U.S. Department of ENERGY

Carbon Transport and Storage Multi-Year Program Plan

December 2024

LIST OF ACRONYMS

Ar	Argon
BIL	Bipartisan Infrastructure Law
CarbonBASE	Carbon Basin Assessment and Storage Evaluation
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CarbonSTORE	Carbon Storage Technology Operations and Research
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CDR	Carbon dioxide removal
CETP	Clean Energy Transition Partnership
CIFIA	Carbon Dioxide Infrastructure Finance and Innovation Act
CO	Carbon monoxide
CO_2	Carbon dioxide
Communities LEAP	Communities Local Energy Action Program
CT&S	Carbon Transport and Storage
DOE	U.S. Department of Energy
EDX	Energy Data eXchange
EDX4CCS	EDX for CCS
EERE	Office of Energy Efficiency and Renewable Energy
EM	Electromagnetic
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
FECM	Office of Fossil Energy and Carbon Management
FEED	Front-end engineering design
FOA	Funding opportunity announcement
FY	Fiscal year
GOM	Gulf of Mexico
H_2	Hydrogen
IEA	International Energy Agency
LBNL	Lawrence Berkeley National Laboratory

LCA	Life cycle analysis
LPO	Loan Programs Office
m	Meter
M	Million
ML	Machine learning
MOU	Memorandum of understanding
MT	Metric tons
MYPP	Multiyear program plan
N_2	Nitrogen
NEPA	National Environmental Policy Act
NGO	Nongovernmental organization
NRAP	National Risk Assessment Partnership
O_2	Oxygen
OCED	Office of Clean Energy Demonstrations
R&D	Research and development
RCSP	Regional Carbon Sequestration Partnership
RD&D	Research, development and demonstration
RITAP	Regional Initiative for Technical Assistance Partnerships
SEI	Subsurface Energy Innovation
SMART	Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications
SO_x	Sulfur oxides
SRMS	Storage Resources Management System
TEA	Techno-economic analysis
UIC	Underground Injection Control
yr	Year

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1. Overview

1.1 Introduction and Background

The U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) Carbon Transport and Storage (CT&S) Program was initiated in 1997 to advance carbon storage technologies and to demonstrate the viability, safety and security of large-scale geologic storage of carbon dioxide (CO_2) (DOE-FECM, n.d.). Prior to 1997, the direct experience and knowledge within the United States related to the geologic storage of CO_2 was primarily focused on CO_2-enhanced oil recovery (CO_2-EOR), which emerged in the 1970s. The application of CO_2 injection for the purposes of CO_2-EOR and decades-long experience of commercial demonstration serve as a technological foundation for the CT&S Program's evolved focus in permanent geologic carbon storage in secure and dedicated geologic formations.

Prior to the appropriations enacted by the Bipartisan Infrastructure Law (BIL), the CT&S Program invested more than $2 billion over two decades to support carbon transport and storage research, development and demonstration (RD&D) projects. Notably, the CT&S Program supported the Regional Carbon Sequestration Partnerships (RCSPs) initiated in 2003 that securely stored approximately 27 million metric tons (MT) of CO_2 through multiple pilot- and large-scale injection tests in the United States (NETL, 2020). These pioneering projects demonstrated several outcomes, including (1) CO_2 can be injected and stored effective in different types of geologic formations throughout the United States; (2) the subsurface movement of CO_2 and resulting changes in geologic storage reservoirs can be monitored; and (3) the long-term fate of CO_2 within geologic storage reservoirs can be predicted and managed. The RCSPs also informed the existing regulatory framework that were developed to be rigorous and capable of managing permitting and review actions while protecting the environment, public health and safety as carbon capture and storage (CCS) projects move forward (CEQ, 2021). While these are important achievements, 27 million MT represent a fraction of annual U.S. greenhouse gas (GHG) emissions today (Larson, et al., 2021), and a concerted and collaborative approach to enable large-scale CCS and carbon dioxide removal (CDR) infrastructure development will be required to achieve net-zero GHG emissions targets economy-wide by midcentury (U.S. Department of State, 2021).

DOE-FECM's Strategic Vision, released in 2022, sets a steep trajectory for annual injection rates and associated CO_2 storage resource utilization over the next 20 years to facilitate reaching national CO2 emissions reduction goals. The nation-wide goal of commercial injectivity of 250 million MT/yr by 2035 will be supported by a 100 million MT/yr injectivity contribution by DOE-FECM (Exhibit 1-2).

