Carbon Containment Lab

Geologic Carbon Sequestration in the Pacific Northwest

A Primer on Siting, Economics, and Model State Legislation for In-Situ Carbon Dioxide Mineralization

August 31, 2026

Meghan E. Gavin, JD, and Michael Oristaglio, DPhil

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ABOUT

The Carbon Containment Lab is a public charity advancing research and education for a public benefit. The Carbon Containment Lab applies scientific, entrepreneurial, and investment expertise, creating an enabling environment for emergent climate solutions.

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This work builds upon the foundational contributions of those who supported, drafted, and passed legislation for geologic carbon sequestration in other parts of the country and those who identified the need to clarify the legal framework for geologic carbon sequestration in states with basalt formations, such as Washington, Oregon, and Idaho.

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DISCLAIMER

I. INTRODUCTION

Washington and Oregon have set ambitious commitments to reduce their greenhouse gas (GHG) emissions 95% and 75%, respectively, from 1990 levels by 2050. [1] To meet these statutory goals—to offset residual emissions and reach net zero—both states will need to capture, remove, and permanently store carbon pollution. Flood basalts of the Columbia River Basalt Group (CRBG)—a massive rock formation created by hundreds of lava flows in the Pacific Northwest between 16.7 and 5.5 million years ago—are a unique geologic asset that can enable the region to meet its ambitious climate goals through permanent geologic carbon sequestration (GCS).

Unlike in standard forms of geologic sequestration in which CO_2 injected into the pore space of depleted petroleum reservoirs or deep saline aquifers is expected to be trapped in place by impermeable rock (caprock) bounding the underground reservoir, CO_2 mixed with water in the pore space of basalt reacts with minerals in the rock matrix to precipitate solid carbonate minerals, such as calcium carbonate (calcite). This process of 'carbon mineralization' locks carbon into the rock matrix with effectively zero chance of leakage (or reversal).

Pioneering laboratory and field work culminating in a 2013 pilot project by Pacific Northwest National Laboratory (PNNL) led to an initial estimate that a region of the CRBG in south-central Washington, representing less than 10% of the total volcanic formation, could sequester 40 billion tons (gigatons, Gt) of CO_2.[2] Recent estimates put the total sequestration potential of the entire basin at 770 Gt, or about 150 times total yearly U.S. (energy-related) CO_2 emission and 20 times the world's annual emissions.[3] Under 45Q provisions of the federal tax code, which provide a credit of $85 per ton of CO_2 captured at point sources and sequestered geologically and $180 per ton of CO_2 removed from the air and sequestered geologically, the pore space of the CRBG is a staggeringly large economic asset.[4]

Yet widespread adoption of GCS in basalt has not taken place. Indeed, carbon capture and sequestration (CCS) remains an underused tool for effective climate action despite its technical readiness and the opportunities it offers states for economic benefit and energy security. Most activity has taken place in the Midwest and in petroleum producing states, like Texas and Louisiana, using aquifers and depleted petroleum reservoirs. Three primary obstacles

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[1] RCW 70A.45.020(1)(a)(iv), (c) (committing Washington to net zero by 2050 with a 95% reduction of GHG emissions from 1990 levels); ORS 468A.205(1)(c) (setting a minimum GHG emissions reduction goal of 75% below 1990 levels by 2050); Executive Order No. 20-04, Directing State Agencies to Take Actions to Reduce and Regulate Greenhouse Gas Emissions (March 2020) (calling for Oregon to reduce its GHG emissions to a target of at least 80% below 1990 levels by 2050).

[2] Ruoshi Cao et al., "Gigaton commercial-scale carbon storage and mineralization potential in stacked Columbia River basalt reservoirs," *Int. J. GHG Control* **137** (2024)**,** no. 104206 (2024), https://doi.org/10.1016/j.ijggc.2024.104206. Throughout, 'tons' are metric tons or 1000 kilograms (kg).

[3] Q.R.S. Miller et al., "Earth as a Reactor: Carbon Mineralization Geochemistry in the Context of Emerging Subsurface Energy and Resources Technologies," *Chemical Reviews* **126**, no. 10 (2026), 5713–5754, https://doi.org/10.1021/acs.chemrev.5c00716.

[4] California, Hawaii, and parts of Arizona and Minnesota also have abundant igneous rock types (mafic and ultramafic) with significant permanent GCS potential. Madalyn S. Blondes et al., "Carbon Dioxide Mineralization in the United States," U.S. Geological Survey Scientific Investigations Report 2018–5079 (2019), https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf.

have hindered progress on permanent GCS as a climate solution: (1) a lack of geophysical data to inform siting, (2) shifting economics, and (3) legislative and regulatory gaps.[5] The uncertainty caused by these obstacles raises a project developer's costs and its exposure to potential liability.

This white paper discusses the context for this inactivity and incentives for CCS and suggests a regulatory and policy framework that might help unblock permanent GCS in the Pacific Northwest. We start in the next section with a brief overview of the need for carbon capture, its economics, and a review of previous work on carbon mineralization in the CRBG, including a new project underway to map the formation under a large area of south-central Washington and northern Oregon using modern geophysical remote sensing. Subsequent sections discuss the regulatory readiness of the region for GCS and considerations needed for legislation to promote a regulatory environment conducive to its commercial development.

Two self-contained appendices are included for completeness:

- Appendix A provides a broad overview of CCS: its necessity for 21st century climate goals, its economics, its implementation in different geologic settings, and its implications for national security.
- Appendix B provides a model statute keyed to the discussion in the core of the paper.

II. DISCUSSION

A. The Need for Carbon Capture and its Economics

All plausible scenarios today for reducing GHG emissions to net zero during the 21st century require capture of carbon dioxide yearly in large quantities and its sequestration from the atmosphere for long periods of time—ideally thousands of years to mitigate long-term global warming.[6] It's helpful to focus on CO_2 in such long-run scenarios because CO_2 is the longest-lived atmospheric gas contributing to warming and the largest contributor to its radiative forcing today.[7] The most realistic (but still ambitious) scenarios see net global GHG emissions eventually declining to zero by 2075 under different 50-year trajectories.

Projecting the world 50 years into the future is (needless to say) loaded with uncertainty.[8] But the broad picture of the world in 2050 painted in these scenarios looks recognizable: CO_2 emissions have been reduced by 50%—through a combination of efficiency, growth of renewables, fuel substitution, and carbon capture—leaving 20 Gt of emissions in 'hard-to-abate' sectors of transportation (air travel, shipping) and in legacy fossil-fuel power (coal and natural

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[5] *See, e.g.*, Meghan E. Gavin et al., *TrapRock: Enabling Geologic Carbon Sequestration on Washington State's Trust Lands to Meet Its Climate and Clean Energy Commitments*, ed. Carbon Containment Lab (2025), available at https://carboncontainmentlab.org/publications/traprock-report-2025.

[6] Appendix A contains a summary. See, eg: *Net Zero Emissions by 2050 Scenario,* International Energy Agency, www.iea.org (accessed 1 August 2026), and *2026 Energy Security Scenarios*, Shell, www.shell.com (accessed 1 August 2026).

[7] See: V. Masson-Delmotte et al., *Climate Change 2021, The Physical Science Basis*, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC (2021).

[8] "It is difficult to make predictions, especially about the future." Danish proverb, often attributed to Niels Bohr. See: *The New Yale Book of Quotations*, Yale University Press, New Haven (2021).

gas). Capture from industrial point sources is expected to contribute an aggregate total of about 25 Gt of global CO_2 abatements by 2050, or 1 Gt per year. And the U.S.—the largest emitter of CO_2 in the 20th century and on track to be the third largest in the 21st, after China and India—is expected to contribute 10% of this total, 100 Mt per year.[9]

The tradable 45Q tax credit of $85 per ton for capture and geologic sequestration sets an economic framework for GCS in the U.S. Capture and GCS of 100 Mt per year in the U.S. thus translates to an economic incentive of $8.5 billion per year.[10] Large-scale capture (1 Mt per year) at fossil-fuel power plants using standard capture technology poses the largest challenge to CCS economics, with the cost of capture alone ranging from $50 to $100 per ton. The remaining steps—including processing, transportation, injection, and monitoring—vary from $8 to $25 a ton. At the low end of capture costs, CCS fits within 45Q economics; the high end breaks the bank. But capture at industrial processes such as ammonia or bioethanol production, with costs as low as $10 to $30 per ton, fits well within the 45Q framework. Premiums for carbon-dioxide abatement in voluntary carbon offset markets can be an alternative, with high-quality offsets trading as high as $400 per ton (mostly for direct air capture). Moreover, developments at new Chinese facilities may provide a cost breakthrough for large-scale capture at power plants. These topics are addressed in Appendix A, within a brief review of the overall global status of CCS.

B. Carbon Mineralization in the Columbia River Basalt Group of Washington, Oregon, and Idaho

Washington, Oregon, and southern Idaho have an opportunity to be part of a regional decarbonization solution using carbon capture or removal paired with permanent GCS in flow tops of the CRBG (Figure 1). Most basalts are not porous and permeable enough to support fluid injection and storage, but the episodic nature of flood-basalt flows in the Pacific Northwest—which erupted from fissures in the ground (not volcanoes) and flooded the landscape over large contiguous areas—exposed the flows to the atmosphere for long periods of time, generating porous, permeable crusts atop the (largely impermeable) flow interiors [11] Effective porosities in the vesicular or brecciated flow tops of the CRBG are as high as 30%.[12] The CRBG is the largest flood basalt province in North America and one of the largest in the world; similar but older flows occurred in India, called the Deccan Traps (dated to 65 million years ago), and in Russia, called the Siberian Traps (dated to 250 million years ago).

In 2013, as part of a pilot project funded by the U.S. Department of Energy, PNNL injected nearly 1000 tons of CO_2 compressed to a buoyant supercritical fluid into two flow tops

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[9] U.S. energy-related CO_2 emissions were about 4.9 Gt in 2025. U.S. emissions were in fact declining from a high of 6 Gt in 2005 along a roughly linear trajectory that would—if not interrupted but policy changes in 2016 and then by COVID—have reached zero just after 2075. See Appendix A.

