 33 km^2 of land to remove 500,000 tCO_2 per year.[1290] Water requirements will depend on the specific DAC pathway, but can be significant; while some systems using solid sorbents and indirect heat can generate water, requiring 0.8 t water per tCO_2, other solvent-based pathways require 7 t water per tCO_2.[1291] DAC does not typically require feedstock to operate.

Rating (Water): Medium

Rating (Land): Low
Rating (Energy): High
Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of direct air capture in Massachusetts is between 1.8 million and 4.1 million tCO_2e per year, which is rated as high and represents approximately 13-30% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. This estimate used electricity in Massachusetts as a constraint to determine possible scale. It is estimated in the 2050 CECP that demand for electricity in Massachusetts will reach over 138 TWh in 2050.[1292] As a reference, currently Massachusetts produces about 850,000 MWh of clean energy a year.[1293] It was assumed that Massachusetts would meet its 2050 electricity demand and add an additional 15% of the demand in 2050, or about 20.7 TWh annually, to cover DAC production. DAC efficiency varies which results in a range of 5-11 MWh needed per tCO_2e removed and the range of possible scale.[1294] This estimate relies on the assumption that Massachusetts would be able to cover not only its needed electricity demand in 2050 but also that an additional 15% on top of it would be covered and entirely used for DAC. Because electricity is a constraint for both DAC and EAP, this estimate assumes DAC would use all this additional available electricity.

Rating: High

Risks to growth: While the estimated maximum potential deployment of direct air capture is approximately between 1.8 million and 4.1 million tCO_2e per year, several factors exist that could prevent deployment at this scale and make deployment at this scale inadvisable, including energy intensity, regulatory uncertainty for project siting, and the need for further development of in-state transmission and generation to meet energy needs. Importantly, current DAC technologies remain highly energy-intensive in nature, with most pathways ranging between 5 and 11 MWh per tCO_2.[1295] As a result, DAC depends on low-carbon electricity and heat to operate under net-negative carbon circumstances.[1296] Without adequate supply of clean energy, net removals are greatly reduced, and in Massachusetts, siting will need to balance proximity to clean energy sources alongside other key considerations like air handling, heat supply, water, and waste disposal.[1297] Additionally, another risk to growth in Massachusetts is the lack of geologic storage to store CO_2 streams from DAC projects. Oftentimes DAC projects leverage CO_2 pipelines and Class VI wells to store CO_2 geologically; however, in Massachusetts this is unlikely to be the case given there is insignificant onshore geologic storage. This is not necessarily a constraint to DAC because CO_2 can also be stored using ex-situ mineralization or being transported offshore or to other regions with appropriate storage, but it is a risk. Long-term growth may depend on establishing regional linkages for CO_2 management—likely via Atlantic offshore storage or interstate transport; this could trigger interstate permitting and legislative concerns that pertain to critical aspects of DAC, such as pipelines and the transport of hazardous materials, and would be extremely difficult to navigate and solidify.[1298] Finally, while the Commonwealth's 2050 Clean Energy and Climate Plan commits to rapid clean-power expansion, regional studies show near-term transmission and integration constraints, implying that Massachusetts-sited DAC is most feasible at pilot scale unless codeveloped with dedicated clean supply.[1299]

Rating: Medium

Local supply chain

Direct air capture CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including providers of gas handling components, gas monitoring and lab analysis services, construction material suppliers, tankard and instrumentation suppliers, and clean energy developers. MA has at least one in-state supplier for key process components such as cyropumps, which are needed for cryogenic handling and gas conditioning and support CO_2 capture, purification, and storage.[1300] The state also hosts several companies who produce FTIR gas analyzers and mass-flow hardware, as well as CO_2 analysis technology, to assist in MMRV, lab analysis and DAC process validation.[1301] Balance-of-plant equipment could be sourced from in-state by companies who provide process piping and instrumentation, as well as components like pyrogel or cryogel insulation for steam and cryogenic lines used for supercritical CO_2.[1302] Additionally, Massachusetts project developers could leverage an in-state supplier of CO_2 compressors for gas logistics and CO_2 transport needed for most DAC pathways.[1303] Finally, Massachusetts-based low-carbon energy providers, especially in-state wind project developers, could supply the clean electricity and process heat that DAC requires to operate.[1304]

Rating: High

Solution providers

Direct air capture is widely deployed and has many active solution providers, with the largest and most notable being Heirloom, Climeworks, and Carbon Engineering (now a subsidiary of Occidental). Massachusetts has one solution provider headquartered in state; DAC technology supplier Verdox, who is commercializing the MIT-originated electro-swing reactive adsorption process in Massachusetts, could be tapped to lead initial pilot projects.[1305] Additionally, while not based in MA, German-based DAC company Phlair is a member of the Boston Greentown Labs accelerator program, demonstrating physical investment in the commonwealth.[1306] However, there are currently no solution providers conducting projects in state; despite Verdox's geographic headquarters, the company has not yet deployed its technology in MA.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Direct air capture CDR has the potential to provide moderate social and environmental co-benefits, including removal of particulate matter and improvements in local air quality, though the most impactful co-benefit DAC deployment offers is permanent, high quality jobs and community investment associated with facility operation.[1307] Because of the sheer amount of ambient air that DAC units must process to remove meaningful amounts of CO_2, intake filters and air handling units are often the first step for DAC technologies. These initial processes have demonstrated the ability to remove PM from air streams they process.[1308] While particulate matter is primarily removed to increase the effectiveness of air contactors sorbent technologies, mainly to protect the contactor and sorbent by preventing fouling/clogging of the contactor & sorbent, air purification remains a real, albeit modest, air-quality co-benefit for areas near deployments.[1309] From a jobs perspective, DAC operations will create meaningful additional employment in areas where deployments occur (potentially as many as ~350 per commercial facility), though this will be explored in the following section on job creation.[1310]

Social and environmental risks: Direct air capture has the potential to pose moderate social and environmental risks, including noise and pollution concerns associated with initial facility construction and continuous operation, depletion of local resources due to DAC's need for large quantities of water and associated land use change from construction, and demand increases for local electricity that could drive up prices for local communities if DAC deployments are not accompanied by added clean energy generation.[1311] When it comes to facility construction for DAC, new plant deployments will likely generate noise pollution, dust, and particulate pollution, not to mention the disturbance of soils and vegetation due to land use change, and the release of additional emissions from transportation of materials and construction.[1312] In MA communities, if not carefully sited, new DAC facilities could also require new access roads and lead to increased traffic and a large construction workforce that could affect nearby communities, impacts are similar to those seen with other major infrastructure projects.[1313] DAC also draws heavily on local resources, particularly water, and life cycle assessments have repeatedly indicated that without adequate freshwater availability, DAC plants could compete with local end uses.[1314] Finally, because of DAC's energy intensity, the pathway has the ability to drive up electricity prices and compete with local energy use if not sited with additional capacity build out in mind.[1315] Particularly in Massachusetts, where consumer demand is one of the two main drivers of wholesale electricity prices, this could disproportionately impact areas where DAC plants are constructed.[1316]

Health impacts: Direct air capture has the potential to pose significant health risks if not properly deployed, including worker exposure to highly reactive acid and base compounds, hazards associated with CO2 transport, and potential to impact local air quality if clean energy generation isn't utilized for all DAC processes. Labor at DAC facilities is also a potentially risky endeavor, as many DAC pathways use reactive acidic and basic chemicals that pose non-zero risks to employee health, adding additional complications for proper and careful disposal once these compounds can no longer be utilized.[1317] Furthermore, Hazards exist when it comes to storing and transporting DAC captured CO2 streams as well; as with conventional storage, ESM, and ISM, CO2 pipeline transport pose risks to health if leakages occur, and CO2 exposure can cause asphyxiation if not properly monitored.[1318] For workers, additional hazards include heat stress from high-temperature equipment and high noise from fans/compressors, necessitating fixed gas detection, ventilation, PPE, heat-stress protections, and hearing-conservation controls. Finally, because DAC is energy- and heat-intensive, air quality problems could occur if plants are deployed and run on the currently gas-reliant Massachusetts grid (natural gas fueled 63% of Massachusetts's total in-state electricity net generation in 2023), which would erode net climate and air-quality benefits without additional low-carbon or renewable energy supply.[1319]

Rating: Neutral

Economic benefit and job creation

Direct air capture has the potential to create between 1,500 and 6,500 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment[1320] and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Because DAC requires significant construction for a facility, most of these jobs will likely be during project construction. Direct air capture is unlikely to direct these economic benefits in the form of jobs to disadvantaged communities within the state, due to the geography-agnostic nature of DAC. DAC facilities will not necessarily be located near these communities and so jobs may not be available for community members.

