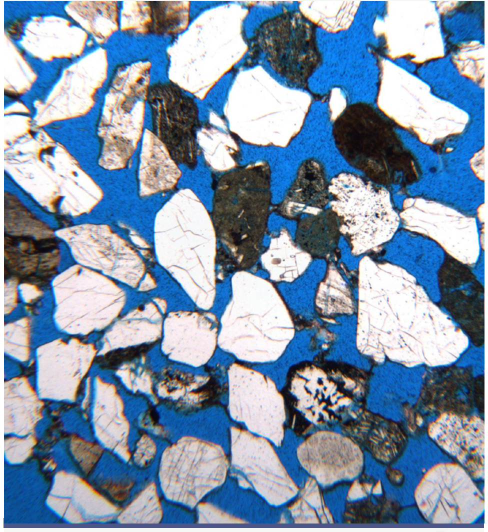
CHAPTER 4



Project-Based Geologic CO_2 Storage and Cost Assessment

SUMMARY

Geologic storage is an integral component of many major types of carbon removal, providing durable storage for CO_2 removed from the atmosphere through processes such as direct air capture with storage (DACS) and biomass carbon removal and storage (BiCRS). Building on extensive previous work, we conducted a new analysis of the distribution and estimated cost of geologic storage resources, introducing two novel elements. First, we explicitly mapped the "storage window"—the subsurface volume where CO_2 storage is possible within sedimentary rocks that are deep enough to be below any fresh water in the area and keep CO_2 as a dense fluid but not so deep as to become logistically difficult to inject CO_2 (**Figure 4-1**). We only considered onshore resources in this study; however, we note that a large capacity for geologic storage exists in sedimentary rocks beneath state and federal offshore waters. Second, we included new factors that impact the cost of geologic CO_2 storage, including how land-leasing costs are affected by CO_2 plume size and pressure, storage fees paid to landowners, the costs of characterization and monitoring, and monetary benefits to communities that host storage projects. We also estimated costs on a project basis, where a "storage project" is defined as 1 million metric tonnes of CO_2 injected per year for 20 years. Our analysis should allow developers to better match removal projects with available storage, based on estimated removal volumes and storage costs.

Key Findings

- More than half the land area in the United States is geologically suitable for CO_2 storage in microscopic pore spaces found within vast underground sedimentary rock formations.
- Well-studied sequences of sedimentary rock that can accept sustained injection of large volumes of CO_2 (>1 million tonnes annually per project for 20 years) are found in the Gulf Coast region and in dozens of inland basin areas, as well as smaller areas on both coasts. These areas make up 22% of US land area, including Alaska and Hawai`i, with average storage costs of less than \$20/tonne CO_2 (**Figure 4-2**).

CHAPTER SCOPE

Geologic storage is an integral component of carbon removal—it provides the most durable form of storage for atmospheric CO_2 and is expected to account for the largest portion of removed CO_2. In this chapter:

- We examine geologic carbon-storage resources in the United States, including distribution of storage resources and estimated project-based costs.
- We consider two types of geologic storage: in sedimentary rocks (the most established CO_2 storage option) and basalt formations.
- Our cost estimates are based on developing and operating the most favorable storage-target formation in each area that has available data.

- An additional ~28% of the United States has rock formations within the storage window that have not been previously assessed (Figure 4-2). These basins have a roughly estimated mean cost of >$53/tonne CO_2. This higher cost is driven by our expectation—albeit based on limited data—that injecting in sites where rock formations are thinner or less permeable will be slower and more costly; these situations may require more wells to sustain 1-million-tonne-per-year projects. Also, it will likely become evident that some locations have no storage resources available; thus, thus the cost of unsuccessful exploration must be factored into the overall cost of development.
- If we consider CO_2 storage via mineral trapping in basalts and other igneous rocks, the total prospective storage area could equal as much as 60% of the United States. However, estimating the costs for this type of storage is not possible due to insufficient data.
- About half of the United States lacks geologic storage resources. These areas are associated with mountainous regions and where basement igneous or metamorphic rocks are found at the surface or at shallow depths and no sedimentary rocks are available for storage. This includes Appalachia, most of the east coast, New England, the greater Rocky Mountain region, much of Alaska, and parts of the mid-continent from Minnesota to the Ozark and Ouachita Mountains.