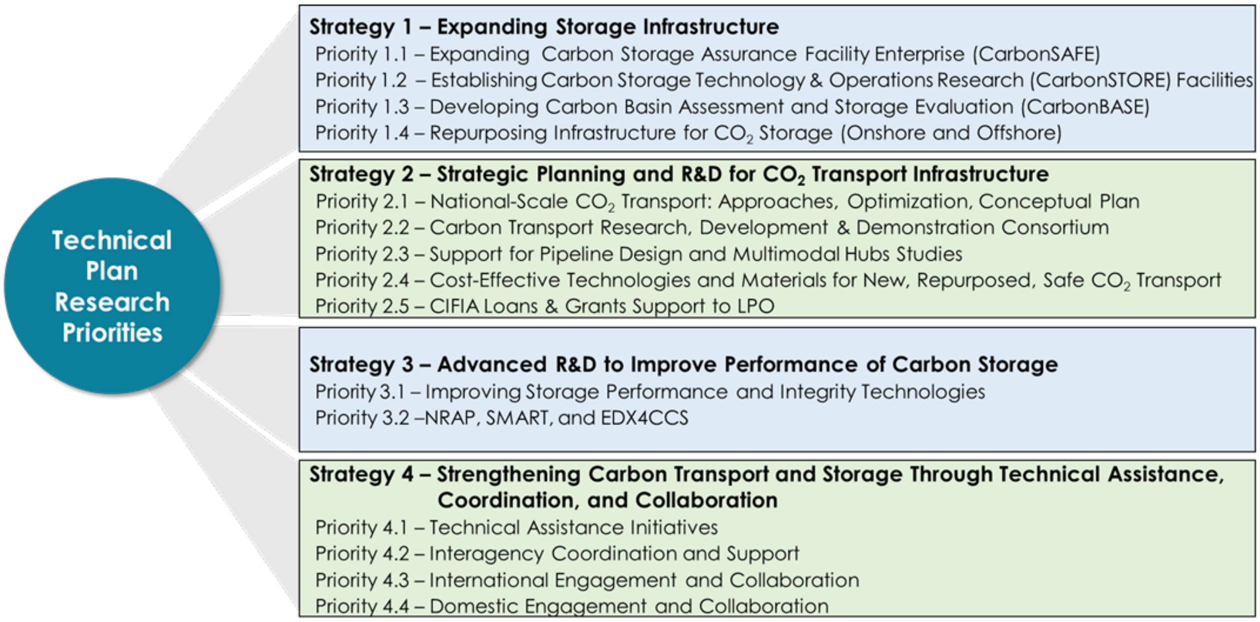
Collectively, the CT&S Program activities have strategically addressed evolving challenges related to deployment and commercial-scale lift-off of carbon transport and storage technology. This multiyear program plan (MYPP) describes the CT&S Program's planned initiatives and RD&D activities, which are designed to ensure that the expected growth in the utilization of the nation's carbon storage resources in a safe and efficient manner. Investments in these initiatives will be critical for meeting national net-zero GHG emissions goals as the investments can work in parallel with other DOE investments (i.e., Carbon Capture Demonstrations, Direct Air Capture Hubs, Industrial Demonstrations Program and Regional Clean Hydrogen Hubs) to support other clean energy industries that will utilize CO_2 transport and storage.

Funding for the MYPP activities is anticipated to be covered by and within scope of the Bipartisan Infrastructure Law (BIL) appropriations (i.e., BIL Sections 40305, 40303 and 40307) and congressional appropriations enacted annually for the base CT&S Program. Of the BIL Section 40305 funding, $2.5 billion is intended to catalyze the growth of large-scale carbon storage projects and hubs. BIL Section 40303 provides $100 million for front-end engineering design (FEED) of transport infrastructure for carbon storage. DOE's coordination on BIL appropriations with other federal agencies, including with U.S. Department of the Interior, is highlighted in Exhibit 2-8. In parallel, the annual base program funding will focus on field- and lab-based RD&D projects and technology advancements that can lower deployment costs and mitigate investment risks while improving performance. The CT&S base program activities are strategically aligned to address high priorities and to complement BIL-funded initiatives that include CO_2 transport and storage.

1.2. CT&S Program Alignment with DOE-FECM Carbon Management Initiatives

The activities of the CT&S Program's MYPP are organized according to four strategies and associated research priorities outlined in the DOE-FECM Strategic Vision Report, as shown in Exhibit 1-1. These strategies combine infrastructure expansion initiatives with priority technology development activities to create a pathway for accelerating the deployment of CCS and CDR. Section 1.3 of this report provides more detailed descriptions of the goals and expected outcomes of implementing these strategies over the next 10 years. Within Section 2, the technical plan details the individual priorities for each of the four strategies.

Exhibit 1-1. Priority R&D areas supporting the four strategies for accelerating at-scale deployment.



DOE-FECM's carbon management strategies also support other DOE initiatives, such as the Energy Earthshots Initiative, which aims to accelerate breakthroughs of abundant, affordable and reliable clean energy solutions within the next decade to reach the goal of net-zero GHG emissions by 2050. The Earthshots Initiative is designed to drive integrated program development across DOE's Science and Innovation office, Infrastructure office, and Advanced Research Projects Agency – Energy (ARPA-E). The geologic CO_2 storage technologies developed by the CT&S Program and outcomes of future RD&D efforts have potential applications in several Earthshots (DOE, 2023) that will require transport and geologic storage of captured CO_2.