<u>Rating</u>: High

CO_2 Storage

Storage of CO2 pathways store captured and concentrated streams of CO2 through trapping, mineralization, or other physical or chemical processes.

Conventional CO_2 Storage

Table 8-21: Conventional CO2 Storage Overview

Pathway: Conventional CO_2 storage	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Low	
Current cost: \$10-30/tCO_2 **Cost reduction potential:** Low	**Scale potential:** Low (0.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 5-80 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 9; commercial scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** Low
<u>Resource requirements</u> ***Water:*** Low ***Land:*** Low ***Energy:*** Medium ***Feedstock:*** Low	**Earliest planned start time:** N/A

Table 8-21: Conventional CO2 Storage Overview

Overview

Conventional CO_2 as a pathway is the process of capturing atmospheric carbon (e.g. via DAC) and then injecting it into subsurface geology for permanent storage. Conventional storage typically involves the utilization of depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization rates in order to confine the CO_2 underground via structural, residual, or solubility trapping. Conventional CO_2 storage is likely not well suited to Massachusetts due to the lack of preferred geology that would allow for injection and storage at scale, though additional geologic characterization to assess potential may be needed.

Conventional CO_2 storage is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, due to the lack of onshore geologic storage. Due to this low scale potential, there is also limited opportunity for job creation from conventional CO_2 storage.

There is a low potential for Massachusetts to be a leader in R&D for conventional CO_2 storage. This pathway is already well-developed and deployed at scale and so R&D opportunities are limited, especially given the lack of geologic storage onshore in Massachusetts.

Deployment suitability rating: Low
R&D leadership potential rating: Medium

Cost

Current cost: The current cost of conventional CO_2 storage ranges from \$10 to \$30 per tCO_2. Conventional CO_2 storage is relatively inexpensive, though its cost only account for storage of CO_2, rather than capture and storage. The cost level is driven by the cost of storage and transport. Onshore storage in the US can be estimated at \$10 per tCO_2,[1321] and transport can increase costs by \$2 to \$15 per tCO_2.[1322] In Massachusetts, the lack of geologic storage means conventional CO_2 storage will require transport, implying that costs will be on the higher end of this range.

Range: \$10 to \$30 per tCO_2

Potential for cost reduction: The potential for cost reduction is low.

Conventional CO_2 storage has low design complexity (e.g., few components, many of which can be mass-produced) but requires high customization for every injection site and thus conventional CO_2 storage falls in the Type 3 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale). [1323] This means that although the components of conventional CO_2 storage are mass-produced, the need to customize the process to each specific site's geology means that conventional CO_2 storage is unlikely to achieve significant cost reductions with scale. Additionally, conventional CO_2 storage is already a mature technology, and so any cost reductions from scaling have likely already occurred. Competition for available and closely located storage sites could also increase costs over time.

Rating: Low

Duration

Risk of reversal: Conventional CO_2 storage provides storage with negligible risk of reversal over 10,000 years.[1324] Reversal occurs if CO_2 leaks from the storage reservoir due to permeable faults or fractures in the storage site, but this can be mitigated through site selection.[1325] Conventional CO_2 storage in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For conventional CO_2 storage, the operating lifetime of a project is 5 to 80 years, depending on the life of the storage site and monitoring requirements. Conventional CO_2 storage projects can operate from 5 years to multiple decades.[1326] Regulations generally require up to 50 years of post-site monitoring, as well.[1327] Conventional CO_2 storage projects in Massachusetts can be expected to align with this range of operating lifetimes due to federal regulations for well monitoring.

Range: 5 to 80 years

Technology Readiness Level

Conventional CO_2 storage is at commercial scale (TRL 9). Projects have existed for decades, such as the Sleipner project in Norway that has been operational since 1996.[1328] Projects are also being developed in the US, such as in the Gulf Coast by project developer Gulf Coast Sequestration,[1329] among others.

Range: TRL 9

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for conventional CO_2 storage is established. The mass of CO_2 received at the storage site and injected into the surface can be measured using existing technologies, such as through sensors and flow meters.[1330] Existing federal regulations exist to provide standards for measurement and reporting.[1331] The main challenge to MMRV for conventional CO_2 storage is long-term monitoring and measuring of any CO_2 leakage.[1332]

Rating: Established

Deployment Timelines

Conventional storage of CO_2 has not been deployed in MA as an end-of-life storage solution for captured CO_2 streams, and no deployments are currently planned as of 2025. As mentioned in the scale and risks to growth section, Massachusetts does not host the suitable geology for conventional CO2 storage, and it's unlikely that any deployments of CO_2 storage by injection either into depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization would occur without significant discoveries elucidated by additional geological characterization.[1333] Future conventional storage projects would need to navigate a host of regulations similar to those applied to oil and gas drilling operations; In MA, this would include securing permits from UIC Class VI wells from EPA Region 1, the regional permitting authority in the absence of primacy, as well as a host of aboveground permits, including those for CO_2 piping and storage, as well as facility siting and construction.[1334] Deployment timelines for MA cannot be estimated, as the state's geology precludes deployment; significant additional geologic characterization would be needed to elucidate whether suitable formations for conventional storage exist in-state.

Resource Requirements

The main resource requirement for conventional CO_2 storage is energy for compression and injection. Estimates report a range of 0.36 to 0.54 GJ is needed per tCO_2.[1335] Because storage occurs underground, the land requirements are only what is necessary for the injection site, which is estimated at 0.2 to 2 m^2 per tCO_2.[1336] No additional water or feedstock is needed for conventional CO_2 storage.[1337]

Rating (Water): Low
Rating (Land): Low
Rating (Energy): Medium
Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of conventional storage in Massachusetts is around 0 tCO_2e, which is rated as low and represents approximately 0% of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. For storage pathways, the percentage of the maximum deployment target would indicate the percentage of removals that could be stored through that pathway. For example, if a storage pathway is estimated to achieve all 14 million tCO_2e per year, a (or multiple) removal pathway(s) would still be necessary. The 0 tCO_2e for conventional storage estimate is due to the lack of onshore geologic storage in the state of Massachusetts.[1338] Because this Study only explores opportunities within the Commonwealth and 50 miles off the coast, this estimate does not consider offshore geologic storage possibilities or onshore geologic storage in other states. Massachusetts could continue exploring these possibilities moving forward.[1339]