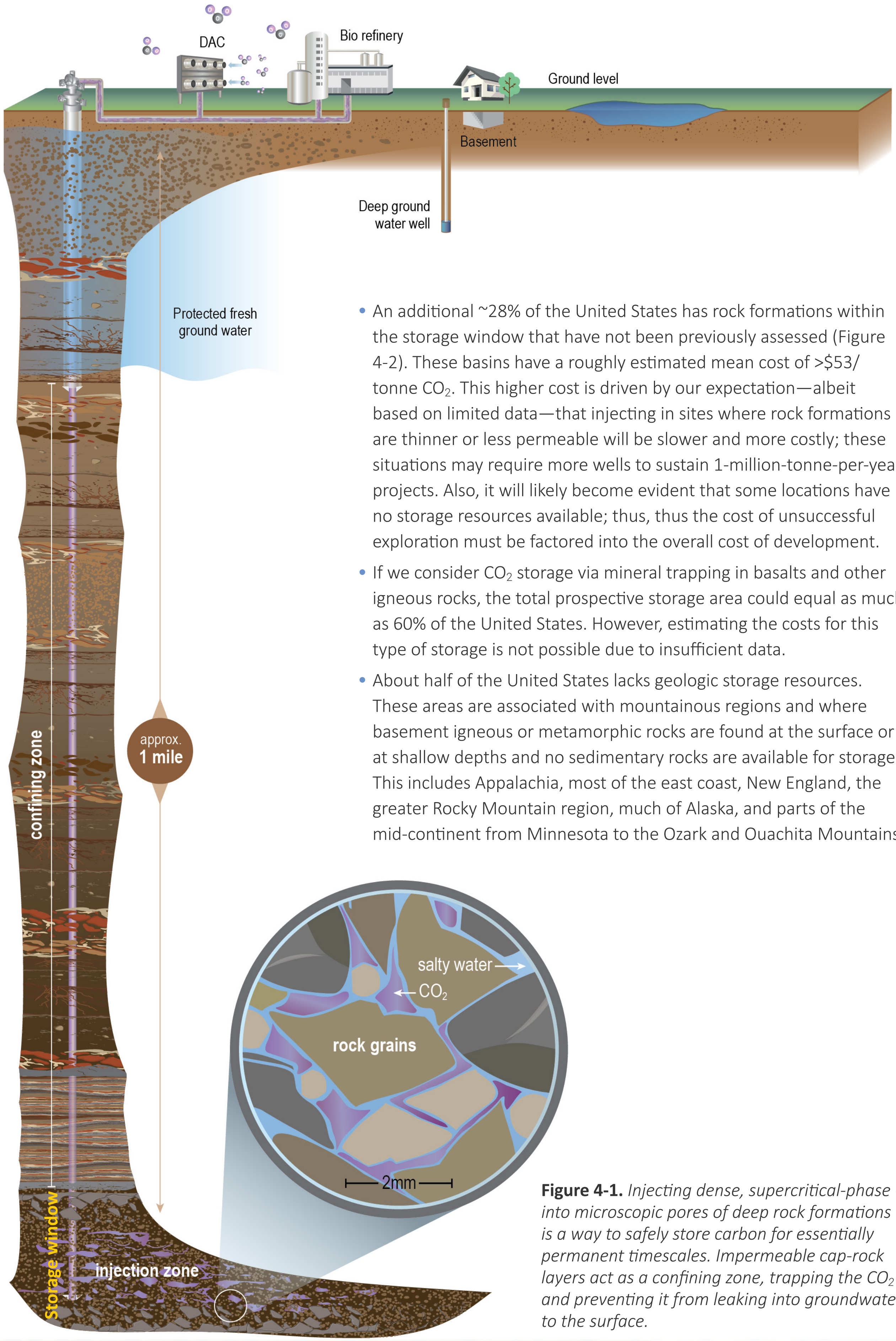


Figure 4-1. *Injecting dense, supercritical-phase* CO_2 *into microscopic pores of deep rock formations is a way to safely store carbon for essentially permanent timescales. Impermeable cap-rock layers act as a confining zone, trapping the* CO_2 *and preventing it from leaking into groundwater or to the surface.*

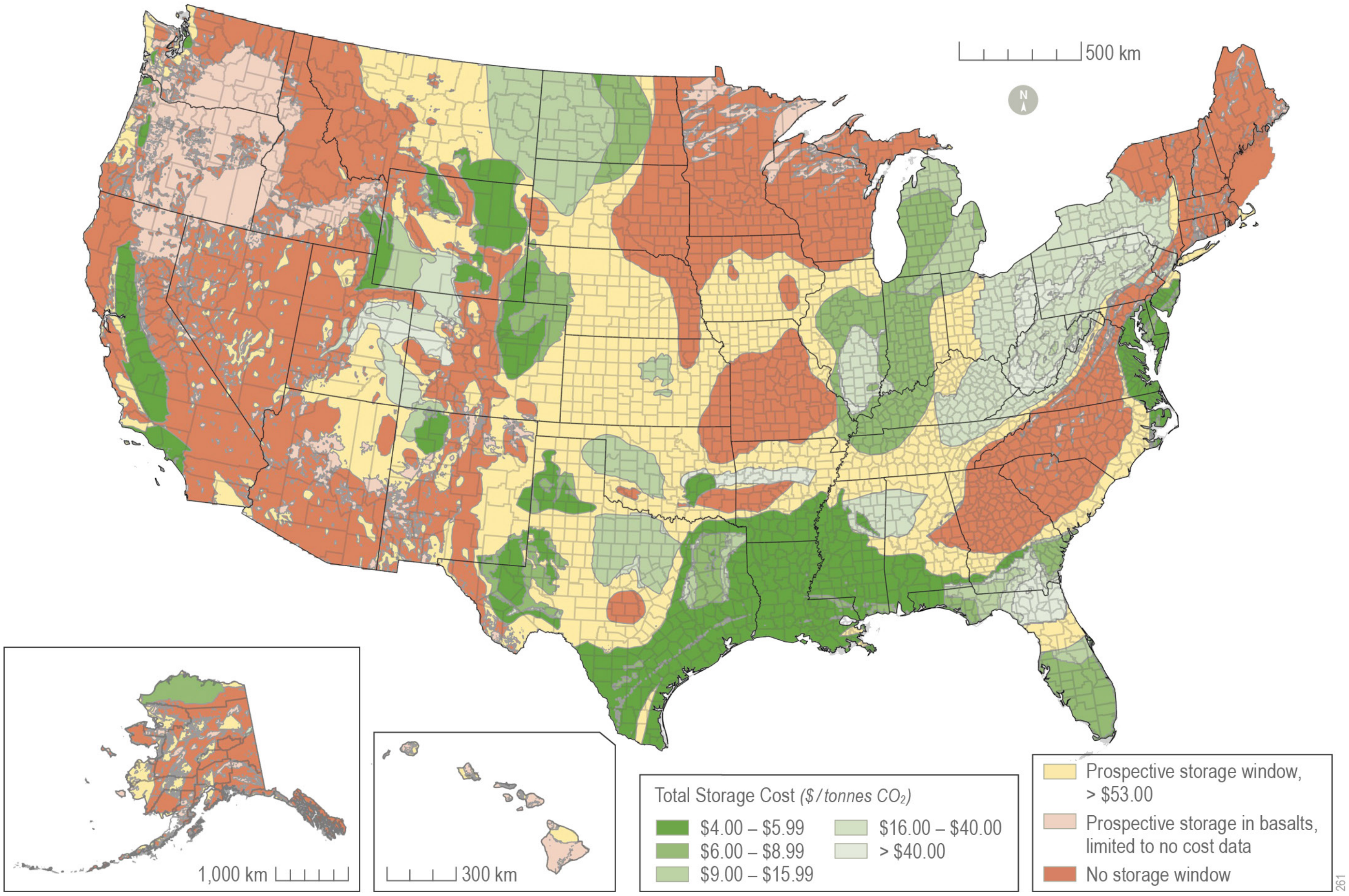


Figure 4-2. *Distribution of geologic CO_2-storage options in the United States, colored by suitability of the storage window and estimated mean project-based cost. Data were analyzed at the county level and are available as a GIS layer at https://roads2removal.org/. Within each colored region, high local variability exists at the sub-county scale but was not assessed.*

Introduction

Geologic storage is essential to many types of CO_2 removal, including DACS and BiCRS. CO_2 removed directly from the atmosphere or captured in the process of creating energy or fuels must be durably stored to realize long-term climate benefits of carbon removal. Geologic storage—where pressurized CO_2 is injected into deep porous rocks—is one of the most durable forms of CO_2 storage; properly sited and operated sites can be expected to retain greater than 99% of injected CO_2 over at least 100 years [1]. Storage of dense CO_2 fluid in porous sedimentary rocks is technologically mature (**Box 4-1**), in part because CO_2 has been injected into oil fields for a technique called enhanced oil recovery (EOR). EOR has been practiced commercially since 1972 at over 100 locations globally; most sites in the United States are located in the Permian Basin of West Texas and southeastern New Mexico. Projects linked to point-source capture have been inventoried by the Global Carbon Capture and Storage Institute [2] including five sustained, large volume, fully commercial projects that store CO_2 in porous sedimentary rocks (Sleipner, Snøhvit, Quest, Gorgon, ADM Decatur). In addition, an extensive body of peer-reviewed published research is available, documenting numerous storage field tests. This extensive experience confirms that CO_2 can be injected and stored with low hazard to humans, ecosystems, and other resources.