[10] In constant 2027 dollars, once the 45Q credit is indexed to inflation starting in 2027 as legislated in the One Big Beautiful Bill (Public Law 119-21). See Appendix A.

[11] Stephen P. Reidel et al., "The Columbia River Basalt Group of Western Idaho and Eastern Washington—Dikes, Vents, Flows, and Tectonics Along the Eastern Margin of the Flood Basalt Province," Exploring the Geology of the Inland Northwest, Geological Society of America Field Guide 41, ed. R.S. Lewis and K.L. Schmidt (Boulder, CO: Geological Society of America, January 2016), 132, https://doi.org/10.1130/2016.0041(04).

[12] N.V. Zakharova et al., "Petrophysical and geochemical properties of Columbia River flood basalt: Implications for carbon sequestration," *Geochemistry Geophysics Geosystems* **13,** no. 11 (2012), Q1 1001.

of the Grande Ronde basalt at a depth of approximately 800 meters (2600 feet). The experimental well is located near the town of Wallula in eastern Washington, where the Columbia River bends sharply to the west towards the Pacific (Figure 1). The Grande Ronde, with a total thickness of over 3 kilometers (2 miles), is the most massive of the four main groups of flows making up the CRBG. Sidewall cores and other measurements collected two years after injection provided evidence that nearly 60% of the injected CO_2 had mineralized—turned into solid rock.[13] PNNL estimates that the nearby portion of the Columbia River Basin, underlain by less than 10% of the CRBG, could permanently sequester over 40 Gt of CO_2.[14]

In the dozen-plus years since the Wallula pilot, no further GCS projects have taken place in the CRBG—or, for that matter, in a basalt formation in any state. (The company Carbfix has, however, undertaken extensive GCS projects in the mid-ocean ridge basalts of Iceland, using a different mineralization process in which a CO_2/water mixture is injected into the basalt layers.[15]) One possible uncertainty limiting further development in the Pacific Northwest has been lack of detailed underground spatial mapping to confirm the 40 Gt estimate by PNNL, which used information from surface outcrops and data from three deep wells in the region.[16]

Starting in 2024, a team of public and private researchers (including the authors), led by the Carbon Containment Lab, has been working to develop more detailed underground maps in a project partly supported by the Washington Department of Commerce under the state's Climate Commitment Act.[17] Airborne electromagnetic (EM) surveys, which are sensitive mainly to fluids in the pore space of rocks and soils, mapped the CRBG down to a depth of about 600 meters (2000 feet) underneath nearly 1800 square kilometers (over 400,000 acres) in Benton, Klickitat, and Yakima counties of Washington and Morrow county of northern Oregon (Figure 1). The new surveys yielded continuous maps of the shallow basin hydrogeology in this region, which has many fewer water wells than other parts of these states. A modern ground-based 3D seismic survey, covering a smaller 5 by 5 km patch of land (about 6250 acres), created a detailed image of geologic structures down to depths of 10 km (33,000 feet). The project is scheduled to finish in September 2026, with results made public by year end.[18]

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[13] Signe K. White et al., "Quantification of CO_2 Mineralization at the Wallula Basalt Pilot Project," *Environmental Science & Technology* **54**, no. 22 (2020), 14609–16, https://doi.org/10.1021/acs.est.0c05142.

[14] Ruoshi Cao et al.; see also A.R. Crimmins et al., *Fifth National Climate Assessment* (2023), 32-24, https://repository.library.noaa.gov/view/noaa/61592/noaa_61592_DS1.pdf?download-document-submit=Download.

[15] Carbfix found that more than 95% of CO_2 injected into oceanic basalt formations mineralized within two years. Juerg M. Matter et al., "Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions," *Science* **352**, no. 6291 (2016): 1312–4, https://doi.org/10.1126/science.aad8132.

[16] Ruoshi Cao et al.

[17] Project TrapRock: Washington TrapRock Geophysical Research Surveys, www.watraprocksurveys.org/ (visited August 1, 2026).

[18] The goal of the research is to produce what the reservoir modeling industry calls a 'digital twin' of the CRBG—a representation of the subsurface in a computer model detailed and accurate enough to realistically simulate what would happen if a well were drilled in the region and fluids were produced from or injected in the rock's pore space. A webinar on the project's results, including a visualization of the digital twin, can be found on the project website.

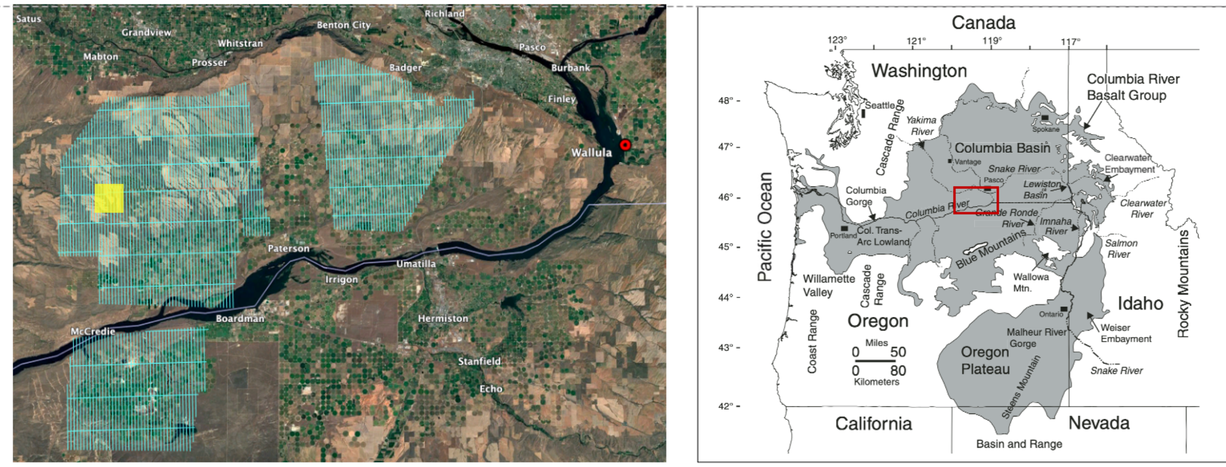

FIG 1 | (LEFT) Survey area in south-central Washington and northern Oregon. Flight lines of the airborne electromagnetic (airborne EM) survey are highlighted in green. The seismic survey covered the area highlighted by the yellow rectangle. The experimental well for the PNNL pilot project is north of the city of Wallula. (Google Earth) (RIGHT) Map of the Columbia River Basalt Group (CRBG). From Reidel et al., 2016.

Preliminary results of the project are consistent with the initial storage estimate by PNNL. The study also helps to identify preferred sites for future demonstration projects, as well as locations to avoid. More underground mapping, especially by low-cost airborne methods,[19] can help to de-risk decisions about permanent GCS throughout the entire Pacific Northwest.

C. Lack of Regulatory Readiness for GCS in the Pacific Northwest

Washington, Oregon, and Idaho, as the states overlying the CRBG, can attract carbon capture and removal technologists and GCS project developers for pilot- and, later, commercial-scale projects by closing legislative and regulatory gaps that discourage field-based progress. Particularly, these states should consider adopting a policy of making state land and state-owned pore space available for GCS and passing legislation clarifying the applicable legal framework for sequestration in basalt formations. (Appendix B contains such a model statute to encourage dialogue and policy action.)

A recent paper, "Is your state regulation ready? A review of geologic carbon sequestration regulations in the United States," looks at each state's regulatory readiness for GCS.[20] The authors considered fourteen regulatory factors, chosen for their relevance to approving and deploying safe projects.[21] For each, they generated a weighted average by

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[19] Total costs for the two airborne surveys were about $600k.

[20] William Gallin et al., "Is your state regulation ready? a review of geologic carbon sequestration regulations in the United States," Carbon Management **17**(1) (March 2026), https://doi.org/10.1080/17583004.2026.2645787; *see also* GSI Environmental, Regulation Ready, https://gsi-environmental.shinyapps.io/regulation-ready/ (accessed May 8, 2026).

[21] *Id.*

assigning a "readiness" value (1–5) and a weight for significance (1–3).[22] Table 1 summarizes the results.

Unsurprisingly, Washington, Oregon, and Idaho, as states with minimal oil and gas production and no active geologic sequestration projects, rank quite low, scoring in the bottom half of all states.[23] Washington's "RegReady" value is 0.85 out of 5, Oregon's is 1.04, and Idaho's is 0.67.[24] These states can improve their regulatory readiness by filling select gaps, as suggested below.

	STATE READINESS			
FACTOR	**WA**	**OR**	**ID**	**Weight**
Primacy over Underground Injection Control Class VI wells	0	2	0	3
Clarity about pore space ownership	0	0	0	3
Allowance for pore space unitization	0	0	0	3
Clarity about short- and long-term storage liability	0	0	0	3
Clarity about ownership of injected CO_2	0	0	0	2
Primacy over Underground Injection Control Class I wells	0	0	2	2
Primacy over Underground Injection Control Class II wells	2	2	0	2
Designation of pipeline safety administrative agency	5	2	2	2
Availability of eminent domain over pipelines	3	5	5	2
Availability of state lands for GCS	0	0	0	1
Clarity about subsurface encroachment	0	0	0	1
Designation of an agency reporting injection volumes	0	2	2	1
Environmental justice criteria	3	2	0	1
Status of Underground Injection Control Class VI permit applications	0	0	0	1

Table 1 | 14 regulatory factors considered by the authors of "Is your state regulation ready? A review of geologic carbon sequestration regulations in the United States."