Rating: Low

Risks to growth: The estimated maximum potential deployment of conventional storage of CO_2 is 0 tCO_2e per year due to several factors, including the lack of adequate in-state geology and the difficulty associated with characterizing and accessing potentially more suitable offshore geologic formations for storage purposes.[1340] Massachusetts primary risk to scaling conventional storage is the state's limited onshore sedimentary basins and crystalline bedrock; The U.S. Geological Survey's national assessment does not identify sizable, site-ready storage formations in the Commonwealth, meaning significant new characterization would be required to meet Class VI criteria.[1341] While offshore sedimentary basins on the Atlantic Outer Continental Shelf (OCS) adjacent to Massachusetts are more promising geologically, they have not yet been characterized or permitted specifically for CO_2 storage, leaving injectivity potential and capacity uncertain.[1342] Known environmental/operational risks for geologic storage, such as pressure management, brine displacement, and induced seismicity, are also additional consideration should additional geologic characterization reveal eligible formations, which could potentially cause community push-back for project siting.[1343] New Class VI-quality characterization (seismic, stratigraphic wells, injectivity testing) would be needed before any in-state storage could proceed, making first injection before the end of the decade unlikely without a step-change in data acquisition and permitting.[1344] Finally, should OCS storage prove viable, Atlantic OCS storage adjacent to Massachusetts depends on the Bureau of Energy and Ocean Management (BOEM) leasing framework, site identification, and environmental review, which are still maturing, thereby further constraining scale deployment.[1345]

Rating: High

Local supply chain

Conventional CO_2 storage is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact at least four sectors in the state's economy, including subsurface and seismic characterization service providers, gas measurement and analysis equipment suppliers, environmental engineering firms, and gas handling equipment manufacturers. Massachusetts has several in-state companies that could provide subsurface and seismic services for improving geologic characterization needed for project siting, as well as monitoring induced seismicity risk and guiding site selection to reduce the risk of unintended impacts from deployments.[1346] Additionally, the state hosts at least one supplier who could provide gas and isotope measurement systems central to verifying injection and CO2 streams prior to storage.[1347] To ensure proper injection and validate long-term storage design, MA is also home to at least one provider of modeling tools for CO_2 conditioning, transport, and storage design, which may be useful once geologic storage is characterized.[1348] For project development, siting, and permit navigation, in-state environmental firms could offer support in complying with MEPA/NEPA regulations and air-permitting for surface construction and infrastructure development.[1349]

Rating: Medium

Solution providers

Conventional CO_2 storage is widely deployed pathway for long-term removal and has many solution providers, though most large deployers of the pathway are oil and gas companies, such as Chevron or Shell.[1350] However, Massachusetts does not have any solution providers headquartered in state, largely due to the lack of depleted oil and gas reservoirs, saline aquifers, and other pore spaces with slow mineralization. Additionally, due to the lack of suitable geology or legacy oil and gas operations in MA, there are no solution providers conducting projects in state.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Conventional storage has the potential to provide negligible social or environmental co-benefits. Massachusetts not well suited for conventional CO_2 storage and, similar to ISM, the pathway offers few co-benefits outside of job creation associated with facility construction, drilling, and geologic analysis. From an environmental standpoint, the pathway delivers the same benefits as other long-term, durable removal pathways, and could offer improved air quality in urban, industrial areas, as sources for conventional storage such as DAC are proven to reduce air contaminants and particulate.[1351] However, this would only occur if the CO_2 streams that were captured and stored for sourced from those areas in MA. Overall, conventional storage in MA is most likely unviable due to geologic constraints, making any benefits negligible.

Social and environmental risks: Conventional CO_2 storage has the potential to pose significant social and environmental risks that resemble those posed by ISM, including induced seismicity from injection and the potential for leakage to cause groundwater acidification.[1352] For well-selected and well-managed injection sites, the retained fraction of injected CO_2 is as high as >99% over 1,000 years, yet leakage risk is not zero, and the risk of leakage is higher in conventional storage due to the lack of mineralization, so conservative siting and monitoring would be essential for any deployment to avoid threatening groundwater sources or state aquifers.[1353] For offshore sub-seabed injection sites, release experiments show that small, localized leaks can alter sediment chemistry and nearby biota, posing risk to marine ecosystems; though these leaks are detectable and spatially limited under robust monitoring, their impacts could still be serious.[1354] Not unlike ISM, conventional storage can also cause induced seismicity; Injecting fluids or gases into subsurface geology increases pore pressure on faults, and this pressure has been known to trigger a range of seismic events that increase in size if faults are critically stressed.[1355]

Health impacts: Conventional CO_2 storage has the potential to pose **significant** health risks to communities at the surface of injection sites or near storage infrastructure, primarily due to the risks associated with CO_2 transport. The principal public risk stems from transport, compression, or injection failures that can release dense CO_2 plumes and displace oxygen. However, pipelines are regulated and, with stringent regulations and safety precautions, this risk could be mitigated.[1356]

Rating: Neutral

Economic Benefit and Job Creation

Conventional CO_2 storage does not have the potential to create any jobs in Massachusetts across R&D, construction, and operations. This estimate is due to the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above, which is negligible because of the lack of in-state, onshore geologic storage. Because this Study only explores opportunities within the Commonwealth and 50 miles off the coast, this estimate does not consider offshore geologic storage possibilities or onshore geologic storage in other states. Due to the lack of in-state, onshore geologic storage, conventional CO_2 storage is unlikely to direct these economic benefits in the form of jobs to disadvantaged communities within the state.

Rating: Low

In-situ mineralization

Table 8-22: In-situ Mineralization Overview

Pathway: In-situ mineralization	
Deployment suitability for Massachusetts: Low **R&D leadership potential:** Low	
Current cost: \$10-400/tCO_2 **Cost reduction potential:** Medium	**Scale potential:** Low (0.0 million tCO_2e/y) **Risks to growth:** High
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 5-80 years	**Local Supply Chain Relevance:** Medium
Technology Readiness Level: 7-8; demonstration scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** Low
Resource requirements ***Water:*** High ***Land:*** Low ***Energy:*** High ***Feedstock:*** Low	**Earliest planned start time:** N/A

Table 8-22: In-situ Mineralization Overview

Overview

In-situ mineralization as a pathway is the process of sequestering atmospheric carbon (e.g. from DAC) and circulating either supercritical CO_2 or CO_2-rich fluid through subsurface alkaline rocks, which in turn stabilizes the carbon underground for durable storage via conversion to solid carbonate minerals, otherwise known as mineral trapping.

In-situ mineralization is unlikely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the low scale potential for deployment in the state, due to the lack of onshore geologic storage. Due to this low scale potential, there is also limited opportunity for job creation from in-situ mineralization.

There is a low potential for Massachusetts to be a leader in R&D for in-situ mineralization, because this pathway is mid-to-late TRL and so has narrowed its R&D needs. Additionally, Massachusetts has minimal potential to deploy in-state and so may be better suited to lead in R&D for other pathways that can be deployed at a greater scale.

Deployment suitability rating: Low

R&D leadership potential rating: Low

Cost

Current cost: The current costs for in-situ mineralization ranges from \$10 to \$400 per tCO_2. In-situ mineralization costs today depend on whether the storage site is on land or in the ocean, with land-based storage ranging from \$10 to \$50 per tCO_2 and ocean-based storage ranging from \$200 to \$400 per tCO_2.[1357] Due to limited suitable geologic formations in-state,[1358] in-situ mineralization in Massachusetts would require significant transport costs, either out of state or out to the ocean, and so costs would likely be on the higher end of this range.

Range: \$10 to \$400 per tCO_2

Potential for cost reduction: The potential for cost reduction is medium.