Storage in sedimentary rocks is the best studied and documented form of geologic CO_2 storage. This broad category includes storage in sedimentary rocks containing salt water or “brine” (often called saline storage) and in sedimentary rocks from which oil and gas have been extracted (often called depleted oil or gas storage) [3]. Porous sedimentary rocks, such as sandstone, limestone, BOX 4-1

Geologic Storage is a Durable, Scalable Carbon Storage Option

Geologic storage is the most permanent and widely available way to store CO_2 removed from the atmosphere. The same geologic systems that stored carbon in the form of oil and gas for millions of years can be used to return carbon emitted from burning those fossil fuels back underground. If suitable target rocks are chosen—the subject of this chapter—and injection is operated correctly, geologic CO_2 storage is safe and permanent. This permanence is demonstrated not only by nature storing fluids underground over geologic time, but by decades of experience, research, testing, and demonstrations by governments worldwide [8]. CO_2 and brine have been injected underground for nearly 100 years. Since the 1990s, numerous projects in the United States, Canada, Europe, Asia, the Middle East, Australia, and South America have successfully captured and stored tens of millions of tons of CO_2 underground. Today, approximately 30 carbon capture and storage projects are operating worldwide, with 11 more under construction and over 150 in development [9]. No dedicated geologic CO_2 storage project has ever resulted in appreciable leakage of CO_2. The multiple overlapping and redundant safety systems at properly selected and operated storage sites are robust, and the long history of safe underground CO_2 storage—both natural and engineered—supports the conclusion that geologic storage is the most durable storage method available today [1].

Geologic CO_2-storage projects are regulated by the US Environmental Protection Agency (EPA) under the authority of the Safe Drinking Water Act (SDWA) through the Underground Injection Control (UIC) program, established in 1980 [10]. The UIC program prevents endangerment of underground drinking water caused by subsurface injection of fluids [11] and regulates distinct classes of wells to address different types of underground injection [12]. In 2010, a new well class, Class VI, was created to specifically regulate geologic CO_2 storage [3].

A properly selected, designed, and operated CO_2-storage project in compliance with its permit will have zero leakage of either CO_2 or brine from the storage zone and will require ongoing extensive monitoring. Leakage is also physically constrained because capillary processes limit movement when two phases of fluids (brine and CO_2) occupy the same microscopic pore spaces between rock grains. Review of a portfolio of past corrective-action reports for 1000s of injection permits shows loss of zonal isolation incidents are rare, volumetrically minor, and most are remediated within days [13].

and dolomite, typically have lower costs for subsurface CO_2 storage, but additional sedimentary rock categories, such as coal, lignite, and fine-grained shales, are also potential storage targets [4].

Ultramafic and mafic (i.e., with a high magnesium and iron content) igneous rocks, such as dunite, peridotite, basalt, and the metamorphosed version of these rocks (e.g., serpentinite), play an important part in the natural carbon cycle as they react with dissolved CO_2 in surface and groundwater, dissolve, and release ions that precipitate to form carbon-bearing minerals (e.g., calcite ($CaCO_3$)). During this process, carbon becomes trapped within the minerals and ultimately reduces CO_2 in the atmosphere and ocean. This same mechanism can be used to geologically store CO_2 removed from the atmosphere. Because basalts contain high concentrations of calcium and magnesium ions that chemically react with CO_2 to make calcite, dolomite, and magnesite, injected CO_2 becomes mineralized and stored as a solid carbonate. Basalt formations are still being evaluated for in situ CO_2 storage [5]. To date, two tests for injection of CO_2 into basalts have been successful. In Iceland, the Carbfix project dissolved CO_2 in large volumes of hydrothermal waste water and documented rapid precipitation of calcite, trapping the CO_2 in the solid phase; commercial injection is now underway [6]. A pilot test in Wallula, WA has measured similar mineralization [7]. Injection into offshore basalt formations of the United States has recently been funded but has not yet been tested [7].

Storage of CO_2 in basalts via mineralization is less well-studied than storage in sedimentary rocks but may have some advantages, based on work to date. If CO_2 is dissolved in water prior to injection, as is done at the CarbFix projects, the CO_2 will no longer be buoyant, which helps minimize the risk that CO_2 may migrate out of the storage formation. The rapid mineralization of CO_2 into solid phases also helps assure permanence.

Analysis Approach

In this analysis, we sought to provide carbon-removal project developers with high-resolution data that convey both suitable locations and the likely costs of geologic storage. The quantitative assessment we produced is granular (in many areas more detailed than county-level) and covers the continental United States, plus Alaska and Hawai'i (Figure 4-2). It focuses primarily on well-established sedimentary-rock geologic storage but also includes prospective storage in poorly characterized geologic basins and basalt and other igneous rocks. This report goes beyond previous analyses by calculating total storage costs and project-based costs.

Total storage cost is a sum of many individual project costs. These costs vary based on many factors, including subsurface properties of a given geologic-storage resource, the area of land and activities needed to access that resource, the amount of existing data available, and the costs to acquire new data. For this study, we took the novel approach of estimating costs on a project basis, where a "storage project" is defined as 1 million metric tonnes of CO_2 injected per year for 20 years. We also include additional novel elements that have not been considered in previous cost studies (pressure area, exploration for new sites, high-resolution geologic data) (see **Table 4-1** and **Appendix 4**). As a result, our analysis allows developers to better match removal projects with available storage by multiplying or dividing the number of storage projects needed to meet estimated removal volumes and by identifying geographic locations with desired $/tonne injection costs.

Past studies and many method developments have focused on subsurface storage capacity [14, 15]. While these studies find differences in storage qualities, they all concur that geologic storage capacity in the United States exceeds what is needed to accommodate captured CO_2 under proposed climate-mitigation plans. In this study, we did not repeat these capacity analyses but rather worked toward a **project-based cost.** While it is theoretically possible to calculate capacity from our values (i.e., by dividing the average project area by the area of the basin where the project is located and then multiplying by the 20-million-tonne-project volume), we do not recommended this approach, in part because overlaps between project areas and areas unsuitable for storage (e.g., urban areas, reserved parklands) would need to be screened out. In the future, this project-based assessment may be a useful tool for those considering build-out of geologic storage as part of capture centers ("hubs"), balancing storage and transportation costs to get storage capacities over time and tied to rate of capture and revenue generated from carbon capture and storage.

Workflow

The methods we used to create the map of resources and storage costs (Figure 4-2) consisted of four broad steps, which are described briefly below and in detail in Appendix 4.

Step 1: Review of Previous Storage-Cost Assessments

Storage costs have been estimated repeatedly in the past 20 years (**Appendix 4, Table A-1**), most commonly as a component of the full value chain of costs that a geologic storage project may incur (capture + transport + storage). The major hurdle for generating national or regional storage-cost assessments is accessing and integrating the subsurface data needed as inputs. While subsurface geologic data are available from many sources, they are frequently difficult to find, discontinuous, incomplete, or inconsistent. And while many excellent sources are available for purchase, copyright rules limit the public release of such data (e.g., the Nehring oil and gas database [16]). For our current cost assessment, we drew upon the NETL saline storage-cost model [17, 18] and the Sequestration of CO_2 Tool (SCO_2T), originally developed

Table 4-1. *Inputs for assessing costs of project-based geologic storage, as conducted for this report.*

Parameter	Used to:	Common to Most Cost Assessments?
Injectivity	Estimate number of injection wells	Yes
CO_2 plume area	Estimate fees for land leasing, monitoring	Some
Pressure area	Assess project spacing, community benefits, monitoring	Novel to this assessment
Exploration for storage sites	Identify viable storage in poorly known areas	Novel to this assessment
Geologic data	Map area of previously poorly described storage window potential. Combined multiple sources for areas of denser data	Novel to this assessment

as a public open-software tool [19-23] and now available commercially from Carbon Solutions LLC [24].