[22] *Id.*
[23] *Id.*
[24] *Id.*

D. Overview of Model Legislation

The model legislation in Appendix B was composed after referencing: the statutes of states with comprehensive GCS legislation (Nebraska[25], Utah[26], Alabama[27], and Pennsylvania[28]); the statues of Alaska[29] and West Virginia,[30] both of which explicitly allow state-owned pore space to be leased for GCS; and comprehensive model legislation published by the Interstate Oil & Gas Compact Commission titled, "Model Statute and Guidance on Geologic Sequestration of Carbon Dioxide: A Guide for States,"[31] and by the Sabin Center for Climate Change Law, titled "Legal Pathways for Deep Decarbonization Model Law: State Legislation for the Geologic Storage of Carbon Dioxide."[32]

This model state legislation is intended to be concise, respectful of Tribal Treaty and other reserved rights, suitable for sequestration in basalt coinciding with future subsurface opportunities like critical minerals recovery and hydrogen production, and noncontroversial for ease of passage. This model legislation fills select statutory gaps around subsurface rights and liabilities so that GCS projects have a pathway to develop in non-oil and gas states lacking this foundational legal framework. It addresses the factors of highest significance identified by "Is your state regulation ready?" (specifically, a mandate to pursue UIC Class VI primacy, pore space ownership, pore space unitization, and storage liability); ownership of stored CO_2 because that factor is closely intertwined with storage liability; and the availability of state lands for GCS because making these lands available for lease would accelerate the time for GCS to scale. This model legislation also includes provisions on penalties and establishment of a fund to support state stewardship activities and encourages inter-state cooperation.

i. Mandate to Pursue Underground Injection Control Class VI Primacy (Model Legislation Section 3)

The Environmental Protection Agency regulates GCS under the Safe Drinking Water Act, which protects underground sources of drinking water and establishes the regulatory requirements of the Underground Injection Control (UIC) program.[33] The program is divided into six well classes.[34] Class VI wells are used for long-term GCS and are not experimental in nature.[35] States with delegated authority (primacy) over UIC Class VI wells include Arizona,

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[25] Laws 2021, LB 650, § 1 (Neb.), effective Aug. 28, 2021, Nebraska Geologic Storage of Carbon Dioxide Act.

[26] H.B. 244, Geological Carbon Sequestration Amendments, 2022 Gen. Sess. (Utah 2022) (enrolled).

[27] H.B. 327, 2024 Leg., Reg. Sess. (Ala. 2024) (enrolled).

[28] S.B. 831, Carbon Capture and Sequestration Act, 2023 Gen. Assemb., Reg. Sess. (Pa. 2024).

[29] H.B. 50, Carbon Capture, Utilization, 5 and Storage Act, 33d Leg., 1st Sess. (Alaska 2024) (enrolled).

[30] S.B. 162, 2023 Leg., Reg. Sess. (W. Va. 2023) (enrolled).

[31] Interstate Oil & Gas Compact commission, Model Statute and Guidance on Geologic Sequestration of Carbon Dioxide: A Guide for States (September 2025), available at https://oklahoma.gov/content/dam/ok/en/iogcc/documents/committees-councils/legal/CCUSModelStatute09.24.25.pdf.

[32] Sabin Center for Climate Change Law, Model Climate Laws Initiative, *LPDD Model Law: State Legislation for the Geologic Storage of Carbon Dioxide*, https://modelclimatelaws.org/model-laws/ (last visited May 20, 2026).

[33] 42 U.S.C. § 300f *et seq.* (1974).

[34] 40 C.F.R. § 146.5(b).

[35] *Id.* §§ 146.5(f), 146.81(b).

Louisiana, North Dakota, Texas, West Virginia, and Wyoming. Alabama, Colorado, Mississippi, Nebraska, Oklahoma, and Utah are actively pursuing it.[36] Historically, primacy shortens permitting processing timelines, making a state more attractive to a project developer. Washington, Oregon, and Idaho should consider passing legislation instructing their relevant state agency to pursue primacy. This model legislation instructs the relevant agency—as determined by the state[37]—to apply for UIC Class VI primacy, as well as allocates funding for the agency to do so.

ii. Pore Space Ownership (Model Legislation Section 5)

The pore space into which CO_2 is injected and trapped/mineralizes is private property. A landowner owns all property below them, except when an estate is severed into surface and mineral estates.[38] The vast majority of states have determined that the surface estate, not the mineral estate, owns the pore space, unless there is express language to the contrary in a conveyance or reservation of property.[39] Washington, Oregon, and Idaho are all silent on this question, which causes uncertainty for project developers needing to procure property rights over their sequestration facility so that they do not infringe on the rights of others. Clarity would reduce legal risk. This model legislation follows the American rule, assigning ownership of the pore space to the surface owner, unless the ownership interest in the pore space has been severed and reserved or conveyed.

iii. Pore Space Unitization (Model Legislation Section 8)

Securing a contiguous block of pore space rights can be onerous, particularly when the injection and monitoring zone extend laterally below numerous separately owned surface estates and involve split estates. Pore space unitization laws lower this obstacle for project developers by authorizing or compelling separately owned adjoined parcels to consolidate for development of the subsurface as a single storage unit—as is common in geothermal and oil and gas development. This model legislation proposes that, if negotiations are unsuccessful, a storage operator may apply to the appropriate agency or hearings board for a unitization order provided that the storage operator has obtained the consent of at least 60% of the relevant pore space owners. Some states utilize a higher threshold.

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[36] U.S. Energy Association, U.S. Class VI Permitting and State Primacy (September 2025), 1, https://usea.org/sites/default/files/US%20Class%20VI%20Permitting%20and%20State%20Primacy.pdf; U.S. Environmental Protection Agency, "Underground Injection Control Grants," https://www.epa.gov/uic/underground-injection-control-grants (last modified July 31, 2025).

[37] While this model state legislation can hopefully jumpstart conversations necessary for a robust democratic process, this legislation is not intended to be a substitute for it. The phrase "State Land Manager/State Geologic Agency/State Environmental Regulatory Agency" is used here and throughout the model legislation as a placeholder, as the decision of which agency should have jurisdiction and responsibility over which aspects of a new GCS program belongs with each state government.

[38] Hannah Wiseman, *Defining Pore Space Ownership and Related Issues: A Summary*, 1–2, https://celp.psu.edu/wp-content/uploads/2022/12/Definition-of-pore-space-and-related-issues_Summary-for-posting.pdf.

[39] *Id.*

iv. Ownership of Storage Carbon Dioxide and Storage Liability (Model Legislation Section 9)

After monitoring a sequestration site for 50 years following the cessation of injection, or an approved alternative duration, a project developer may pursue regulatory closure.[40] They must plug the injection and monitoring wells.[41] Such a long monitoring period may be unnecessary in ultramafic and mafic formations like basalt, where PNNL and Carbfix have shown that most of the injected CO_2 will mineralize into solid rock in less than two years. Additionally, the oil and gas industry has seen long monitoring periods lead to the unfortunate consequence of developers abandoning their site before well plugging. Several states with GCS laws have sought to avoid this situation by transferring long-term liability for the storage of CO_2 to the state. Doing so enables the project developer to finance and build additional GCS projects and reassures the public that the site is indeed being monitored. This model legislation adopts that approach, authorizing a project developer to apply to the appropriate agency to accept title to the stored CO_2 at such time as the state may establish. The state may condition its acceptance of title on the requirement that title to all equipment, installations, and buildings of the sequestration facility necessary for long-term monitoring will concurrently transfer to it. Upon acceptance of title, liability also transfers to the state, though under no circumstances may a storage operator or owner's criminal and contractual liability transfer to the state. This model legislation also establishes a fund paid into by project developers to compensate the state for any long-term monitoring and management of sequestration facilities that it agrees to.

vi. Availability of State Lands (Model Legislation Sections 6 and 7)

Some states, like Alaska and Alabama, have passed legislation making state lands available for GCS.[42] Texas has similarly announced its desire to lease state lands.[43] Leasing state land for GCS would ensure that the benefits of this solution flow to the state, including trust beneficiaries in Washington, Oregon, and Idaho, and would ensure development occurs responsibly and respectfully, in consultation with local federally recognized Indian Tribes. This model legislation makes public lands and state-owned pore space available for GCS. It also creates a licensing program whereby a project developer may apply for the exclusive right to investigate the suitability of state-owned pore space for GCS with an option to convert the license into a long-term lease.

If Washington, Oregon, and Idaho pass legislation like that in Appendix B, their "RegReady" values would rise to 3.4, 3.37, and 3.22, respectively, placing them in and just outside the top quartile of all states. Passage would increase their attractiveness to this new economic sector while vastly improving their likelihood of timely achieving their climate

[40] 40 C.F.R. § 146.93.

[41] Id.

[42] AK HB 50 (2024); AL HB 327 (2024), Ala. Code § 9-17-165.

[43] Texas General Land Office, "Texas Land Commissioner Buckingham Secures Largest Carbon Sequestration Lease in the United States," effective October 4, 3024, https://www.glo.texas.gov/about-glo/press-releases/texas-land-commissioner-buckingham-secures-largest-carbon-sequestration.

commitments. Pursuit of delegated authority and establishment of a comprehensive program regulating the deployment of GCS projects should follow.

III. CONCLUSION

All plausible scenarios today for reducing GHG emissions to net zero during the 21st century require capture of carbon dioxide yearly in large quantities and its sequestration from the atmosphere for long periods of time—ideally thousands of years to mitigate long-term global warming.[44] The Pacific Northwest has a unique opportunity to contribute to this needed abatement through permanent GCS in the CRBG, a massive volcanic (igneous) formation underlying most of Washington and parts of Oregon and Idaho.

Sequestration of CO_2 in depleted petroleum reservoirs and saline aquifers, the hosts of most GCS today, requires impermeable caprock bounding the underground reservoirs in three dimensions, to ensure that buoyant supercritical CO_2 does not leak to the surface over the thousands of years of storage needed for effective climate action. Flood-basalt reservoirs, by contrast, provide natural impermeable seals (massive flow interiors) and the potential for truly permanent GCS by turning CO_2 injected into the permeable tops of basalt layers into solid rock, effectively eliminating the likelihood of leakage.