In-situ mineralization has medium design complexity (e.g., a moderate number of components of which many are mass-produced) and requires a moderate degree of customization to each site, and thus in-situ mineralization falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale).[1359] This means that because some components of in-situ mineralization can benefit from economies of scale, this is limited by the need to customize a project to the site specifics. Therefore, in-situ mineralization is likely to achieve moderate cost reductions with scale. Costs could also decrease with innovation in MMRV technology.[1360]

Rating: Medium

Duration

Risk of reversal: In-situ mineralization creates storage with negligible risk of reversal over 10,000 years, through the formation of stable carbonate minerals.[1361] Scientific literature has shown that less long-term monitoring is needed for in-situ mineralization than conventional CO_2 storage, due to a decreased risk of CO_2 leakage,[1362] which emphasizes the low risk of reversal of in-situ mineralization. The risk of reversal can be further decreased by pre-dissolving CO2 before injection.[1363] In-situ mineralization in Massachusetts can expect a slightly higher risk of reversal due to the lack of in-state geologic storage; transportation of CO_2 will be necessary which offers additional opportunities for leakage.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For in-situ mineralization, the operating lifetime of a project is typically 5 to 80 years. The operating lifetime for an in-situ mineralization project will likely be similar to that of conventional CO_2 storage, which can operate for decades.[1364] Regulation for conventional CO_2 storage generally requires up to 50 years of post-site monitoring,[1365] but in-situ mineralization may have shorter monitoring requirements.[1366] In-situ mineralization projects in Massachusetts can be expected to align with this range of operating lifetimes, though in-state projects will be limited due to the lack of geologic storage.

Range: 5 to 80 years

Technology Readiness Level

In-situ mineralization is at the demonstration scale (TRL 7 to 8).[1367] A major project developer is Carbfix, whose Silverstone project is planned to store 34,000 tCO_2 per year once fully operational.[1368] Integration with DAC plants could offer a way to increase project scale and move along the TRL scale.

Range: TRL 7 to 8

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for in-situ mineralization is established. The mass of CO_2 received at the storage site and injected into the surface can be measured using existing technologies, such as through sensors and flow meters.[1369] Additional techniques have also been established, such as using chemical tracers to measure mineral carbonate formation.[1370] The may be fewer challenges than conventional CO_2 storage because there may be less of a need for long-term monitoring with in-situ mineralization.[1371]

Rating: Established

Deployment Timelines

In-situ mineralization of CO_2 has not been deployed in MA and no deployments are currently planned in the state as of 2025. While the prevalence of eligible geologic formations for ISM is likely higher than those relevant for conventional CO2 storage, appropriate geology in Massachusetts is still very minimal and will likely be major source of extended deployment timelines, if deployments occur at all.[1372] Future ISM storage projects would need to navigate a host of regulations similar to those applied to oil and gas drilling operations; In MA, this would include securing permits from UIC Class VI wells from EPA Region 1, the regional permitting authority in the absence of primacy, as well as a host of aboveground permits, including those for CO_2 piping and above ground storage, as well as state and municipal codes for facility siting and construction.[1373] Deployment timelines for MA ISM projects cannot be estimated during this decade, as the state's geology precludes deployment in the absence of significant additional geologic characterization, which would be needed to reveal suitable formations for in-situ mineralization storage; the characterization process for sites with minimal existing data typically occurs on the order of five to ten years, as demonstrated by existing projects.[1374]

Resource Requirements

The main resource requirement for in-situ mineralization is energy and water. Estimates suggest 10 GJ are needed per tCO_2.[1375] The water requirement can be large, at approximately 25 to 30 t water per tCO_2.[1376] Because storage occurs underground, the land requirements are only what is necessary for the injection site, which can be assumed to be similar to conventional CO_2 storage and is estimated at 0.2 to 2 m^2 per tCO_2.[1377] No feedstock is directly required for in-situ mineralization, though the process requires access to mafic and ultramafic rock formations underground.[1378]

Rating (Water): High
Rating (Land): Low
Rating (Energy): High

Rating (Feedstock): Low

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of in-situ mineralization in Massachusetts is around 0 tCO_2e per year, which is rated as low and represents none of the maximum 14 million tCO_2e per year that Massachusetts could deploy in 2050 to achieve its net zero target. For storage pathways, the percentage of the maximum deployment target would indicate the percentage of removals that could be stored through that pathway. For example, if a storage pathway is estimated to achieve all 14 million tCO_2e per year, a (or multiple) removal pathway(s) would still be necessary. The 0 tCO_2e estimate for in-situ mineralization is due to the lack of relevant onshore geologic storage (basalt formations) in the state of Massachusetts.[1379] Possible deposits are limited to thin, discontinuous areas.[1380] Because this Study only explores opportunities within the Commonwealth and 50 miles off the coast, this estimate does not consider offshore geologic storage possibilities or onshore geologic storage in other states. Massachusetts could continue exploring these possibilities moving forward.[1381]

Rating: Low

Risks to growth: The current estimated maximum potential deployment of in-situ mineralization is 0 tCO_2e per year due primarily to the lack of eligible geology in the state.[1382] Reactive rock is present in Massachusetts, but it limited to thin Early Jurassic basalts in the Deerfield Basin and small, discontinuous ultramafic/serpentinite bodies, which would constrain injectivity and potential project size.[1383] If these formations proved eligible, however, it's also important to note that while dissolved-CO_2 injection can mineralize carbon on ~2-year timescales, robust monitoring is required to verify mineral formation and plume evolution.[1384] Additionally, for dissolved CarbFix-style injection (~25 t water per t CO_2), water requirements are high, and deep well injection of aqueous solutions will necessitate careful groundwater protection under federal underground injection controls.[1385] Policy and permitting risks for ISM are also very similar to those that will hinder conventional storage pathways; Massachusetts does not have Class VI primacy and the EPA Region 1 is the permitting authority.[1386] Furthermore, there are currently no Massachusetts Class VI projects on the federal tracker; thus, in addition to geologic characterization and initial subsurface analysis, the wait time for initial injection projects likely will be a minimum of an additional 24 months, creating timeline and financing risk for first-of-a-kind projects.[1387] The 2050 Clean Energy and Climate Plan recognizes engineered CDR but lacks a dedicated in-situ mineralization siting framework, so proponents likely will need to navigate MEPA in parallel with federal permitting.[1388]

Rating: High

Local supply chain

In-situ mineralization CDR is of medium relevance to Massachusetts-based supply chain actors, with the potential to positively impact four sectors in the state's economy, including stratigraphic drilling operations, CCUS and geologic engineering companies, gas analysis technology providers, and piping and instrumentation component suppliers. Massachusetts hosts a variety of companies specializing in subsurface engineering; the state has several organizations who possess experience working with CO2 storage workflows, reactive-transport modeling, and compression/pipeline engineering, and these providers could assist with core planning and design needs for in-state ISM deployment.[1389] Local projects could also leverage MA-based consultants with carbon-storage expertise to address the various of environmental planning and permitting aspects necessary for siting and project development.[1390] Massachusetts also hosts a state-of-the-art drilling company with experience navigating hard volcanic/ultramafic formations; Their proprietary millimeter-wave drilling pathway could be ideal for stratigraphic test wells and eventual injection exploration.[1391] Additionally, surface and piping systems needed for ISM development can take advantage of in-state providers who supply flow-control and reliability hardware.[1392] Finally, in-state producers of precision gas/isotope analyzers could assist ISM developers by offering and local source for project monitoring, reporting, and verification equipment to be used ongoing operations.[1393]

Rating: Medium

Solution providers

In-situ mineralization CDR is not a widely deployed pathway and has only a few solution providers pursuing the pathway globally. The most notable leaders in ISM today are Iceland's Carbfix and Oman's 44.01. [1394] [1395]Because there are so few companies globally pursuing ISM and given the fact that Massachusetts does not have abundant geologic formations that would support ISM, there are no solution providers headquartered in state. As a result, there are no solution providers conducting projects in state, and further geologic characterization and subsurface exploration would be necessary before deployments occurred.

Co-benefits and potential negative impacts

Social and environmental co-benefits: In-situ mineralization has the potential to provide negligible social and environmental co-benefits outside of job creation and durable CO_2 removal. While deployments of ISM in-state would create jobs for geologic and construction industries, such as drilling, geologic / seismic characterization and monitoring, and facility construction, there would be little to no additional social benefit for standing up ISM in Massachusetts. Similarly, outside of the benefit of storing CO_2 in its most durable form (mineralized carbonates underground), the process of ISM does not offer any additional environmental co-benefits.