To define basin-wide costs for characterized basins, we used the US Geological Survey (USGS) Storage Assessment Units data [25]; however, these data fall short of the county-scale-resolution goal of this study. To overcome this issue, we used less complete but more detailed data from 22 representative basins that are compiled in the Gulf Coast Carbon Center (GCCC) CO_2 Brine Database [26]. This database draws upon some data from the oil-and-gas industry and is augmented by diverse data from published local studies. We made a series of approximations to fuse these datasets together (see Appendix 4). We also used the US Department of Energy's (DOE's) NATCARB atlas [4], which includes relevant nationwide data, although it lacks the detailed reservoir parameters we needed for this cost assessment

Step 2: Storage-Project Mapping

To create a map of the options for geologic CO_2 storage in the United States, we determined which areas of the country are underlain by rocks suitable for CO_2 storage (storage window), those with only prospective storage, and areas with no storage window (**Figure 4-3**). We defined the top of the storage window as sedimentary rocks more than 750 m below groundwater. The base of the storage window is the depth at which compaction limits porosity and permeability and thus the ability to feasibly inject CO_2. In much of the United States, the base of the sedimentary rock interval is well-mapped. Commonly, the sedimentary section sits above igneous and metamorphic "basement" rocks that are low porosity, have little matrix permeability, are not layered, and are generally not viable for geologic storage. Our method for calculating the storage window is further explained in **Appendix 4**.
We applied three criteria to determine locations with no sedimentary storage window: (1) areas where metamorphic or igneous rocks are present at the surface, (2) areas where the storage window is too shallow to store CO_2 as a dense fluid, and (3) areas where the surface elevation is greater than 1000 meters (mountainous regions) or areas with steep slopes, which would complicate construction and logistics.

Step 3: Pressure Space and Injectivity

For our analysis, we focused on the volume of rock required to accept 1 million tonnes of CO_2 for 20 years, taking into account both the volume of rock in which CO_2 is stored and the (typically larger) volume of rock in which pressure is

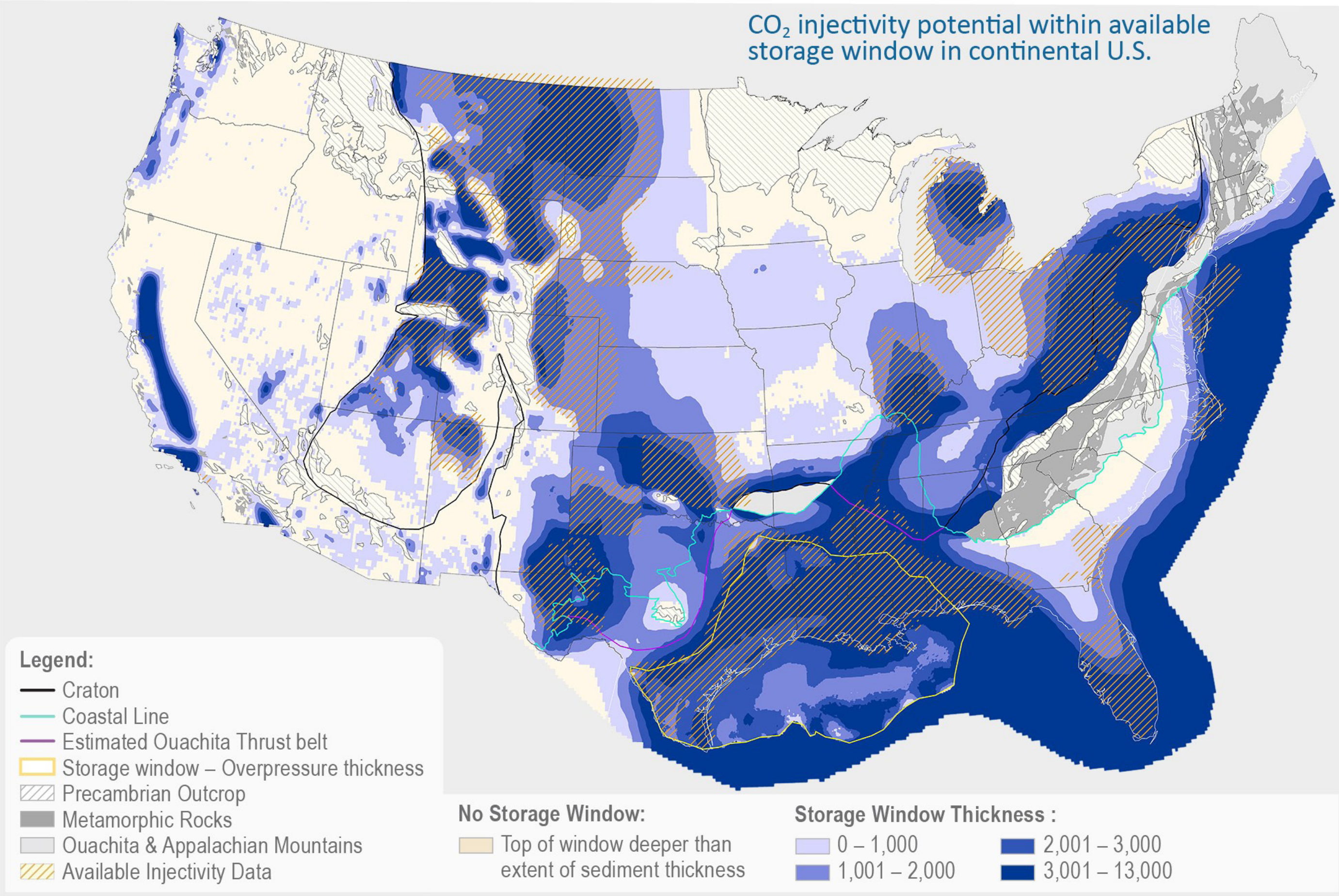


Figure 4-3. *Map of storage-window thickness derived from sedimentary thickness, digital elevation model (DEM), and depth-to-groundwater data as a raster file.*

elevated due to the injection process (**Appendix 4, Figure A4-2**). We refer to this volume of rock as the pressure space. Our analysis differs from some previous studies because we assume full deployment of CO_2 capture and storage, meaning that each storage project has other projects nearby, adding up to the many millions of tonnes of CO_2 storage needed. This scenario leads to a grid of wells occupying the storage resource. Inputs to our calculation include pressure increase, compressibility, CO_2 density, porosity, area, storage-window thickness, injectable interval, formation depth, and reservoir temperature and salinity; Appendix 4 describes these inputs in detail.

Pressure characteristics naturally change with depth. To construct pressure curves (**Figure 4-4**), we accounted for sedimentary compaction and changing brine salinity. We calculated the maximum allowable injection pressure, ΔPmax, using initial reservoir pressure and fracture pressure [27]. Then we included a 10% safety factor to arrive at the pressure-increase input for the pressure-space calculation (Appendix 4).

Injectivity, a critical subsurface property, provides a measure of how easily CO_2 can flow into and through a geologic storage formation. Past cost assessments have heavily weighted injectivity, largely because it determines the number of wells needed to accomplish injection at a supplied rate of CO_2. Variables including the volume of rock the CO_2 occupies, the volume of rock with elevated pressure, and corresponding land surface area determine how closely injection wells can be spaced and thus the area of land needed for a given storage project. Since the data needed to calculate injectivity are not readily available at a regional level, we took a simplified approach. We estimated injectivity by multiplying the permeability of the storage reservoir by the storage-window formation thickness and the net-to-gross injectable interval (Appendix 4).