The technology of capturing carbon dioxide from the waste streams of natural-gas power plants and other industrial processes is well understood and already economic, under 45Q provisions of the federal tax code, for industrial processes such as ammonia or bioethanol production, even including the costs of transportation, storage, and monitoring.[45] Further cost reductions in large-scale capture technology from combustion flue streams are needed to make full CCS economic at many power plants. But steady cost reductions are expected as demand for CO_2 increases—for its use in enhanced oil and gas recovery and as a feedstock for novel materials—and as China advances plans to decarbonize its vast coal industry under its new Five-Year Plan (2026–2030).[46] Finally, the possibility of extracting critical minerals from basalt by using engineered injection fluids as the carrier of CO_2 for its underground mineralization may completely change the economics and narrative of carbon sequestration in basalt.[47]

Permanent GCS in the Pacific Northwest is a climate, economic, and national energy security challenge and opportunity for the region. Momentum can build to encourage demonstration projects leading to commercial development of the region's unique pore space as a multi-generational resource—through more extensive spatial mapping with geophysical remote sensing to de-risk siting decisions and, most important, through adoption of a regulatory framework putting more decision-making control of the resource into state hands.

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[44] Appendix A contains a summary. See, eg: *Net Zero Emissions by 2050 Scenario,* International Energy Agency, www.iea.org (accessed 1 August 2026), and 2026 Energy Security Scenarios, Shell, www.shell.com (accessed 1 August 2026).

[45] *Id.*

[46] *Id.*

[47] Q.R.S. Miller et al. See also Appendix B.

APPENDIX A: Status of Carbon Capture and Sequestration

All plausible scenarios today for reducing greenhouse-gas emissions to net zero during the 21st century require capture of carbon dioxide yearly in large quantities and its sequestration from the atmosphere for long periods of time—ideally thousands of years if the goal is to mitigate long-term global warming.[48] Examples from three very different groups include:

- The *Net Zero Emissions by 2050 Scenario* published in 2025 by the International Energy Agency (IEA), an NGO;
- The *Carbon Capture, Transport, and Storage: Supply Chain Deep Dive Assessment* published in 2022 by the U.S. Department of Energy (DOE), a government agency;
- Three *2026 Energy Security Scenarios* published in the spring of 2026 by Shell, a publicly traded energy company; the scenarios model net zero by 2050 (Horizon) and 2080 (Surge) and a business-as-usual scenario (Archipelagos), which drags well into the 2100s.

Scenarios for reaching net zero by 2050 are designed to stabilize Earth's climate within 1.5 to 2.0°C of warming above pre-industrial levels during the 21st century, under the now widely accepted concept of a 'carbon (dioxide) budget' for the atmosphere. This budget, which varies with the warming target and with uncertainties in the predictions of climate models, is of course not a precise figure; a workable estimate is about 500 billion tons (gigatons, Gt) of CO_2 as of 2025. For simplicity, we will refer to this target as simply '2°C.'[49]

The many steps in capturing carbon dioxide (CO_2)—then processing, transporting, storing the gas (in some form outside the atmosphere), and monitoring its storage over time—are traditionally called just CCS, for Carbon Capture and Sequestration[50] or CCUS, with U for Utilization. The terminology can be confusing because it's gaseous CO_2 that traps heat in the atmosphere, not solid carbon (C), and the mass quantities described in nearly all discussions of CCS (as here) are masses of molecular CO_2.[51] Although true net-zero scenarios must deal with all greenhouse gases, this white paper focuses on carbon dioxide, the most important long-lived greenhouse gas causing long-term warming, and its sequestration in geologic formations easily accessible on land.

Figure 1 illustrates the size of the global CCS challenge. The graph on the left, Net Zero 2050, shows an idealized scenario in which global emissions of carbon dioxide, estimated at

[48] 'Net Zero' (as often capitalized) refers to a balance between anthropogenic emissions of greenhouse gases to the atmosphere and their removal by natural and artificial means, averaged over a suitable period of time—say, 2 to 5 years—to smooth fluctuations. True net zero involves tracking all greenhouse gases, which is usually done by balancing their emissions and removals weighted by appropriate 'carbon-dioxide equivalent' warming potentials.

[49] All 'tons' are metric tons or 1000 kilograms (kg). The concept of an atmospheric carbon (dioxide) budget for warming less than 2°C, independent of a specific emissions trajectory, was first elaborated using modern global climate models in a paper by Myles Allen and his colleagues at Oxford University: M.R. Allen et al, 2009, Warming caused by cumulative carbon emissions towards the trillionth tonne, *Nature* **458**, 1163–1166. A budget of 500 Gt of CO_2 at the end of 2025 is within the range of recent estimates. See: V.P Masson-Delmotte et al., *Climate Change 2021, The Physical Science Basis*, IPCC (2021).

[50] Or Carbon Capture and Storage; the terms are used interchangeably.

[51] The molecule CO_2 has a molar mass of 44 grams; pure carbon (C) has a molar mass of 12 grams. The ratio of the molar masses is thus 44/12, or 3.75: i.e., 3.75 tons of CO_2 contain 1 ton of carbon and 2.75 tons of oxygen.

about 40 Gt in 2025, are reduced to zero by 2050 along a linear trajectory. Aggregate CO_2 emissions abated along this 25-year trajectory total 500 Gt, half the area of the rectangle in the graph. The other half goes into the atmosphere, filling the atmospheric budget for 2°C.

Most reasonable analyses of just about any such net-zero scenario conclude that CCS has to contribute at least 10% to the total reduction. (Other possible contributions are shown on the graph.) Thus, Net Zero 2050 in Figure 1 implies that 50 Gt of global CO_2 emissions (10% of 500) are captured and stored in aggregate from 2025 to 2050, or about 2 Gt per year on average. Today, only about 50 million tons (Mt) of CO_2 are captured and sequestered yearly; so, reaching 50 Gt in aggregate by 2050 implies that cumulative quantities would have to increase by a factor of 1000 over 25 years—or double about every 2.5 years—a prodigious but not inconceivable rate of growth (about 32% per year).

The right graph of Figure 1 shows a more realistic scenario, Net Zero 2075, in which net emissions are reduced to zero along a linear trajectory of 50 years. This scenario has 20 Gt of emissions occurring in 2050, mostly in 'hard-to-abate' sectors of transportation (air travel and shipping) and power (legacy coal and natural gas). It's more realistic given the announced net-zero targets of China (2060) and India (2070), the countries on track to be the world's largest emitters in the 21st century. Such publicly announced goals are usually optimistic. Moreover, in 2015 energy-related CO_2 emissions in the U.S., the largest emitter of the 20th century, were on a linear track to reach net zero between 2075 and 2080. (The trend was disrupted by policy changes in 2016 and by the COVID economic see-saw; see the graph in footnote 6. U.S. emissions have since stalled around 4.9 Gt and in fact increased by 115 Mt in 2025.)

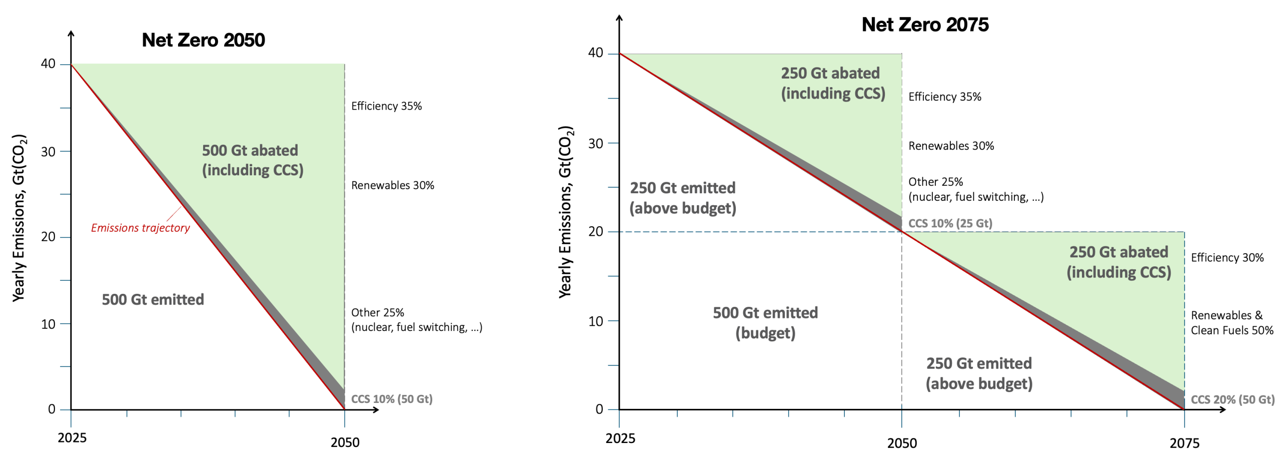


FIG A1 | Net Zero Scenarios. (Left) In Net Zero 2050, net CO_2 emissions starting at 40 Gt in 2025 are reduced to zero by 2050 along a linear trajectory. 500 Gt of CO_2 are emitted to the atmosphere (the atmospheric 'carbon budget'); 50 Gt are abated. Any practical analysis of this ambitious scenario sees CCS taking up (at least) 10% of this reduction (gray triangle); most of the reduction comes from aggressive efficiency efforts, a rapid transition to renewables, and other initiatives such as growth in nuclear energy and fuel switching (e.g., coal to natural gas, diesel to synthetic fuels). (RIGHT) In Net Zero 2075, a linear trajectory to net zero emissions requires 50 years, leaving 20 Gt of hard-to-abate emissions in 2050. A practical analysis of this scenario sees CCS taking up a larger portion (say, 20%) of the reduction to net zero from 2050 and 2075. In this scenario, 1000 Gt of CO_2 are emitted to the atmosphere.

Three things happen in Net Zero 2075:

(1) Aggregate CCS needed from 2025 to 2050 is reduced to 25 Gt, or 1 Gt per year on average.
(2) CCS (by most analyses) has to take up a larger percentage (20% in Figure 1) of remaining reductions from 2050 to 2075, with a total of 50 Gt captured, or 2 Gt a year on average.
(3) Most important, 500 Gt of CO_2 is emitted into the atmosphere beyond its budget for 2°C.

If the climate models are correct—and if 2°C is the right target—the additional 500 Gt of atmospheric burden in Net Zero 2075 will have to be removed (captured) from the atmosphere and sequestered for thousands of years to re-stabilize climate at its pre-industrial equilibrium.