Social and environmental risks: In-situ mineralization has the potential to pose significant social and environmental risks, including induced seismicity from injection and the potential for leakage to cause groundwater acidification.[1396] [1397] Induced seismicity is a serious risk for subsurface injection of CO_2, particularly liquid or supercritical CO_2; Injecting fluids or gases into subsurface geology raises pore pressure on faults, and this pressure has been known to trigger events ranging from micro seismicity to measurable earthquakes, especially if faults are critically stressed.[1398] In MA, because the available geologic storage for ISM pathways is minimal, this pressure could increase faster with smaller amounts of injection, and while faults in MA are less substantial than those present in the American west, they can still cause serious seismic events.[1399] In terms of groundwater, injected CO_2 can cause contamination issues between the time of injection and mineralization.[1400] As injected gaseous CO_2 or formation brine driven by injection pressure responds, it can travel through legacy faults or fractures in the geology; as a result, aquifers can see acidification, increases in total dissolved solids increases, and mobilization of trace elements (As, Se, etc.), depending on local mineralogy.[1401]

Health impacts: In-situ mineralization has the potential to pose significant health hazards, the most notable being risks of asphyxiation associated with CO_2 pipelines.[1402] CO_2 pipelines carry real asphyxiation risk if they leak, primarily because CO_2 is colorless, odorless, heavier-than-air at ambient conditions, and can pool in low spots while displacing oxygen.[1403] However, pipelines are regulated and, with stringent regulations and safety precautions, this risk could be mitigated.[1404]

Rating: Neutral

Economic Benefit and Job Creation

In-situ mineralization does not have the potential to create any jobs in Massachusetts across R&D, construction, and operations. This estimate is due to the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above, which is negligible because of the lack of in-state, onshore geologic storage such as basalt formations. Because this Study only explores opportunities within the Commonwealth and 50 miles off the coast, this estimate does not consider offshore geologic storage possibilities or onshore geologic storage in other states. Due to the lack of in-state, onshore geologic storage, conventional CO_2 storage is unlikely to direct these economic benefits in the form of jobs to disadvantaged communities within the state.

Rating: Low

Ex-situ mineralization

Table 8-23: Ex-situ Mineralization Overview

Pathway: Ex-situ mineralization	
Deployment suitability for Massachusetts: High **R&D leadership potential:** High	
Current cost: \$10-600/tCO_2 **Cost reduction potential:** High	**Scale potential:** High (19.5 million tCO_2e/y) **Risks to growth:** Medium
Risk of reversal: Negligible over >10,000 years **Facility operating lifetime:** 20-100 years	**Local Supply Chain Relevance:** High
Technology Readiness Level: 6-7; pilot to demo scale	**Co-benefits and potential negative impacts:** Neutral
Measurement readiness: Established	**Economic benefit and job creation:** High
Resource requirements ***Water:*** High ***Land:*** Low ***Energy:*** High ***Feedstock:*** Medium	**Earliest planned start time:** January 2028

Table 8-23: Ex-situ Mineralization Overview

Overview

Ex-situ mineralization as a pathway is the process of reacting CO_2 with either natural alkaline minerals or artificial alkaline byproducts / wastes in engineered reactors. In comparison with ambient conditions, engineered reactions for ESM typically go to completion within minutes using high temperatures, pressures, electrochemistry, and/or pH changes, accelerating the mineralization process and increasing the speed of CO_2 uptake.

Ex-situ mineralization is likely to be well-suited to Massachusetts as a pathway to meet a substantial fraction of the state's total need for CDR. This rating is driven by the high scale potential for deployment in the state, due to the state's large production of aggregate. Additionally, due to this high scale potential, there is a significant opportunity for job creation from ex-situ mineralization in the state. However, taking advantage of this large scale potential means that Massachusetts will need to convert to low-carbon aggregate, which is more expensive than conventional aggregate.

There is a high potential for Massachusetts to be a leader in R&D for ex-situ mineralization as well, because this pathway is still developing and has open research questions, such as on the use of alkaline industrial wastes and the production of aggregate. Massachusetts may be especially well-suited to lead on this due to the potential for ex-situ mineralization to be a huge CO_2 sink for the state.

Deployment suitability rating: High
R&D leadership potential rating: High

Cost

Current cost: Ex-situ mineralization costs today range from \$10 to \$600 per tCO_2. The large range is largely driven by differences in the type of feedstock used and the energy needs for the reactor.High pressure and temperature systems at the high end of that range, while using feedstock from waste streams decrease costs.[1405] The cost level is driven by high resource needs, especially energy to achieve the conditions needed to accelerate the mineralization process. Ex-situ mineralization projects in Massachusetts may be toward the upper end of this range given Massachusetts' relatively high industrial electricity prices.[1406] This cost range refers to the gross cost of the ex-situ mineralization process; using the mineral outputs in cement or aggregate would reduce the marginal cost of carbon removal.

Range: \$10 to \$600 per tCO_2

Potential for cost reduction: The potential for cost reduction is high.

Ex-situ mineralization has low design complexity (e.g., few components, many of which can be mass-produced) but requires a moderate level of project customization due to feedstock specifics. Therefore, ex-situ mineralization falls in the Type 2 section of the cost reduction potential matrix (see Appendix D on potential for cost reduction with scale). [1407] This means that because some components of in-situ mineralization can benefit from economies of scale, this is limited by the need to customize a project to the site specifics. Therefore, in-situ mineralization is likely to achieve moderate cost reductions with scale. Costs may also decrease through improvements in reactor and system design, optimized feedstock pre-processing, and process waste heat integration.[1408] Costs can also decrease by co-locating reactors with alkaline minerals (including industrial wastes) near CO_2 sources.[1409]

Rating: High

Duration

Risk of reversal: Ex-situ mineralization creates storage with negligible risk of reversal over 10,000 years, through the formation of stable carbonate minerals.[1410] Reversals could occur if there is strong acid weathering at the site of carbonate mineral storage, but this can be mitigated through site selection and monitoring.[1411] E-situ mineralization projects in Massachusetts can expect this same level of reversal risk due to the known chemistry and mitigation strategies for ex-situ mineralization.

Rating: Negligible risk of reversal for greater than 10,000 years

Operating lifetime of a plant: For ex-situ mineralization, the operating lifetime of a project is 20 to 100 years. Studies estimate the capital equipment like the reactor in ex-situ mineralization to have a 20 year lifetime,[1412] while concrete, in which the CO_2 can be added to through ex-situ mineralization, can last 100 years. Ex-situ mineralization projects in Massachusetts can be expected to have the same operating lifetime due to the dependence of lifetime on technology, not geography.