We did not include certain factors in our analysis:

1. **Plume Shape –** Even at a county scale, we were unable to add geologic complexities in the injection zone that impact subsurface flow and therefore the number of wells and the project area leased and monitored. The ultimate distribution of CO_2 will depend on how it encounters these barriers and how it spreads beneath them. The distribution of CO_2 within a reservoir can vary widely from concentrated to diffuse zones (**Appendix 4. Figure A4-3**).
2. **Induced Seismicity –** Change in fluid pressure in the subsurface can cause earthquakes, which can be hazardous if the earthquake is large. Correct assessment of the maximum pressure tolerable in seismically prone areas [28] is the major mitigation approach for earthquake risk; however, this assessment is best done at the project scale rather than the national or even county scale and therefore we did not include it in our analysis.
3. **Stacked Storage –** Many geologic basins often have more than one geologic formation suitable for storage due to the layered nature of the subsurface. Project developers can access and store CO_2 in these multiple layers from the same surface location. This approach allows some cost savings in characterization and monitoring; however, we did not consider this factor in our cost estimates due to the complexities involved.
4. **Incompatible Surface Land Use –** We did not exclude areas of land that would be unsuitable to site injection wells, such as national parks, developed areas, or sensitive or protected habitats, as this issue is best assessed at the project scale.

Step 4: Mean Storage Cost

The most data on subsurface properties are available in geologic regions where oil and gas have been extracted, but CO_2 storage may be possible in other areas, even

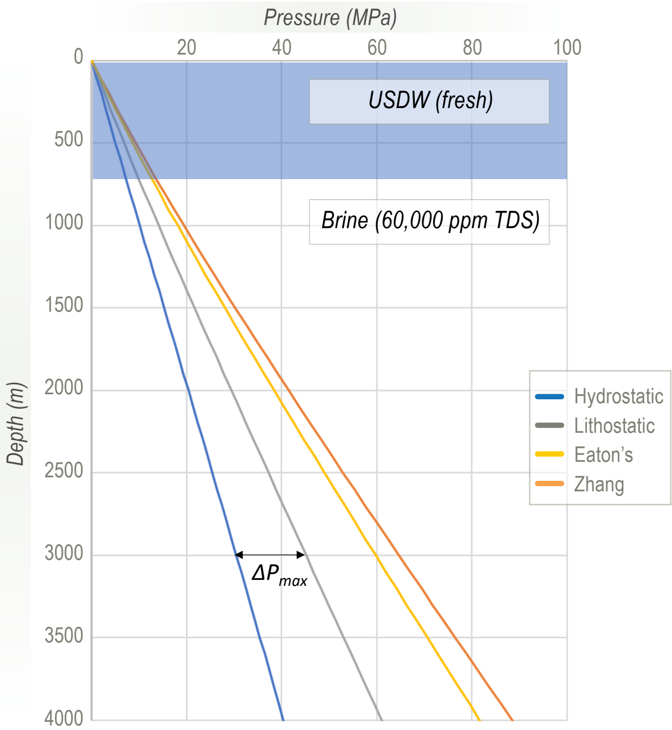


Figure 4-4. *Graph of pressure versus depth, showing curves for hydrostatic pressure and lithostatic pressure and two estimates of fracture pressure—Eaton's Method (grey line) and Zhang's equation (yellow line)—that bracket the range given by commonly accepted fracture-pressure calculations [27]. TDS = total dissolved solids.*

though available characterization data are sparse. As such, we included the novel element of exploration costs in our study to characterize these poorly understood areas, which increases the total project cost [29].

Mapping regions with prospective storage adds large areas to our storage-resource map (Figure 4-2). Although uncertainty is high and costs are more difficult to estimate, we included these areas because (1) local storage at higher risk and higher cost has potential value if the cost and risk of pipeline construction can be minimized and (2) some CO_2-removal methods (DACS in particular) are modular and capture units could be scaled to match relatively low injectivity wells. For our cost estimates, we assumed three exploration wells would be required to identify a viable storage target and that injectivity in these areas would generally be poor (thus they are assigned in our lowest quartile of mapped injectivity).

To estimate the costs of a geologic storage project over the project lifetime, we accounted for costs accrued during each project phase: exploration, development, operation, closure, and post closure. Appendix 4 includes a table of assumptions and input values selected for each of these costs. For geologic storage projects in poorly characterized regions, we assume three exploration wells will be needed to find one viable storage site. For all geologic storage projects, we made the following assumptions:

- Costs include collecting the data required to submit a Class VI injection permit
- Two monitoring wells will be required per storage project
- Bulk of monitoring costs will be related to geophysical surveys used to track CO_2 and pressure plumes
- Operational costs include leasing/easement fees paid to the surface landowner, insurance or bonding [30], and benefits paid to host communities (e.g., [31])
- For the closure phase, costs include well plugging and abandonment, removal of surface equipment, and restoration of the surface
- After closure, commercial projects will use advanced monitoring techniques that require minimal effort once it has been demonstrated that the CO_2 and pressure plumes have stabilized

Storage in basalts

Although promising geologic CO_2-storage pilot projects have been completed in basalt rock formations, the knowledge and experience base is far smaller than for conventional storage in sedimentary rocks, and targeted research needs to be conducted to test the fate of injected CO_2, ways to monitor it underground, and reaction kinetics. For our current analysis, we regard basalts as having only prospective storage. Consideration of basalts as storage resources expands the potential storage resource areas, which is especially valuable in areas such as in the Pacific Northwest—where solidified lava flows form a massive series of formations known as the Columbia River Basalt Group [32]—and in Hawai`i. More evaluation is needed to determine the viability of CO_2 storage in basalts at scale, and therefore we have chosen not to provide an estimate of storage costs for basalt-based CO_2 storage.

Major Findings

Our analysis builds off a number of previous geologic-storage cost and capacity studies and confirms the findings of those studies that the United States has abundant onshore storage resources; however, plans involving the use of this resource must take into account its uneven distribution.

Suitable geologic storage is available in many parts of the country where BiCRS and DACS methods can be used for CO_2 removal, and storage capacity is much greater than 1000 million tonnes per year or any potential demand. Well-known sequences of sedimentary rocks that can accept sustained large-volume injection (1 million ton per year for 20 years) are found in the Gulf Coast and dozens of inland basin areas, as well as smaller areas on both coasts. These areas make up 22% of US land area, including Alaska and Hawai`i and will cost less than \$20/tonne (**Figure 4-5**). Small areas in known basins were assessed as having poor injectivity, requiring either many injection wells or large land areas to host a 1 million ton per year project for 20 years; these areas will likely cost in the range of \$20–\$54/tonne.