The bottom line of the CCS climate challenge is thus:

Start capturing CO_2 now where it's being emitted in large quantities.
Or: Capture CO_2 later from the atmosphere in very large quantities (a much harder task).

Both will likely be needed. But the costly burden of atmospheric capture—which is several times more expensive than point-source capture with today's technologies—can be reduced significantly by a growing CCS industry in the 21st century. This is the main conclusion of most realistic scenarios for the energy transition.

Economics of CCS

The logistical challenge of CCS comes with a large economic opportunity—and challenge. To be specific with amounts, it's helpful to focus on the U.S. because, today, the closest thing to a single value for CO_2 abatement is the credit under Section 45Q of the U.S. tax code: 45Q provides an $85 per ton federal tax credit for "point source carbon dioxide capture and geologic storage" and a $180 per ton credit for "direct air capture and geologic storage." The credit is tradable and is intended in the current law to be indexed to inflation starting from 2027.[52]

Adapting the scenarios in Figure 1 to the U.S. essentially means dividing all quantities by a factor of 10, the approximate ratio in 2025 of annual global CO_2 emissions (40 Gt) to U.S. emissions (4.9 Gt).[53] Thus, under Net Zero 2050 (and the assumptions above), the U.S. would

[52] The credit was implemented in the Bipartisan Budget Act of 2018, updated in the Inflation Reduction Act of 2022 and again in the One Big Beautiful Bill Act of 2025. Performance based and at a set price, the credit is a genuine premium for emissions mitigation, unlike emissions trading systems (ETSs), which are in effect allowances to emit fixed amounts of CO_2 at a traded market price under a regional cap on emissions. An ETS is also called 'cap and trade.' ETS prices vary widely. Allowances under the European Union ETS have been trading recently at about €80 per ton (about 90 USD); allowances in the Chinese ETS, the world's largest, have been trading at about 100 RMB per ton (about 15 USD). Some carbon offsets traded on voluntary markets come close to pricing a premium to abate, but carbon offset prices vary even more widely, from $5 to over $400 per ton of CO_2 (or CO_2-equivalent), depending on the type of offset, its quality and (often most important) the buyer.

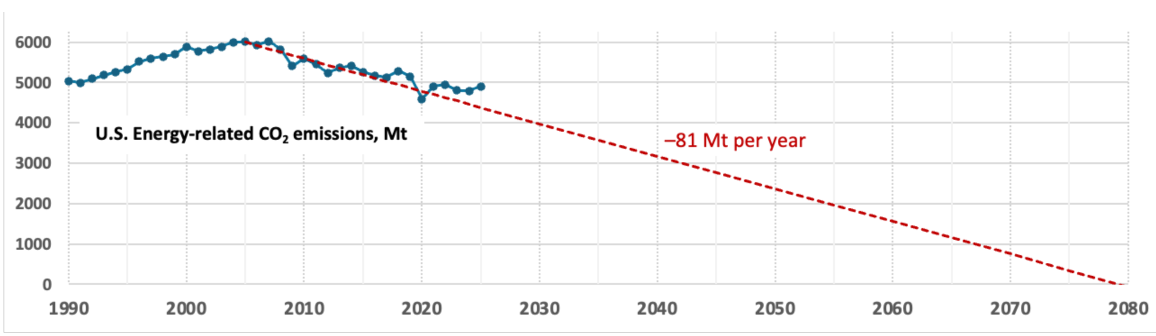
[53] A factor of 8.2 is accurate. U.S. energy-related emissions were declining from a peak of 6 Gt in 2005 along a roughly linear trajectory (below) that would have reached nearly 4 Gt by 2025 if not interrupted by changes in policy after 2016 and the COVID see-saw. Extrapolating the trend beyond 2015 leads to zero U.S. (energy-related) emissions between 1975 and 2080. But the reductions from 2005 to 2015 came mostly from fuel replacement, with natural gas replacing coal in power generation, which stops when coal is eliminated from the power sector (not yet).

capture and sequester a total of 5 Gt of CO_2 by 2050. Ignoring inflation, 45Q would thus deliver $425 billion in value over 25 years, or $17 billion a year. This value falls to $8.5 billion per year from 2025 to 2050 under Net Zero 2075. By any metric, either figure presents a significant financial incentive over the next 25 years for legislatures to adopt policies encouraging capture and sequestration from point sources of CO_2 emissions in their states. (Projecting incentives and policies beyond 25 years is its own challenge.)

The economic difficulty of course is fitting all of CCS within a fixed budget. For geologic sequestration, the steps include: capture; processing; transportation (as a gas in pipelines or in vehicles after compression to a supercritical fluid); wellsite handling (including possible compression after transportation as a gas); injection; and monitoring in place.

Figure 2 illustrates the economic challenge in power generation, the largest-emitting industrial sector where point-source capture is feasible at large scale (Mt per year). IEA estimates that the levelized cost of CO_2 capture from a fossil-fuel power plant, using standard amine-capture technology, ranges from $50 to $100 per ton of CO_2, depending mostly on its concentration in the flue stream.[54] The cost of all the other steps ('the rest') is typically a fraction of the capture cost; in integrated assessment modeling, these costs are often set at a total of about $10 per ton. A recent comprehensive review estimates a range from about $8 to $25 per ton, depending on distance, scale (Mt per annum), quality of the geologic reservoir, and difficulty of monitoring.[55] In Figure 2, this range has been added to the capture costs to give a range of costs for full CCS, as described in the caption.

Transportation is the worst sector for U.S. emissions at 1.9 Gt (38%), followed by power generation at 1.5 Gt (31%). See: U.S. Energy-Related Carbon Dioxide Emissions, 2025, U.S. Energy Information Administration, July 2026.



[54] Capture-cost data available at www.iea.org (visited 1 August 2026). The standard technology for capturing carbon dioxide from a stream of waste gases is by bubbling the stream through amine solutions which bind preferentially to CO_2, then release the gas when heated (the main energy input). The technology has been used for decades. For a recent review, see: Bryce Dutcher et al., 2015, "Amine-Based CO_2 Capture Technology Development from the Beginning of 2013—A Review," *ACS Appl. Mater. Interfaces* **7,** no. 4, (2015), 2137–48.

[55] F. Smith et al., "The cost of CO_2 transport and storage in global integrated assessment modeling," *Int. J. GHG Control* **109** (2021), 10367, https://doi.org/10.1016/j.ijggc.2021.103367

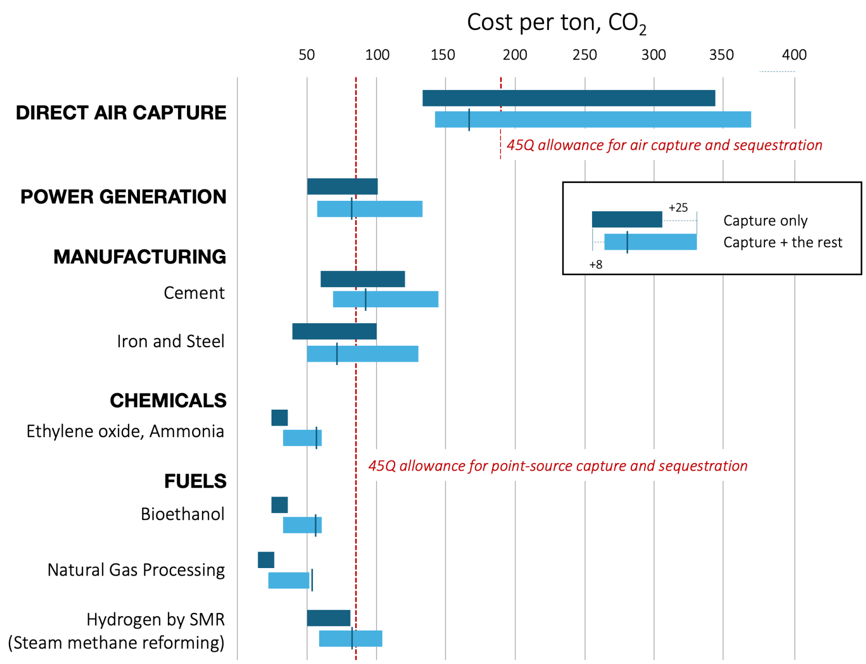


FIG A2 | Cost of CCS. Dark blue bars show estimated cost ranges of CO_2 capture from industrial processes and for direct air capture. Light blue bars show the total cost of CCS—including processing, transportation, wellsite handling, injection, and monitoring ('the rest')—obtained by (1) adding the low estimate for these tasks to the lower end of the capture cost and (2) adding the high estimate to the upper end of capture cost. The bar on the total cost shows the lowest cost of full CCS if the high cost for 'the rest' is added to the lowest capture cost.

At the low end of costs in Figure 2, $50 per ton for capture and $8 per ton for the rest, CCS from power plants is well within the 45Q allowance. At the high end, $100 for capture and $25 for the rest, CCS from power plants breaks the bank. As a result, CO_2 captured at power plants has mostly been targeted for enhanced oil and gas recovery, with its additional economic return.[56] But even with the higher range of costs for the entire CCS process, capture from industrial processes such as bioethanol or ammonia production and natural gas processing is economic by a wide margin. Most 45Q activity to date has focused on this low-hanging fruit. Recent developments in China may reset the bar for power plants.

Geologic Carbon Sequestration

Four settings have been tested in the field for geologic sequestration of CO_2 on land:

(1) Geologic traps of (depleted) petroleum reservoirs, usually for enhanced oil recovery (EOR);
(2) Saline aquifers;

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[56] See the next section. We will return to this point later in discussing recent research in the most secure form of sequestration, carbon mineralization in basalts. Using CO_2 for EOR qualifies as climate mitigation by reducing the (nominal) carbon intensity of crude oil: Under good conditions, 1 ton of injected (and sequestered) CO_2 generates up to 3 barrels of crude oil (about 0.4 tons), which produce about 1.2 tons of CO_2 when burned. The reduction is thus 80% (1/1.2). The situation is much better with EGR in which up to 30 tons of CO_2 is injected to produce 1 additional ton of natural gas (methane, CH_4), which produces 2.78 tons of CO_2 when burned: Thus, the nominal carbon intensity of EGR is negative. Neither calculation includes the carbon footprint of energy to run the process.