Range: 20 to 100 years

Technology Readiness Level

Ex-situ mineralization is at the pilot to demonstration scale (TRL 6 to 7).[1413] The supplier Paebbl recently started operating its first demonstration plant at a scale of 500 tCO_2 per year,[1414] while Blue Planet has partnered with San Francisco Bay Aggregates to integrate the limestone and concrete aggregate in which captured CO_2 has been mineralized.[1415]

Range: TRL 6 to 7

Measurement, monitoring, reporting, and verification (MMRV)

MMRV for ex-situ mineralization is established. Mineralization occurs in a closed reactor, allowing for direct measurements to quantify CO_2 removal.[1416] Methodologies exist from multiple registries, including Verra,[1417] Gold Standard,[1418] and Puro.earth.[1419] Challenges include accurately accounting for the entire process's lifecycle emissions, which will affect a project's net CO_2 removal.[1420]

Rating: Established

Deployment Timelines

Ex-situ mineralization has not been deployed in MA and no deployments are currently planned as of 2025. Relevant permitting and regulations for future ex-situ mineralization projects would resemble those applied to existing industrial manufacturing facilities for construction materials. MA deployment would need to abide by state regulation 310 CMR 7.00, which outlines pollution control standards and permit requirements for ESM facilities with pollutant emissions either from the mineralization reaction or the processing of feedstocks prior to the reaction process.[1421] Additionally, given the use of pure CO_2 streams for the mineralization process, ESM developers would need to adhere to OSHA process safety management, which is aimed at reducing risk around the unexpected releases of toxic, reactive, or flammable gases, of which CO_2 is included.[1422] Finally, depending on the type and source of feedstocks used in the ESM process, deployments would be held to MA's 310 CMR 30.00 guidance, which ensures public and environmental health / safety by regulating the generation, storage, collection, transport, treatment, and use of hazardous waste materials.[1423] From a deployment standpoint, some ESM project developers can accelerate timelines by retrofitting existing concrete plants, while others require standalone commercial facilities. Acknowledging these differences, existing ESM projects indicate a deployment in MA could move from planning to operations in approximately two years, with the registry and crediting process taking an additional six to twelve months, though these timelines could shift depending on differences in-state regulation and solution provider.[1424]

Resource Requirements

The main resource requirements for ex-situ mineralization is energy, feedstock, and water. The process requires significant energy, as approximately 10 GJ per tCO_2 is required.[1425] Feedstock requirements depend on the alkaline mineral used, similar to surficial mineralization. Assuming full conversion of common alkaline mineral feedstock means about 1.6 t mineral per tCO_2 is needed for olivine, 1.3 t mineral per tCO_2 for brucite, and 2.0–2.5 t mineral per tCO_2 for serpentine and wollastonite.[1426] Water requirements will depend on the reaction but could be on the order of 5 to 10 t water per tCO_2.[1427] Land requirements are minimal, especially if the reactor is integrated into an existing industrial site.[1428]

Rating (Water): High

Rating (Land): Low

Rating (Energy): High

Rating (Feedstock): Medium

Scale and growth

Scale possible in Massachusetts: The estimated maximum potential deployment of ex-situ mineralization in Massachusetts is around 19.5 million tCO_2e per year, which is rated as high and represents over 100% of the maximum 14 million tCO_2e per year that Massachusetts could store in 2050 to achieve its net zero target. For storage pathways, such as ex-situ mineralization, the percentage of the maximum deployment target indicates the percentage of removals that could be stored through that pathway. For example, although ex-situ mineralization is estimated to be able to store all 14 million tCO_2e per year of removals, a (or multiple) removal pathway(s), such as DAC or EAP, would still be necessary to source the stream of CO_2. The ex-situ mineralization scale potential was calculated using the USGS data on aggregate production across US states which shows that, in 2023, Massachusetts produced over 44 million tons of crushed stones, sand and gravel, and other aggregates for construction.[1429] In some instances, one ton of aggregate can mineralize and store 44 $kgCO_2e$.[1430] If all the mineral aggregates in Massachusetts included in the USGS data could be produced using ex-situ mineralization, around 19.5 million tCO_2e could be stored per year. If the estimate included aggregates produced in all of New England, about 71 million tCO_2e could be stored per year.

Rating: High

Risks to growth: While the estimated maximum potential deployment of ex-situ mineralization is 19.5 million tCO_2e per year, there exist several factors that could prevent deployment at this scale or make deployment at this scale inadvisable, including energy usage, adoption rates, and potential environmental risks.[1431] The primary risk for scaling ex-situ mineralization CDR in MA is the pathway's energy-intensity. Recent reviews place typical demand for engineered mineral carbonation in the range of ~2.7–3.2 MWh per tCO_2 net removed, with wide variation by feedstock and process configuration (e.g., aqueous vs. gas-solid), implying strong dependence on electricity decarbonization for climate efficacy.[1432] MA's maximum scale estimate assumes that energy allocation will not be a limiting factor for deployment, which will require the state to meet its significant scale up goals for energy (and specifically renewable) production. From an environmental risk standpoint, ESM's impact on environmental contaminants is mixed. Carbonation of industrial alkaline feedstocks can lower leaching of some metals (e.g., Cu in MSWI bottom ash) but may increase the leaching others (e.g., Chromium), so Massachusetts projects will require site-specific treatability testing and leachability verification before product use.[1433] Finally, the above scale estimate assumes that all aggregates in MA are produced using ESM; while this is possible, adoption at an 100% scale could prove challenging or even impractical, making this scale estimate unattainable.

Rating: Medium

Local supply chain

Ex-situ mineralization CDR is of high relevance to Massachusetts-based supply chain actors, with the potential to positively impact five sectors in the state's economy, including solid waste disposal operations, quarrying operations, tankard and reactor manufacturers, piping and CO_2 instrumentation suppliers, and gas analysis and measurement equipment producers. On the feedstock side, Massachusetts has several companies prepared to provide mineral feedstocks for ESM projects; these companies could supply materials like quarry fines and recycled-concrete fines, monetizing otherwise disposable waste streams while also ensuring reliable source of alkaline materials for mineralization. [1434] [1435] The Commonwealth also operates five municipal waste-to-energy facilities that together burn about half of the state's MSW, generating alkaline bottom ash—a well-studied, highly reactive ESM feedstock.[1436] On the equipment side, Massachusetts hosts several wholesalers and fabricators of pressurized reactors and tankard components that could be utilized for building out the infrastructure for ESM reactions.[1437] Additionally, MA has several in-state suppliers who could supply vacuum, flow, and control instrumentation for fluid handling and CO2 transport to reactor systems.[1438] Local companies could also lead on supplying process analytics and QA/QC lab systems equipment used for measuring mineralization of feedstocks and quantifying CO_2 removal.[1439] Overall, Massachusetts has adequate in-state capacity to support the development of an ESM industry while ensuring many of the economic benefits of deployment impact domestic business and operations.

Rating: High

Solution providers

Ex-situ mineralization CDR is widely deployed and has several solution providers globally, including companies such as Blue Planet Systems, CarbiCrete, and CarbonBuilt.[1440] While Massachusetts does not have solution providers headquartered in state, the company CarbonCure, a prominent ESM provider, is partnering with MIT's Masic Lab in Cambridge, anchoring commercial ESM development to Massachusetts research.[1441] Despite the fact this partnership could indicate in-state deployments are soon to follow, there are currently no solution providers conducting projects in state.

Co-benefits and potential negative impacts

Social and environmental co-benefits: Ex-situ mineralization has the potential to provide **moderate** social and environmental co-benefits, including reduction of risks associated with metal leaching from above ground alkaline feedstocks, and quantity reduction of legacy waste residues.[1442] A significant benefit from ESM deployment is the way in which accelerated carbonation of alkaline residues can lower metal leaching and strengthen materials; by reacting CO2 with feedstocks that can produce metal leaching, ESM can reduce risks to groundwater (e.g. contamination) and enable safer, stronger building practices where people live and work.[1443] Additionally, ESM is also an effective tool for mitigating and removing legacy stocks of waste that are difficult to dispose of and pose potential risks to local environments.[1444] Particularly for feedstocks like municipal solid waste incineration fly ash, ESM could both reduce the need for in-state quantities and storage of these waste streams while delivering significant removal benefits.[1445] Massachusetts hosts five municipal waste-combustor facilities, creating an in-state residue stream that could be stabilized and reused if projects meet reuse standards.[1446]

Social and environmental risks: Ex-situ mineralization has the potential to pose **negligible** social and environmental risks when deployed, including additional local health impacts from particulate if processes are not powered by clean energy sources, as well as some leaching concerns due to a lack of uniformity in heavy metal carbonation.[1447]