In this study, we augment previous studies by explicitly mapping the storage window where sedimentary rocks are deep enough to be below fresh water and keep CO_2 as a dense-phase fluid but also shallow enough to be above the point where injectivity decreases. Injectivity decreases in basement rocks (igneous and metamorphic rock below the sedimentary rocks) and at depths where either over-pressure or over-compaction limits injectivity. By mapping the storage window, we found additional areas outside of previously assessed basins where exploration potentially could locate storage, primarily in the central United States (yellow areas of Figure 4-2) , bringing the area of the United States (including Alaska and Hawai`i) that could potentially have sedimentary-rock storage to 50%. Inclusion of the storage window highlights frontier areas where there is potential to site removal projects with minimal or no need to transport the CO_2 for storage. However, the additional costs for exploration—particularly those that do not locate useful geologic storage resources—must be considered within the total cost of development. Also, the regions we have designated as having prospective storage are unlikely to have high injectivity. We expect that, under the best scenario, developers might locate thin permeable zones or low permeability in these zones. This scenario would require more wells per unit area to sustain 1-million-tonne-per-year projects, leading us to estimate a higher cost—very roughly estimated at \$53/tonne CO_2. Adding prospective storage by mineral trapping in basalt increases the coverage to almost 60% of the United States (including Alaska and Hawai`i). But because no systematic regional assessment of storage in basalt exists, we did not calculate a cost estimate for these resources.

By mapping the storage window and where prospective storage in basalts exist, we also illustrate areas where no conventional geologic storage is available. CO_2 removed from these regions will need to be transported to areas that are more favorable for geologic storage or stored via other mechanisms that are not assessed in this chapter (**Box 4-2**).

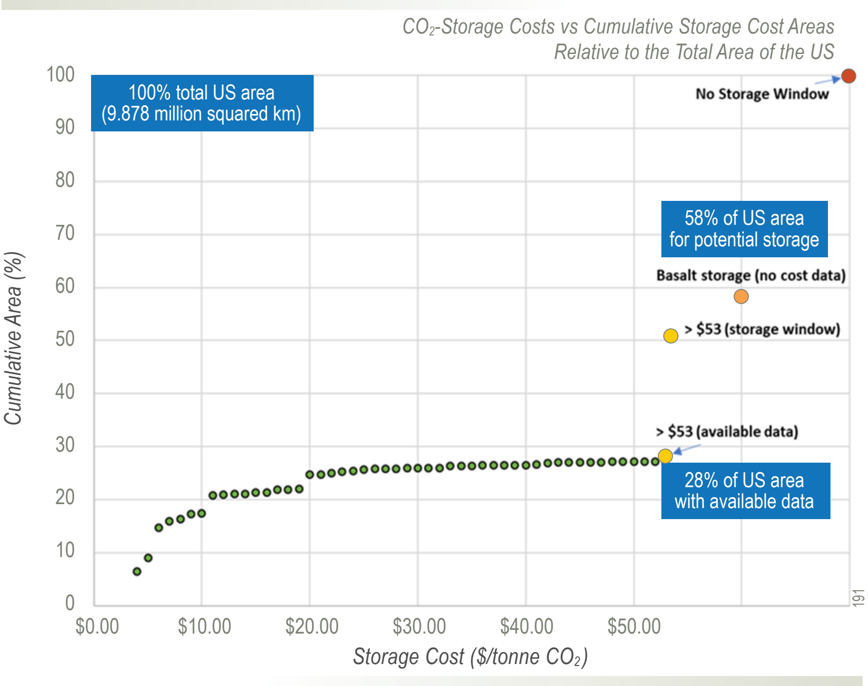


Figure 4-5 *Storage cost curve. This graph plots \$/tonne CO_2 storage costs as a function of the cumulative land area for which storage is available at the stated cost. As shown, 28% of the United States contains geologic formations in which storage can be accomplished for less than \$53/tonne, with an average cost of less than \$20/tonne. Storage may be possible in an additional ~32% of the United States, but we lack sufficient data to make detailed cost estimates for these areas.*

BOX 4-2

Roads Not Traveled

Other types of geologic storage exist that we did not consider in this report:

- Large-volume, high-quality storage resources offshore in sedimentary rocks beneath federal and state-owned marine waters. Offshore sub-seabed storage in deep sedimentary rocks is technically similar to the same setting onshore. This storage option is higher cost than adjacent onshore geologic storage but may be attractive because of public ownership, distance from most but not all human uses, high technical quality, and low technical and environmental risks. This option may be attractive in areas with limited onshore storage resources, such as the East Coast, and could also serve to augment capacity over large regions.
- Storage in ocean water itself, which incorporates a substantial amount of CO_2 via exchange with the atmosphere. Some have proposed that ocean storage could be enhanced by placing cold liquid CO_2 at depths where its density is higher than sea water, so it would pool on the ocean floor. CO_2 could also be emplaced to form hydrates (CO_2-water-methane “ice”) on or just beneath the deep-ocean seabed. CO_2 can also be dissolved in marine water, enhancement and buffering via augmenting alkalinity is proposed, or “fertilization” to enhance biologic uptake from ocean water.

We inventoried the regions of the database represented in our national geologic-storage map (Figure 4-2) to assess the distribution of storage costs. Note that these are estimated mean costs. A wide uncertainty bar should be placed around the values due to local geologic variability—which impacts cost but cannot be represented at the scale of our assessment—and the relatively high uncertainty of the input costs.

We constrained costs based on the observed distribution of the few current projects for which data are available. While they provide clues to possible emerging trends, it is apparent that all the parties involved in cost-setting—financiers, developers, landowners, permit writers—are in the early stages of building the system, and a reassessment of actual costs should be undertaken as approaches mature and more information is made public.

Our geologic-storage cost assessment includes several novel elements:

1) Exploration costs for areas that are poorly characterized but deemed to have prospective storage
2) Both the CO_2 plume and pressure plume in calculations of the number and spacing of wells required for a "storage project"
3) Decreased monitoring costs compared to previous studies because of the development of improved permanently installed data-collection systems and because permits with limited monitoring are already being approved
4) Fees to landowners (both on a per-acre-leased and a per-ton basis) in the total project cost
5) Insurance and bonding costs related to project closure and government incentive programs
6) Community benefits costs (albeit with high uncertainty since we do not yet know what types of benefits at what cost will become a best practice)

Estimated project costs in this analysis, although calculated differently than in previous studies, fall within similar cost ranges and have roughly the same geographic distribution as previous cost studies (**Appendix 4, Table A-1**). The novel output of this study is the storage availability and cost map, which allows carbon-removal project developers to identify places with both favorable storage and favorable costs.

Geologic Carbon Storage through Socioeconomic and Environmental Perspectives

Geologic CO_2 storage is purely a storage mechanism and is independent of any capture process, as opposed to the CO_2-removal methods analyzed elsewhere in this report. Post-construction, the storage-well head and potential pipeline connecting a storage site to CO_2 sources will have a minimal above-ground footprint. However, these storage projects still pose opportunities for co-benefits and potential negative impacts for the environment and local communities. Here, we compare the trade-offs for geologic carbon storage and efforts that can maximize co-benefits while avoiding or minimizing potential negative impacts (**Table 4-2**).

Many key co-benefits for geologic CO_2 storage are economic in nature, largely due to its geospatial overlap with counties experiencing persistent job losses in the traditional energy sectors (e.g., oil, gas, mining) [53, 54]. Counties whose workforces are predominantly based on carbon-intensive industries, such as fossil-fuel extraction or fossil-fuel-based electricity generation, are at risk of economic and public health stress if their workforces are not transitioned purposefully amidst decarbonization [55, 56]. Beyond solely jobs, counties will earn additional tax revenue. County residents can negotiate for public goods in the community-benefits-agreement negotiation phase of geologic CO_2 project development (e.g., profit sharing or infrastructure improvements). By prioritizing counties with the greatest job-loss rates in traditional energy sectors and economic dependence on these jobs, policymakers and project developers can assess which counties are poised to maximally benefit from geologic CO_2 storage projects.