(3) Fractured shale-gas reservoirs, for enhanced gas recovery (EGR);
(4) Flow tops of certain volcanic (basalt) formations.

The first two settings account for nearly all CCS done today. In the standard process, gaseous CO_2 is compressed at the surface to a supercritical fluid then injected into the reservoir rock's pore space at temperatures and pressures (effectively, depths) suitable for maintaining the liquid-like state.[57]

Supercritical CO_2 is buoyant in groundwater, so its confinement and sequestration requires long-term impermeable seals (caprock) bounding the reservoir in three dimensions—the definition of a geologic trap. The Sleipner site in the North Sea has demonstrated that millions of tons of CO_2 can be injected over decades and monitored with geophysical remote sensing. The project, which started in 1996, has injected about 1 Mt per year into a saline aquifer overlying the Sleipner natural gas field, which produces CO_2-rich gas that is separated at the surface into methane (CH_4) and CO_2.[58] Another long-running project using a deep aquifer is the ADM site near Decatur (Illinois), which since 2014 has stored approximately 4.5 Mt of CO_2 in the Mount Simon sandstone, a porous saline aquifer about 5000 feet (1500 meters) below the surface. The CO_2 is captured from corn milling and bioethanol production.[59]

Several mechanisms for trapping CO_2 in unconventional shale-gas reservoirs (setting 3) have been proposed and studied. The most likely is preferential adsorption of CO_2 (compared with methane) onto the rock matrix of organic-rich shale formations called 'black shales.' In this process, CO_2 is injected as a supercritical fluid into the horizontal sections of shale-gas wells, where it flows along artificial and natural fractures opened up by the fracking process and displaces methane adsorbed onto the rock matrix.[60] The displaced methane flows back through the fractures and well to the surface, giving enhanced gas recovery (EGR) between 7 to 20%. EGR is a growing practice in the Marcellus and Utica shales of Pennsylvania and Ohio.

Sequestration in basalt formations (setting 4)—a focus of the model legislation discussed in this white paper—has been tested at small scale with injection of supercritical CO_2 into the flood basalts of the Columbia River Basin and at a larger scale with injection of a CO_2/water mixture into the mid-ocean ridge basalts of Iceland. In either process, CO_2 in water present in the

[57] If CO_2 is injected as a gas at depth, it quickly reaches the supercritical state at the typical pressures and depths of depleted oil and gas fields or deep saline aquifers. The critical point of CO_2 is 32.1°C and 7.4 MPa (about 1100 psi) which is reached at depths just below 1000 meters (3300 feet), in an average geothermal gradient (25°C per 1000 meters) and the hydrostatic pore-pressure profile of most water-saturated rocks.

[58] Anne-Kari Furre et al., "20 years of monitoring CO_2-injection at Sleipner," *Energy Procedia* **114** (2017), 3916–3926.

[59] Sui Gollakota et al., "Commercial-Scale CCS Project in Decatur, Illinois – Construction Status and Operational Plans for Demonstration, *Energy Procedia* **63** (2014), 5986–93. See also: "ADM Monitoring Well Developments, Summary and Timeline," ADM Fact Sheet available at www.adm.com (visited 1 August 2026).

[60] *Adsorption* refers to a process in which molecules of a substance adhere to the surface of the *adsorbent*, as opposed to being *absorbed* into the interior volume of the *absorbent* (watch your d's and b's!). See: Michael Godec et al., "Potential for enhanced gas recovery and CO_2 storage in the Marcellus Shale in Eastern United States," *Int. J. Coal Geology* **118** (2013), 95 –104. The argument for EGR (compared to EOR) as CO_2 mitigation becomes stronger if the additional natural gas produced is used in power generation at a plant with carbon capture, creating a fully circular CO_2 cycle.

pore space of basalt reacts with minerals in the rock matrix to precipitate carbonate minerals such as calcite (calcium carbonate or limestone, $CaCO_3$), magnesite (magnesium carbonate, $MgCO_3$), and siderite (iron carbonate, $FeCO_3$)—locking carbon into the solid matrix.

This process called 'carbon mineralization' has been studied in the laboratory extensively since the 1990s. A pioneering field test in 2013 by Pacific Northwest National Laboratory (PNNL) in a well near the city of Wallula (Washington) showed that carbon mineralization can proceed rapidly in the porous, permeable flow tops of the Columbia River Basalt Group (CRBG), a massive flood basalt formation underlying much of Washington State and parts of Oregon and Idaho. Most basalts are not porous and permeable enough to support fluid injection and storage, but the episodic nature of flood-basalt flows in the Pacific Northwest, which erupted from giant fissures in the ground (not volcanoes) and flooded the landscape over large contiguous areas, exposed the flows to the atmosphere for long periods of time, generating a porous, permeable crusts atop the thicker (and largely impermeable) flow interiors. Effective porosities in the vesicular or brecciated flow tops of the CRBG are as high as 30%.[61]

In the PNNL pilot project, 1000 tons of (supercritical) CO_2 were injected into flow tops of the Grande Ronde basalt at a depth of about 800 meters (2600 feet). Sidewall cores and other measurements collected two years later provided evidence that nearly 60% of the injected CO_2 had mineralized—turned into solid rock.[62]

The company Carbfix has obtained similar results injecting CO_2 mixed with water in operations in Iceland, where approximately 70,000 tons were sequestered during an initial phase starting in 2014 and lasting for 3.5 years. Injecting a CO_2/water mixture requires large volumes of water (1:25, CO_2:H_2O), but this poses no problem in Iceland, since seawater sourced close to injection sites can be used. Pre-mixed injection has the advantage that the mixture is denser than groundwater and therefore not forced upwards through the groundwater column by buoyancy. There is also evidence that the (mildly) acidic mixture accelerates mineralization. Carbfix plans to store up to 3 Mt annually at a new site scheduled to open in 2026. [63] A recent USGS report put the total carbon-mineralization potential in the U.S. at (at least) several hundred Gt of CO_2, mostly in the massive flood basalts underlying the Pacific Northwest.[64]

Although basalt formations have, to date, been tested at much smaller scales than the other three settings, storage of carbon dioxide as solid carbonate minerals offers the potential of sequestration that is both long-term and highly secure—truly permanent for all practical

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[61] N.V. Zakharova et al.

[62] Signe K. White et al.

[63] C.M. Holdsworth et al., "Monitoring CO_2 mineralisation and dissolution at CarbFix2 using inherent isotopes of CO_2, H2O, and noble gases," *Int. J. GHG Control* **151** (2026), 104584.

[64] Madalyn S. Blondes et al. As described in the Introduction, the authors are engaged since 2015 in a research project funded by Washington State Department of Commerce under the state's Climate Commitment Act (CCA) to map the sequestration potential of parts of the Columbia River basin in south-central Washington using geophysical remote sensing. A description of the project and preliminary results can be found on the project's public website, www.watraprocksurveys.org,

purposes. In fact, Earth's largest natural reservoir of sequestered carbon (by far) resides in carbonate minerals in the shallow crust.[65]

CCS and National Security

Carbon sequestration is not usually posed as a national security issue, certainly not across the U.S. political spectrum. But energy security is: Everywhere. For example, all three Shell *2026 Energy Security Scenarios* include a large and growing CCS industry in the 21st century. Even Archipelagos, the least aggressive scenario for climate action—named for an imagined future in which countries isolate for economic self-interest rather than collaborate to face shared global challenges—has CCS emerging at scale no later than 2040 with 300 industrial CCS projects operating around the world and 1.5 Gt of CO_2 captured and stored yearly by 2060. The rationale in this mostly business-as-usual scenario is that climate change unfolds inexorably through this century, to a greater or lesser extent depending on the volume of emissions, and becomes a growing national security issue through its effect on regional economies and populations, with more frequent and intense extreme weather events causing massive floods and wildfires; with rising sea level leading to large population displacements from flooded lowlands; and with a warming climate moving viable agricultural and ranch lands towards the poles.[66] Popular pressure thus builds to temper warming by cleaning up legacy fossil-fuel industries that continue to operate, even as a clean-energy future becomes economically compelling for its lower costs and greater energy security by tapping abundant local natural energy flows—once these flows can be stabilized by better energy storage technology, especially batteries.

Geopolitical tensions can create strangleholds on global trade flows of fossil fuels at strategic chokepoints but cannot prevent the sun from shining in Spain, Italy, Africa, India, and the U.S. Southwest, or the wind from blowing over continental prairies and plains or the North and South China Seas.[67]

According to the Global CCS Institute, China is poised to become the leading player in CCS with a series of initiatives in its 15th Five-Year Plan (2026–2030) designed to accelerate decarbonization of its massive coal industry.[68] China also claims to be building large-scale CCS facilities with capture costs of $30–$40 per ton. Those costs would make CCS profitable at just about any U.S. fossil-fuel power plant under 45Q.[69] Ceding leadership to China in renewable

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[65] Carbonate minerals in the crust store 100,000,000 Gt of atomic carbon (C), dwarfing the second largest reservoir, the Oceans at 40,000 Gt. The atmosphere contains about 830 Gt (and rising). *Climate Change 2013, The Physical Science Basis*, IPCC Fifth Assessment Report.

[66] *The 2026 Energy Security Scenarios*, Shell, available at www.shell.com (visited 1 August 2026).

[67] At least not until geoengineering becomes weaponized, a topic for a different white paper.

[68] *Global Status of CCS Report 2025, Staying the Course*, Global CCS Institute. An example is Huaneng Longdong Energy Base, a 1.5 Mt per annum CCS installation which went into operation in September 25 as the world's largest coal-fired carbon capture demonstration project.