As with several other pathways, the net climate benefit depends on energy sourcing for grinding, curing, and gas handling and the level of carbon intensity of the overall energy grid where ESM processes are drawing from; site-specific life-cycle assessments and clean power are necessary to ensure CDR is taking place and to ensure emissions impacts from existing power sources are not shifting the burden of increased CO_2 concentrations from one community to another.[1448]

Additionally, carbonation via ESM does not uniformly reduce all pollutants; oxyanions such as hexavalent chromium and antimony can persist or increase, so long-term leaching tests and Beneficial Use Determination approvals are needed.[1449] Especially when deploying ESM-carbonated construction material usage near sensitive lands or waters, Massachusetts permitting and monitoring should verify leachate performance under local conditions rather than relying on generic data.[1450]

Health impacts: Ex-situ mineralization has the potential to pose moderate health risks and hazards, including respiratory risks from rock dust, potential exposure to acid / base compounds, and respiratory risks from damaged or mishandled CO_2 streams. Handling alkaline solids and operating carbonation reactors can generate dust and aerosols, which can be potentially hazardous for respiratory health; Massachusetts requires controls through air permits (e.g., fugitive dust plans), though project siting will still be important to avoid unintended health risks.[1451] Additionally, corrosive chemical exposures from acids/bases used for pH control, and carbon-dioxide asphyxiation hazards in confined spaces are also potential risks for ESM facilities.[1452] Standard controls to mitigate these effects exist in MA, including enclosed handling, local exhaust, spill containment, continuous CO_2 monitoring/alarms, PPE, and a written respiratory-protection program, and prove effective when instituted.[1453]

Rating: Neutral

Economic benefit and job creation

Ex-situ mineralization has the potential to create between 23,000 and 30,000 jobs in Massachusetts across R&D, construction, and operations. This estimate is generated from existing estimates of job creation for 100 Mt of CDR deployment,[1454] assuming a similar job creation profile as direct air capture, and the potential scale of deployment in Massachusetts estimated in the Scale and Growth section above. Ex-situ mineralization has a high potential to create jobs in Massachusetts largely due to its potential for large scale deployment. Ex-situ mineralization is unlikely to direct these economic benefits in the form of jobs to disadvantaged communities within the state, due to the geography-agnostic nature of ex-situ mineralization. Ex-situ mineralization facilities will not necessarily be located near these communities and so jobs may not be available for community members.

Rating: High

8.2 Appendix B: Pathway summary template

Table 8-24: Pathway Summary Table Template

Pathway: Name of Pathway	
Suitability for Massachusetts: Low/Medium/High	
Current cost: $XXX-YYY/tCO_2$ **Cost reduction potential:** Low/Medium/High	**Scale potential:** Low/Medium/High **Risks to growth:** Low/Medium/High
Risk of reversal: Significant over 100 years / Significant over 1000 years / Negligible over >10,000 years **Facility operating lifetime:** XX-YY years	**Local Supply Chain Relevance:** Low/Medium/High
Technology Readiness Level: #-#; 1-2 word description	**Co-benefits and potential negative impacts:** Negative/Neutral/Positive
Measurement readiness: Early stage/Developing/Established	**Economic benefit and job creation:** Low/Medium/High
Resource requirements ***Water:*** Low/Medium/High ***Land:*** Low/Medium/High ***Energy:*** Low/Medium/High ***Feedstock:*** Low/Medium/High	**Earliest planned start time:** Month, 20XX/NA/Underway

Table 8-24: Pathway Summary Table Template. Color code pathway tables: Negative/Neutral/Positive.

8.3 Appendix C: Technology Readiness Levels

Table 8-25: Technology Readiness Levels (TRLs) Explained

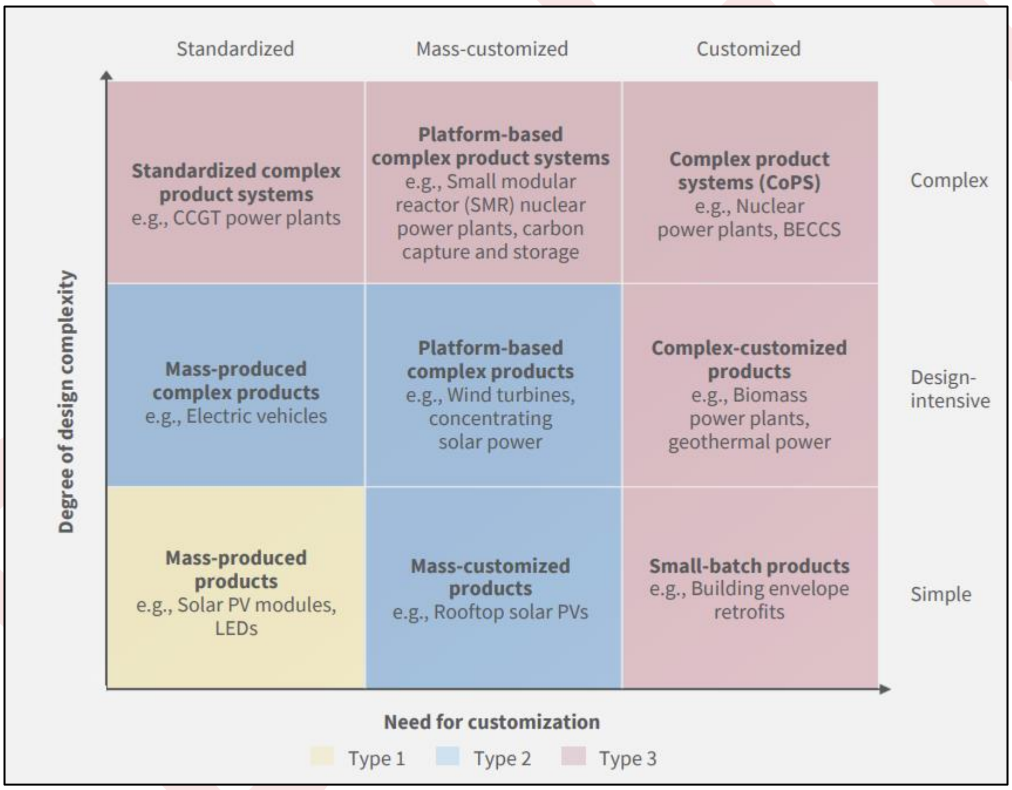
Technology Readiness Level	Relative Level of Technology Development	Definition
TRL 1	Basic Technology Research	Basic principles observed and reported. Scientific research begins to be translated into applied research and development.
TRL 2	Basic Technology Research	Technology concept and/or application formulated. Practical applications are identified but speculative; no experimental proof yet.
TRL 3	Research to Prove Feasibility	Analytical and experimental critical function and/or characteristic proof of concept. Active R&D initiated, including analytical studies and lab-scale validation.
TRL 4	Technology Development	Component and/or system validation in a laboratory environment. Basic technological components integrated to establish that they work together.
TRL 5	Technology Development	Component and/or system validation in a relevant environment. Fidelity of technology improves; basic components integrated with realistic supporting elements.
TRL 6	Technology Demonstration	System/subsystem model or prototype demonstrated in a relevant environment. Representative model or prototype tested in a relevant environment.
TRL 7	System Commissioning	System prototype demonstrated in an operational environment. Near or at planned operational system; requires demonstration in actual operational environment.
TRL 8	System Commissioning	Actual system completed and qualified through test and demonstration. Technology proven to work in its final form and under expected conditions.
TRL 9	System Operations	Actual system operated successfully in operational environment. Technology proven through successful mission operations.