It remains a prevailing concern that siting of geologic CO_2 storage projects may be optimized solely for traditional energy communities. This approach could lead to inequitable siting of geologic CO_2 storage projects in vulnerable communities that are not equipped for advocacy or emergency response [57]. Beyond perceived safety concerns with geologic CO_2 storage due to residents' unfamiliarity (which can be addressed through education and capacity building, **Box 4-3**), another risk is that leasing/purchasing of pore space could disproportionately benefit corporations or a subset of private landowners that do not represent the diversity of the US population. Ideally, pore-space

Table 4-2. *Geologic-storage community benefits and negative impacts trade-off table.*

GEOLOGIC CARBON STORAGE	
Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Direct job creation and/or retention Focus on projects where the existing workforce has expertise relevant to geologic carbon storage and are exposed to job loss from the net-zero transition [33, 34].	Community hesitancy or distrust Begin two-way communication with the local community before a project begins and commit funding and personnel to continue engagement through the active and decommissioning stages of a project [35].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in domestic manufacturing and induced jobs [36, 37]. Consulting with chambers of commerce or small-business associations can also increase the economic flows to small, local and minority-owned businesses as support contractors for a project **(Chapter 10 – Regional Opportunities)**.	Construction impacts Make plans public and set up channels for local communities to voice concerns well ahead of time to allow for project adjustments and prevent public backlash [38, 39].
Non-federal tax revenue State and local policies, similar to those developed for renewable energy, that stipulate revenue sharing rates and mechanisms [40, 41].	Oversold benefits The project benefits should be communicated to communities in sufficient detail (e.g., permanent versus construction jobs) as early as possible so that they can holistically assess whether they wish to proceed, ideally with locally grown capacity to assess promised benefits [42, 43].
Alternative income sources for landowners (e.g., farmers) Implement outreach to a wide diversity of farmers from diverse backgrounds, whose land (e.g., farmland) is likely to become marginalized amidst climate-change impacts. This creates economic resiliency for landowners (See **Chapter 3 – Soils** and **6 – BiCRS** of this report) [41].	Increased socioeconomic division Regional maps of minority and female land ownership/farm operations should be consulted pre-investment to assess equitable distribution potential [44-46].
Community identity Implement distinct outreach efforts focused on the target audience to build a broad base of pride for the project in the community [38].	Incomplete decommissioning Decommissioning and site-restoration plans, along with associated financial commitments and carbon-emission estimates, should be shared with the community and oversight authorities prior to permitting [47, 48].
Infrastructure improvements To gain site access and setup monitoring equipment, infrastructure (e.g., roads, culverts, broadband access, etc.) will likely need improving. This opens opportunities for rural communities to negotiate for additional infrastructure improvements, through a community benefits agreement **(Chapter 10)**.	Ownership disputes Compensate all property owners in the potential storage project footprint in advance in exchange for control over the entire storage field [49]. Utilize federal lands for CO_2 storage [50]. Gain clarity on pore-space rights for the specific locality during the planning stage [51]. Avoid sites that have been identified as culturally or ecologically important by community stakeholders [52].

agreements could be made with large tracts of public land, which will inherently disperse financial benefits to the public agency's constituents. Parallel development of community capacity to engage in project development from an informed place of power to maximally benefit public priorities, while building trust in CO_2-storage practices, will be critical to avoid contributing to historical siting inequities in the United States (e.g., [58]).

By investing in community-capacity building around geologic CO_2 storage in regions our analysis has identified as having outsized storage potential, agencies can increase community support for projects, which is key to successful scale-up of this industry. Using renewable-energy projects as an analog, previous research suggests that if there is local opposition to a project, there is a ~50% chance that the project will be cancelled permanently and a ~34% chance that it will incur costly delays due to permitting [59]. With the urgency of climate change and the role that geologic storage has in supporting scale up of CO_2 removal to both help meet US net-zero targets and transition at-risk workforces, geologic

BOX 4-3

Community Benefits and Capacity Building

In the context of CO_2-removal methods for which many individuals may lack familiarity (e.g., geologic CO_2 storage), "capacity building" refers to fostering the development of local expertise and trusted leadership on the topic, which can advance transformative community engagement around new technology projects. Examples of capacity building methods may include providing educational opportunities for interested parties and workforces, designating or electing local individuals/committees to represent community interests in projects, or instigating benefits from technological opportunities that will sustain long-term stewardship of projects Thus, it may be advisable that early projects be strategically.

CO_2 storage projects cannot afford to waste time or resources with stoppage or delays. Thus, *it may be advisable that early projects repeat proposed in counties that have the capacity and interest to engage and stand to maximally benefit from the project with minimal risk.*

To efficiently synthesize socioeconomic and environmental data relevant to DOE's energy equity and environmental justice (EEEJ) goals [60], we constructed an average EEEJ Index value for each US county (**Chapter 9 – EEEJ**). In these indices, values closer to 1 represent high opportunities for co-benefits, and values closer to 0 represent lower likelihood for co-benefits and potentially greater challenges pertinent to EEEJ considerations. The impact of each variable, positively or negatively, on the overall EEEJ Index value for each county is presented in **Figure 4-6**. Following the construction of each index, we compared to the Center for Disease Control's (CDC's) Social Vulnerability Index (SVI) and geologic carbon-storage costs to assess potential biases in the index toward vulnerable counties (**Figure 4-7, Appendix 9**). We found no relationship between this report's EEEJ Index and the SVI, which suggests that our EEEJ Index does not bias for geologic CO_2-storage project siting in more- or less- vulnerable counties (**Chapter 9 – EEEJ**). Evaluating SVI alongside this report's EEEJ Index may be useful for policymakers or project developers who want to assess which US counties may be best poised to collaborate on geologic CO_2-storage projects as early adopters and which counties would benefit from capacity building. See **Chapter 9 – EEEJ** for further examination of the socioeconomic and environmental contexts considered for the counties identified here.