[69] "China claims 70–90% cost advantage in power plant carbon capture as European projects face costs approaching US$300 per tonne," Wood MacKenzie, available at www.woodmac.com (visited 1 August 2026). An ironic twist here is that if China succeeds in fully greening its coal industry, it may increase the value of U.S. coal reserves, which exceed those of China by nearly a factor of 2 (1.7).

energy technologies (wind, solar, and batteries) as well as in fossil-fuel abatement technologies will be looked back on as a major strategic mistake.

Finally, recent work by PNNL highlights a significant co-benefit possibly emerging from large-scale CO_2 sequestration in basalt. Models of the chemical reactions in CO_2 mineralization, along with laboratory experiments, suggest that using specially engineered fluids as carriers for CO_2 injection in basalt can not only accelerate carbon mineralization, leaving CO_2 underground as solid rock, but may also pull minerals from the rock matrix into the fluid. A mineral-rich brine could then be extracted downstream of the injection site and processed to yield significant quantities of critical minerals like copper (Cu), nickel (Ni), and chromium (Cr). Reaction of dissolved CO_2 with basalt is also known to produce (under certain thermodynamic conditions) a reaction called 'serpentinization,' which releases free hydrogen gas (H_2).[70] Portions of the basaltic oceanic crust have become naturally rich in the mineral serpentine through this process after extrusion at mid-ocean ridges.

The chemical processes of carbon mineralization using specially engineered fluids require further study and testing in the laboratory, in computer simulations, and in the field. But if proven practical, using 'Earth as a chemical reactor' would significantly change the economics and narrative of CCS as a commercial activity.

[70] Q.R.S. Miller et al.

APPENDIX B: MODEL STATUTE

Geologic Carbon Sequestration Act

Section 1. Legislative findings and declaration.

(a) The Legislature finds and declares that it is in the public interest to promote the permanent storage of carbon dioxide in geologic formations for a purpose other than fossil fuel extraction. Doing so will benefit the citizens and residents of the state, the state's environment, and the global environment by reducing the amount of greenhouse gas in the atmosphere. The legislature further finds that providing geologic carbon sequestration opportunities will benefit the state's economy, including trust beneficiaries, manufacturers, energy providers, and agricultural landowners.

(b) Geologic carbon sequestration requires cooperative use of surface and subsurface property interests and the collaboration of neighboring property owners. This chapter encourages geologic carbon sequestration as a beneficial use of natural resources; safeguards ownership and use of the subsurface for other purposes, including groundwater management, critical mineral extraction, and artificial recharge; and ensures the integrity and safety of facilities used for geologic carbon sequestration.

(c) The [State Land Manager/State Geologic Agency/State Environmental Regulatory Agency] shall expedite and prioritize work under this chapter and shall work with project sponsors to site the state's first commercial facility for geologic carbon sequestration by 2030.

Section 2. Definitions.

(a) **Account.** The "Geologic Carbon Sequestration Trust Account," which is a dedicated fund established and administered by the state for activities related to geologic carbon sequestration, including to ensure the availability of financial resources for long-term monitoring and any other stewardship obligations assumed by the state. The Account is funded through fees and other payments collected from storage operators.

(b) **Carbon storage exploration license.** A license providing a qualified applicant the right to investigate whether a reservoir with state-owned pore space can meet regulatory requirements for storing carbon dioxide. Such investigation work may include geological, geomechanical, hydrological, environmental, and other assessments needed to satisfy permit application requirements and industry standards, such as constructing and operating characterization wells for evaluating reservoir performance and well productivity, but may not include injecting carbon dioxide for storage.

(c) **Corresponding right.** The right of all pore space owners in a unit area to be equitably compensated for use of the sequestration reservoir by a sequestration facility.

(d) **Geologic carbon sequestration.** Long-term storage of carbon dioxide in a reservoir, excluding carbon dioxide injected underground as part of an enhanced oil or gas recovery project.

(e) **Permit.** A permit or authorization to inject carbon dioxide and operate a sequestration facility issued under the Underground Injection Control program of the federal Safe Drinking Water Act, 42 U.S.C. § 300f et seq., as amended.

(f) **Pore space.** A void between mineral grains in a reservoir.

(g) **Public lands.** [In Washington, this term would be defined consistent with RCW 79.02.010(12). In Oregon, it would be defined consistent with ORS 273.006(7). In both cases, aquatic lands are included. In states without an existing definition, such as Idaho, it would mean, "Land or improvements thereon owned by the state or any agency thereof."]

(h) **Reservoir.** Any onshore or offshore subsurface geologic stratum or formation suitable for, or capable of being made suitable for, geologic carbon sequestration.

(i) **Sequestration facility.** The sequestration reservoir, subsurface installations and equipment, and surface buildings and equipment used for geologic carbon sequestration, excluding pipelines or other infrastructure transporting carbon dioxide from one or more capture or removal facilities to the site of sequestration.

(j) **Sequestration reservoir.** The portion of the reservoir proposed, authorized, or used for storing carbon dioxide pursuant to a permit, including any necessary and reasonable monitoring zones or buffers designated by the [State Environmental Agency] or federal government.

(k) **Site closure.** Regulatory closure of a sequestration facility, consistent with permit terms and conditions and as approved by the [State Environmental Agency] or federal government. For Class VI wells, site closure must conform with the requirements of 40 C.F.R. § 146.93.

(l) **Storage operator.** Any person, corporation, partnership, limited liability company, or other entity applying for or holding a permit to inject carbon dioxide and operate a sequestration facility.

(m) **Unit.** A sequestration reservoir designated by voluntary or compulsory unitization for operation by a single storage operator.

Section 3. Application for Class VI primacy; study of regulatory fitness.

(a) Subject to amounts appropriated for this specific purpose, the [State Land Manager/State Geologic Agency/State Environmental Regulatory Agency] shall [by July 1, 2027] investigate the fitness of federal and state regulations governing the well classes of the Underground Injection Control program of the Safe Drinking Water Act, 42 U.S.C. § 300f et seq., for sequestration in basalt formations. This investigation shall consider whether and where these regulations could be safely and appropriately differentiated for various storage methods or geologic formations.

(b) Subject to amounts appropriated for this specific purpose, the [State Environmental Agency] shall [by December 1, 2027] apply for primacy to regulate Class VI injection wells and issue aquifer exemptions for geologic carbon sequestration under the Safe Drinking Water Act, 42 U.S.C. § 300f et seq., as amended.

Section 4. Authority; consultation process.

(a) The [State Geologic Agency], in consultation with [the State Land Manager/State Geologic Agency, State Environmental Regulatory Agency, State Agricultural Department, and other pertinent agencies] and Indian Tribes, shall establish a collaborative process to, [by December 1, 2027], adopt rules reasonably necessary to administer and achieve the purposes of this chapter, including but not limited to establishing requirements, procedures, and rates for licensing and leasing public lands, state-owned pore space, and state-held water rights for geologic carbon sequestration purposes.

(b) The [State Land Manager/State Geologic Agency and State Environmental Regulatory Agency] may each, by rule or order, impose additional requirements as reasonably necessary to enforce the objectives of this chapter.

(c) The [State Land Manager/State Geologic Agency] may charge a reasonable fee, to be paid by an applicant for a license or a lease, for processing and considering such applications.

Section 5. Pore space ownership and conveyance.

(a) Title to pore space underlying a surface estate is vested in the owner of the surface estate, unless the ownership interest in the pore space has been severed and reserved or conveyed.

(b) Conveyance of ownership of a surface estate also conveys all the grantor's ownership of the underlying pore space, unless the conveyance instrument expressly reserves the pore space or the pore space has been previously severed, by reservation or conveyance, from the ownership of the overlying surface estate. A conveyance of the ownership of a mineral estate or another subsurface interest does not convey the grantor's ownership in the pore space, unless the conveyance instrument expressly provides for conveyance of the grantor's ownership of the pore space.

(c) A conveyance of the ownership of pore space does not convey any right to enter upon or otherwise use or interfere with the surface estate or the mineral estate, unless the conveyance expressly so provides.

(d) Notwithstanding any provision of law to the contrary, nothing in this section:

(1) increases, diminishes, or invalidates any property right established under the laws of the state;

(2) increases, diminishes, or invalidates rights to pore space that were acquired by contract or lease prior to the effective date of this chapter; nor

(3) prevents a mineral owner or mineral lessee exercising their mineral rights from drilling through or near a sequestration reservoir provided that the drilling preserves the integrity of the sequestration facility.

Section 6. Licensing, leasing, and conveying public lands for geologic carbon sequestration.

(a) The [State Land Manager/State Geologic Agency] may lease public lands and state-owned pore space for geologic carbon sequestration purposes. Before entering into a long-term lease, or as a condition of one, the [State Land Manager/State Geologic Agency] may issue a qualified applicant a carbon storage exploration license to investigate whether a reservoir with state-owned pore space can meet regulatory requirements for storing carbon dioxide.

(b) No license, lease, or conveyance of interest in public lands or a portion thereof, including state-owned pore space, for geologic carbon sequestration purposes may be made without public notice and a reasonable opportunity for public comment.

(c) Rates for licensing and leasing must be set to optimize the state's competitiveness to attract geologic carbon sequestration projects while balancing the state's obligation to trust beneficiaries and desire to not adversely impact Tribal rights and resources including, but not limited to, those protected by treaty, executive order, or federal law. Rates to be set may include an annual rental charge for use of the surface estate of public land, an annual rental charge for use of state-owned pore space, a charge on injected volumes of carbon dioxide, and any other charges that the [State Land Manager/State Geologic Agency] determines are necessary for fair compensation, such as royalty payments for production of hydrogen, geothermal energy, critical minerals, or any other commodity generated from a geologic carbon sequestration project.

(d) Only wells or other improvements authorized in writing by the [State Land Manager/State Geologic Agency] may be placed on or under licensed or leased public land. Improvements become the property of the state at the expiration or termination of the license or lease, unless otherwise agreed upon under the terms of the license or lease. The [State Land Manager/State Geologic Agency] may require improvements to be removed at the end of the term at the licensee's or lessee's expense.

Section 7. Carbon storage exploration licenses.