Table 8-25: Table 8-25: Technology Readiness Levels (TRLs) Explained. Adapted from the DOE Technology Readiness Guide.[1455]

8.4 Appendix D: Potential for cost reduction with scale

The potential for cost to decrease with scale for each CDR pathway was based on the methodology outlined in *The Applied Innovation Roadmap*, published by RMI. [1456] The CDR pathway is categorized as a Type 1, 2, or 3 technology based on its degree of complexity and need for customization, as shown in the matrix and table below. In this report, we refer to a CDR pathway's degree of complexity as how complex the machine components of the pathway are. If the technology required for a CDR pathway has few components and/or most components are mass-produced, the CDR pathway is rated low in design complexity. If the technology required for a CDR pathway has many components and many of these components are not mass-produced, the CDR pathway is rated high in design complexity. A CDR pathway's need for customization is defined here as the need to customize each project or plant of a pathway to the specific site at which it is located, on a scale from low (standardized) to high (customized). The ranges for the high, medium, and low learning rates are based on the work of Malhotra et. al (2020).[1457]

Figure 8-1: Cost Improvement Framework and Key.



TYPE	EXPECTED LEARNING RATE	EXPLANATION[1]
Type 1	High	Simple, mass produced products have high learning rate potential
Type 2	Medium	More complex and customized products may not come down in price as quickly as type 1 technologies
Type 3	Low	Complex and/or customized technologies are the least likely to come down in cost

Figure 8-1: Cost Improvement Framework and Key.

8.5 Appendix E: Authorizing Legislation

SECTION 111. The Massachusetts clean energy technology center shall conduct and publish a study of prospects and opportunities for carbon dioxide removal innovation and operations within the commonwealth or in waters not more than 50 nautical miles off the commonwealth. Methods of carbon dioxide removal shall include, but not be limited to: (i) sequestration and storage involving terrestrial mineralization or enhanced rock weathering; (ii) sequestration and storage involving biochar, woody waste, agricultural waste or other waste products; (iii) ocean-based solutions including electro-chemical alkalinity enhancement, marine permaculture, deep-ocean sequestration and storage of biomass and coastal enhanced weathering; (iv) construction materials and products, the production of which directly contributes to the sequestration and storage of carbon dioxide or other greenhouse gases, including mass timber; and (v) direct air capture paired with either durable geologic sequestration and storage or durable sequestration and storage in the built environment including in concrete.

The study shall include, but not be limited to: (i) cost considerations, including ranges of likely prices per ton of carbon dioxide removed; (ii) the scale potential of various potential carbon dioxide removal processes; (iii) the likely duration of various potential carbon dioxide removal operations; (iv) projected start times of various activities and operations; (v) the conservation efficiency of various activities and operations in terms of their use of water, land and energy resources with explicit consideration of projects with low water, land and energy requirements and of projects that exclusively employ renewable energy; (vi) the number of potential jobs within the commonwealth, including research and development jobs, that are likely to be created by various activities and operations; (vii) the potential of various activities and operations to involve purchases of equipment and supplies from businesses located in the commonwealth; (viii) the potential of various activities and operations to generate significant agricultural, ecological or ecosystem co-benefits, harms or effects of ocean acidification on the marine environment, habitats and species, including shellfish, lobsters and other commercially-important fisheries in the waters of the commonwealth; (ix) the extent to which various activities and operations may generate economic benefit to 1 or more disadvantaged communities; (x) methods of measuring, reporting and verifying carbon dioxide removal technologies; and (xi) recommended next steps, if any, for legislative or executive branch action.

The center shall publish a draft study for comment no later than December 31, 2025 and a final study no later than April 30, 2026.[1458]

8.6 Appendix F: Legislative Requirements index

From: An act promoting a clean energy grid, advancing equity and protecting ratepayers.[1459]

Table 8-26: Mapping Legislative Requirements to Report Locations

Requirement	Report location
Terrestrial mineralization	Surficial mineralization
Enhanced rock weathering	Terrestrial enhanced weathering
Biochar	Pyrolysis (biochar) and storage

Requirement	Report location
Woody waste	Biomass direct storage
Agricultural waste	Biomass direct storage
Other waste products	Biomass direct storage
Ocean electrochemical alkalinity enhancement	Electrochemical alkalinity production
Marine permaculture	Macroalgae in open water
Deep ocean sequestration and storage of biomass	Microalgae in open water Macroalgae in open water
Coastal enhanced weathering	Coastal enhanced weathering
Construction materials and products	Other biomass building products Mass timber Ex-situ mineralization
Mass timber	Timber building products
Direct air capture with geologic storage	Direct air capture Conventional CO2 storage In-situ mineralization
Direct air capture with storage in the build environment including in concrete	Direct air capture Ex-situ mineralization
Cost considerations, including ranges of likely prices per ton of carbon dioxide removed	Cost
The scale potential of various potential carbon dioxide removal processes	Scale and growth
The likely duration of various potential carbon dioxide removal operations	Duration
Projected start times of various activities and operations	Deployment timelines
The conservation efficiency of various activities and operations in terms of their use of water, land and energy resources with explicit consideration of projects with low water, land and energy requirements and of projects that exclusively employ renewable energy	Resource requirements
The number of potential jobs within the commonwealth, including research and development jobs, that are likely to be created by various activities and operations	Job creation and economic benefit
The potential of various activities and operations to involve purchases of equipment and supplies from businesses located in the commonwealth	Local supply chain
The potential of various activities and operations to generate significant agricultural, ecological or ecosystem co-benefits, harms	Co-benefits and potential negative impacts

Requirement	Report location
or effects of ocean acidification on the marine environment, habitats and species, including shellfish, lobsters and other commercially-important fisheries in the waters of the commonwealth	
The extent to which various activities and operations may generate economic benefit to 1 or more disadvantaged communities	Economic benefit and job creation
Methods of measuring, reporting and verifying carbon dioxide removal technologies	Measurement, monitoring, reporting, and verification
Recommended next steps, if any, for legislative or executive branch action	Recommendations

Table 8-26: Mapping Legislative Requirements to Report Locations

Glossary

Community engagement: Any action from the state that supports accessible and thorough community engagement practices fits in this policy section. These recommendations are aimed at supporting communities that may be impacted by CDR, prioritizing co-benefits of CDR pathways, reducing harms and risks, and ensuring transparency and accountability during research and deployment.

Demand policy: Any policy or program that stimulates demand for CDR, whether CDR credits, products, byproducts, or practices. These policies can be incentive-based, procurement-based, compliance-based, or otherwise stimulate demand.

Disadvantaged Communities (DACs): a community that falls into one of the three tiers using an annual affordability calculation. This calculation is performed to determine the adjusted per capita income (APCI) of each city and town in Massachusetts. Adjusted Per Capita Income (APCI) = PCI * Employment Rate * Population Change. Tier 1: Communities with APCI more than 80% but less than 100% of the state's APCI, Tier 2: Communities with APCI more than 60% but less than 80% of the state's APCI, Tier 3: Communities with APCI less than 60% of the state's APCI.[1460] This map shows the 2025 disadvantaged communities by tier.

Governance: In this Study, governance refers to any action Massachusetts takes to clarify the role CDR will have in climate or other priorities. Oftentimes, governance refers to Massachusetts clarifying goals and priorities related to CDR, including more tangible actions like establishing a governing body or defining CDR in statute.

Permitting and standards creation: Any action from the state that clarifies permitting or standards for CDR fits within the permitting and standards creation policy section. Permitting refers to the process developers, researchers, or others must follow, as outlined by a government, to be authorized to conduct an action (e.g., building a facility, conducting research that may impact the environment). Standards refer to the high-level principles that a project must follow related to quality, MRV, community engagement, environmental impacts, and more.

Supply policy: Any policy or program that stimulates supply of CDR, whether CDR credits, products, byproducts, or practices. These policies are largely focused on supporting innovation, R&D, and overcoming deployment barriers.

Workforce support: Any policy or program that helps develop or support a CDR-relevant workforce in Massachusetts, from early stage education to workforce development programs.

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