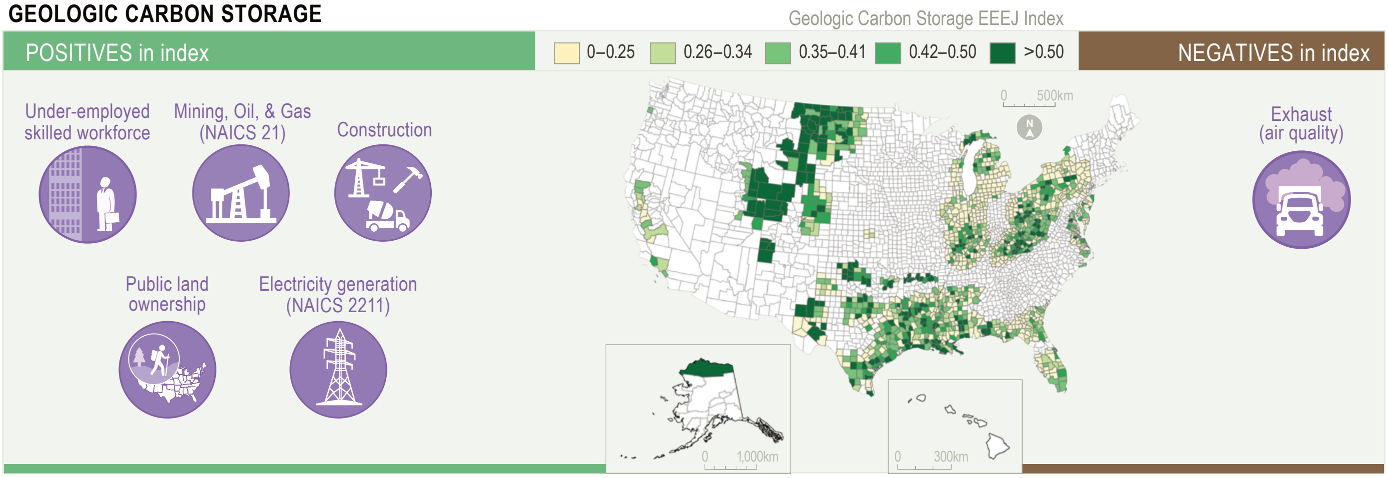


Figure 4-6. *Map of the EEEJ Index for geologic carbon storage, alongside each variable that contributed, positively or negatively, to the Index. The Index is normalized from 0 to 1, where values higher values represent a potentially greater opportunity for socioeconomic co-benefits, including re-employment of skilled workforces and public pore space that distributes revenues to the tax base. Higher values also represent a smaller potential for negative environmental impacts from the construction phase, specifically traffic and health impacts from diesel-derived PM2.5.*

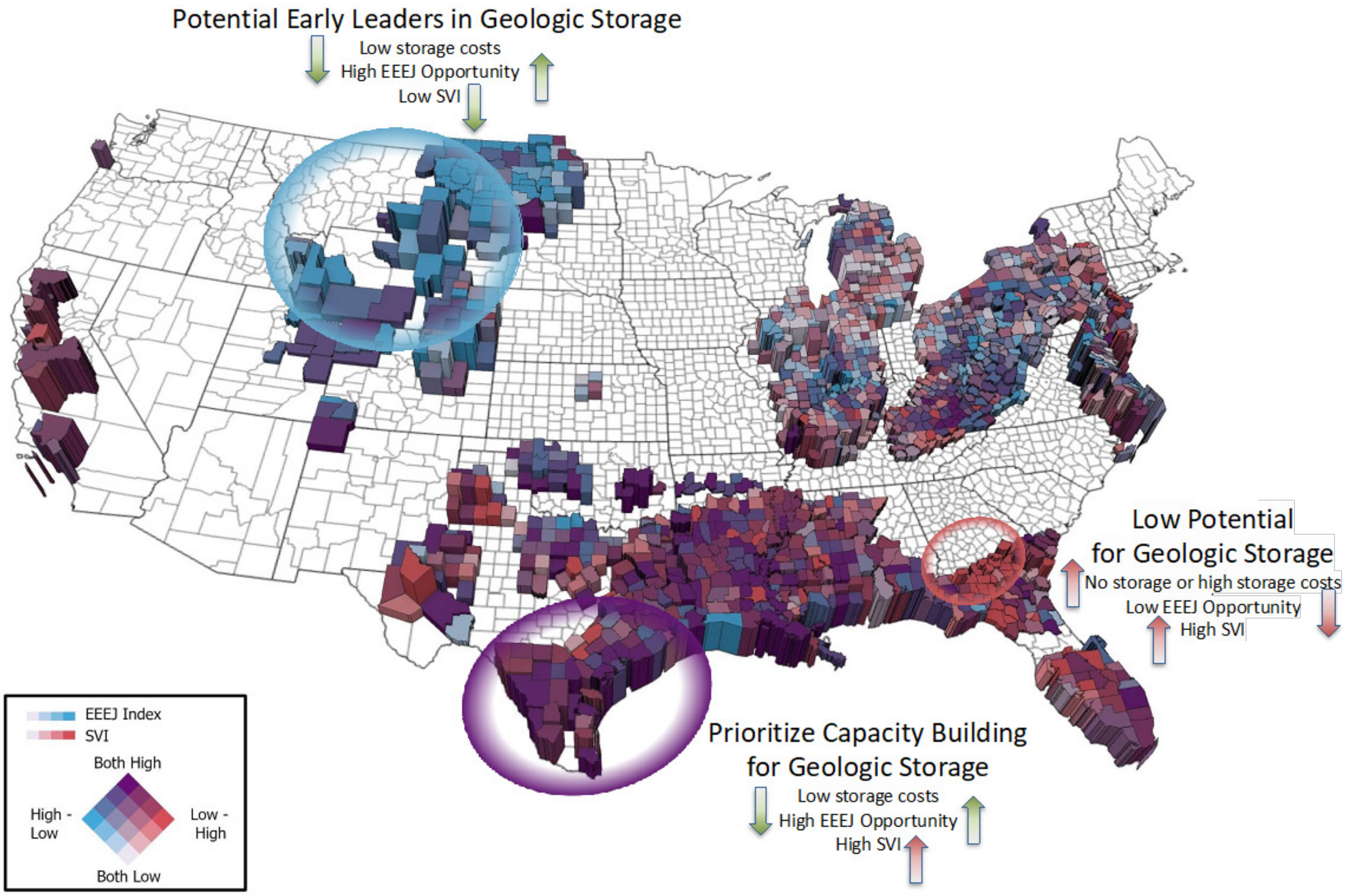


Figure 4-7. *Map of EEEJ Index data (blue) and the CDC's Social Vulnerability Index (SVI) (red) for the US counties whose storage costs were well-characterized in Figure 188 (depicted as green in that figure). The height of counties in this map represents potential for geologic carbon storage, where taller counties have the most affordable geologic carbon storage costs and flatter counties have higher storage costs. The map is annotated to reflect this report's hypothesis around geologic carbon storage: if a county has high opportunity for co-benefits and low social vulnerability, then they may be better poised to become early leaders in the practice. Similarly, counties with high opportunity for co-benefits but also high social vulnerability may benefit from investment in local capacity building to engage on the topic of geologic carbon storage.*

Conclusions

Well known sequences of sedimentary rocks that can accept sustained large-volume injection (1 million tonnes per year for 20 years) are found in the Gulf Coast and in dozens of inland basin areas, as well as in smaller areas on both coasts (Figure 4-2). These areas make up 22% of the land area of the United States, including Alaska and Hawai'i, with average storage costs of <\$20/tonne CO_2 (Figure 4-5). Small areas in known basins were assessed as having poor injectivity, requiring either many injection wells or large land areas to host large-volume projects, with mean costs of \$20–\$54/tonne CO_2. In this study we augment previous studies by explicitly mapping the storage window, bringing the areas which could potentially have storage in sedimentary rocks up to 50% of the Unites States. Adding prospective storage by mineral trapping in basalt increases the coverage to almost 60%. This study confirms the findings of previous geologic-storage cost and capacity studies, which had found that the United States has abundant onshore storage resources and can accommodate projected removal targets.

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