(a) A carbon storage exploration license grants the licensee, for geologic carbon sequestration purposes, the following:

(1) For a five-year term, the exclusive right to investigate the suitability of state-owned pore space as described in the license and, if applicable, an easement to access overlying public lands; and

(2) the option to convert the license into a lease, provided that the conditions of provision (h) and any requirements established by rule are satisfied.

(b) The [State Land Manager/State Geologic Agency] may grant a carbon storage exploration license if, after consultation with [State Environmental Agency] and federally recognized Indian Tribes, the [State Land Manager/State Geologic Agency]:

(1) makes a preliminary determination that the reservoir proposed for exploration is suitable and feasible for geologic carbon sequestration and such use will not endanger human health or the environment; and

(2) finds that the applicant is qualified to investigate whether a reservoir with state-owned pore space can meet regulatory requirements for storing carbon dioxide.

(c) An application for a carbon storage exploration license shall contain, at a minimum, a description of the reservoir proposed for investigation and the horizontal and vertical limits to be included therein with a map or plat thereof attached, as well as a proposed work plan. If the reservoir contains commercially valuable minerals, the application must include a statement that the interests of the mineral owners will not be adversely affected or have been adequately addressed in an arrangement entered into by the mineral owners and the storage operator. The applicant must commit to remediating the site upon cessation of its exploration activities or, if authorized, its commercial activities.

(d) A carbon storage exploration license must be conditioned on the posting of a bond or other security acceptable to the [State Land Manager/State Geologic Agency] and an obligation of the licensee to submit an annual report describing its investigatory activities undertaken in the previous calendar year to the [State Land Manager/State Geologic Agency/State Environmental Agency].

(e) The [State Land Manager/State Geologic Agency] may revoke a carbon storage exploration license before expiration of the five-year term, or deny a renewal application, if the licensee commits non-use or fails to comply with the requirements of this section or applicable regulations.

(f) The [State Land Manager/State Geologic Agency] may renew a carbon storage exploration license for a term sufficient to determine whether the licensee's application for a permit to inject carbon dioxide and operate a sequestration facility will be accepted, if the licensee meets the following minimum conditions:

(1) before expiration of the license, applies for a permit to inject carbon dioxide and operate a sequestration facility;

(2) is in compliance with the conditions of the license; and

(3) submits to the [State Land Manager/State Geologic Agency] an executed renewal form affirming the original terms of the license for the renewal term.

(g) A carbon storage exploration license that has been renewed terminates immediately if the licensee's permit application is denied.

(h) Upon application of a licensee, the [State Land Manager/State Geologic Agency] shall convert a carbon storage exploration license to a long-term lease for carbon storage if the licensee meets the following minimum conditions:

(1) is in compliance with the conditions of the license;

(2) has obtained a permit to inject carbon dioxide and operate a sequestration facility; and

(3) has demonstrated the ability to meet the commercial terms for a lease.

Section 8. Unitization.

(a) If, after attempting good faith negotiations with all persons owning the pore space within a sequestration reservoir, a storage operator does not obtain the consent of all of them, the storage operator may apply to the [State Land Manager/State Geologic Agency/Hearing Board] for a unitization order. The pore space of the nonconsenting owners shall be included in a proposed unit if:

(1) the storage operator has obtained the consent of persons owning no less than [60%] of the pore space within the sequestration reservoir;

(2) after public notice and a reasonable opportunity for a hearing, the [State Land Manager/State Geologic Agency/Hearing Board] finds that unit operation of the sequestration reservoir, or a portion thereof, is reasonably necessary for geologic carbon sequestration or to protect corresponding rights; and

(3) all nonconsenting owners will be fairly and equitably compensated.

(b) Pore space owned by a municipality, state, federal government, or an Indian Tribe may not be included in a unit over their objection.

(c) An application for unitization shall contain, at a minimum, a description of the proposed unit and the horizontal and vertical limits to be included therein with a map or plat thereof attached; a statement that the proposed area of the unit has been reasonably defined based on site characterization and modeling conducted pursuant to the federal Safe Drinking Water Act, 42 U.S.C. § 300f et seq., as amended, and any rules established by the applicable Underground Injection Control program; and a proposed plan of unitization and operation.

(1) The proposed unitization and operation plan must address the manner in which the unit will be supervised and managed and how pore space owners within the proposed unit will be fairly and equitably compensated. No nonconsenting owner may be forced to contribute upfront project costs.

(d) The terms and conditions of an order authorizing formation and operation of a unit must be just and reasonable and shall include the following:

(1) a precise definition of the vertical and horizontal limits of the unit area;

(2) a statement of the nature of the operations contemplated;

(3) a provision designating the storage operator as operator of the unit;

(4) a provision for recording in the land records of each county in the unit area documents sufficient to give constructive notice of the establishment of the unit;

(5) a provision to protect corresponding rights, allocating to each pore space owner in the unit just and equitable compensation for use of the reservoir for geologic carbon sequestration;

(6) the manner in which, and the circumstances under which, operation of the unit can be terminated and the unit dissolved; and

(7) additional provisions found to be appropriate to carry on operation of the unit or to protect corresponding or other rights.

(e) Upon application, the [State Land Manager/State Geologic Agency/Hearing Board] may for good cause terminate operation of a unit and dissolve the unit on just and equitable terms. Otherwise, operation of a unit shall terminate upon site closure. At the time of dissolution of the unit, the storage operator shall file with the [State Environmental Agency] and record in the land records of each county in the unit area documents sufficient to give constructive notice of dissolution of the unit.

(f) An order providing for unit operation may be amended by an order of the [State Environmental Agency/Hearing Board] in the same manner and subject to the same conditions as an original order providing for unit operation.

(g) Except to the extent that all affected parties agree, an order providing for unitization does not result in a transfer of all or any part of a person's title to their pore space in the unit.

Section 9. Title to carbon dioxide; liability; long-term monitoring.

(a) Title to carbon dioxide injected into a sequestration reservoir is vested in the storage operator, unless the storage operator has conveyed title to another person.

(b) The owner or operator of a sequestration facility may be subject to liability, including for a release of carbon dioxide attributable to the sequestration facility, unless and until the state has accepted a transfer of liability.

(c) Upon such time after the cessation of injection operators as the [State Land Manager/State Geologic Agency/State Environmental Agency] may establish, a storage operator may apply for the [State Land Manager/State Geologic Agency/State Environmental Agency] to accept title to stored carbon dioxide. Such an application shall contain, at a minimum, information indicating that the storage operator is in compliance with all applicable laws governing the sequestration facility, injection wells have been plugged, the carbon dioxide is stable and contained within the sequestration reservoir and expected to so remain, and the storage operator has deposited all payments due to the Geologic Carbon Sequestration Trust Account. A description of the sequestration facility and the horizontal and vertical limits included therein with a map or plat thereof also shall be attached. The [State Land Manager/State

Geologic Agency/State Environmental Agency] may set different application periods for different geologic formations or sequestration methods.

(d) The [State Land Manager/State Geologic Agency] may condition its acceptance of title to the stored carbon dioxide on the requirement that title to all equipment, installations, and buildings of the sequestration facility necessary for long-term monitoring will concurrently transfer to the [State Land Manager/State Geologic Agency], without payment of any compensation by the state. All such equipment must be in good condition.

(e) Upon acceptance by the [State Land Manager/State Geologic Agency] of title to stored carbon dioxide:

(1) the storage operator shall be released from all bonds and other security obligations posted by the storage operator; and

(2) primary responsibility and regulatory liability for any remaining long-term monitoring and management of the sequestration facility shall be transferred to the state. However, if any the following circumstances is found to exist, regulatory liability will remain with the storage operator:

(i) the storage operator or owner has violated, or is alleged to have violated, a legal obligation and the limitations period has not run;

(ii) the [State Environmental Agency] determines, after notice and opportunity for a hearing, that the storage operator provided deficient, erroneous, or knowingly false information that was material and relied upon when the decision to accept title or site closure was made;

(iii) the [State Environmental Agency] determines, after notice and opportunity for a hearing, that the sequestered carbon dioxide is migrating and threatens an underground source of drinking water, unless the storage operator can demonstrate to the [State Environmental Agency] at a hearing that the cause of migration was inadequate or improper management of the sequestration facility after its transfer to the state; or

(iv) the balance of the Account is insufficient to cover the costs of monitoring the site.

(3) Under no circumstances may a storage operator or owner's criminal and contractual liability transfer to the state.

(f) For the purposes of this chapter, carbon dioxide injected in accordance with a valid permit and that remains sequestered within the sequestration facility is not a pollutant or nuisance.

Section 10. Penalties.

Any person who violates any provision of the Geologic Carbon Sequestration Act or any rule or order issued thereunder or who commits false reporting with knowledge that the information is false shall be guilty of a [class __ misdemeanor/subject to a fine of __]. Each day that such violation continues shall constitute a separate offense.

Section 11. Establishing the Geologic Carbon Sequestration Trust Account.

(a) The Geologic Carbon Sequestration Trust Account is hereby created as a special, interest-bearing fund in the state treasury. Monies received under this chapter shall be deposited to the Account's credit, except that rental charges for leasing the surface estate of public land or state-owned pore space shall be deposited into the [State Fund for Trust Beneficiaries].

(b) The Account may be used by the [State Environmental Agency/State Land Manager/State Geologic Agency] only for purposes related to geologic carbon sequestration, including reviewing applications; compliance and enforcement; emergency remedial measures; and long-term monitoring and management of sequestration facilities for which the state has accepted title to the stored carbon dioxide.

Section 12. Cooperative agreements.

(a) The [State Environmental Agency/State Land Manager/State Geologic Agency] is hereby authorized to enter into agreements with other states, Tribes, and federal agencies for the purpose of effectively regulating sequestration facilities that cross jurisdictional boundaries or include federal pore space, which may include reconciling any regulatory inconsistencies between or among jurisdictions.

(b) An agreement executed pursuant to this section shall ensure effective regulatory oversight and enforcement, compliance with regulatory requirements, and coordination among the involved jurisdictions.

(c) The [State Environmental Agency/State Land Manager/State Geologic Agency] shall submit an annual report to the [legislative committee] detailing the status of any agreements entered into under this section.