Another DOE office, the DOE's Office of Clean Energy Demonstrations (OCED), was established in 2021 to accelerate market adoption and deployment of decarbonized energy systems by supporting at-scale clean energy demonstration projects. OCED's portfolio includes relevant carbon management provisions, including Carbon Capture Large Scale Pilots and Demonstrations, Direct Air Capture Hubs, Industrial Demonstrations Program, and Regional Clean Hydrogen Hubs. These commercial demonstrations will rely on CO_2 transport and geologic storage technologies.

The CT&S Program is also engaged in the Subsurface Energy Innovation (SEI) Crosscut, formed to identify strategic approaches for collaborative work specific to subsurface resources. Within this crosscut, a team of representatives from multiple DOE offices identified common challenges for multiple subsurface energy and environmental applications. The CT&S Program will consider these challenges when identifying opportunities that build on the activities outlined in this MYPP.

1.3. CT&S Program Goals

With transformative investments for carbon management from the BIL and the Inflation Reduction Act (IRA), alongside the administration's incremental net-zero GHG emissions goals leading up to 2050, it is beneficial to frame the MYPP in three distinct phases. The entirety of CT&S Program activities up to 2025 is referred to as the ***Validation Phase*** **(inception–2025)**, during which investments have focused on testing, validating and further demonstrating the geologic CO_2 storage technologies. Funding provided through the BIL will accelerate the build-out of commercial-scale individual and hub storage facilities and transport systems. The build-out period of these systems is referred to as the ***Activation Phase*** **(2025–2030)**. Following the *Activation Phase*, the ***Expansion Phase*** **(2030–2035)** will begin, during which the investments made by the CT&S Program will augment the expansion of industry-led CCS and CDR projects initiated during the *Activation Phase*. The CT&S Program's initial anchor points, including nationwide commercial storage facilities as well as large regional storage hubs and associated pipelines, will establish a common infrastructure upon which the emerging industry can expand national-scale deployment. The key goals associated with each phase and its related timeline, shown in Exhibit 1-2, are based on current and future required CT&S Program appropriations.

Exhibit 1-2. Key goals for the CT&S Program

	2025 VALIDATION	5-YEAR GOAL 2030 ACTIVATION	10-YEAR GOAL 2035 EXPANSION
Targeted Commercial Injectivity[1]	5 million MT/yr	65 million MT/yr	Up to 100 million MT/yr
Contingent Storage Resource[2]	Identify 1,500 million MT	Identify 5,500 million MT	Identify 6,000 million MT
Facilitating and De-risking Storage Deployment[3]	• Technical and community engagement assistance up to 6 large-scale/hub storage developers. • Identify storage resources across 15 states, 8 basins, Mid-Atlantic Offshore, and the GOM.	• Monitoring systems for basin-scale site selection and storage performance. • Up to 5 CarbonSTORE facilities.	• Up to 2 commercial in situ mineralization projects underway.
CO_2 Transport Infrastructure	• At least 5 FEED/Pre-FEED studies on regional and/or national network infrastructure. • 4 CIFIA loans or Future Growth Grants and begin NEPA reviews. • Establish Transport RD&D Consortium, fund early-stage and applied research.	• At least 5 Pre-FEED and FEED studies on regional and/or national network infrastructure that can transport 250 million MT/yr. • Complete NEPA process and begin construction of transport network.	• Complete FEED studies on regional and/or national CO_2 transport networks. • Conclude research funding for Transport RD&D Consortium, report technology transfer.

1. "Targeted Commercial Injectivity" refers to CarbonSAFE projects for target injection rates estimates listed in their granted (passed the final decision phase) "permit to construct" UIC Class VI permit applications.
2. "Contingent Storage Resource" refers to the amount of storage (as classified through application of the SRMS system) for the estimated storage resource in CarbonSAFE projects.
3. "Facilitating and De-risking Storage Deployment" refers to the knowledge sharing as well as other technical help DOE co-funded projects are performing to facilitate designing, permitting, and deployment of secure storage projects.

Accomplishing these goals will accelerate the responsible deployment of CCS and CDR in the United States. Accordingly, initiatives supported by the base program will create the technological foundation for expanding CCS and CDR deployment in complex geologic settings, which will de-risk the next generation of storage projects and enable an expansion of CT&S infrastructure that is aligned with achieving national net-zero GHG emissions goals.

1.3.1. Quantification of Resources

Over the past two decades it has been widely acknowledged that a systematic approach for estimating storage resource volumes is necessary to convey the technical and commercial aspects of projects. Applying a standardized set of methods and definitions allows for clear communication between project developers, government entities and other stakeholders.

In 2017, the Society of Petroleum Engineers (SPE) published the Storage Resource Management System (SRMS), which has since been widely adopted due to the parallels it draws with the globally accepted Petroleum Resource Management System (PRMS) used for reporting hydrocarbon resources. In 2024, the United Nations Economic Commission for Europe (UNECE) agreed to develop a bridging document to correlate the SRMS with the United Nations Framework Classification (UNFC).

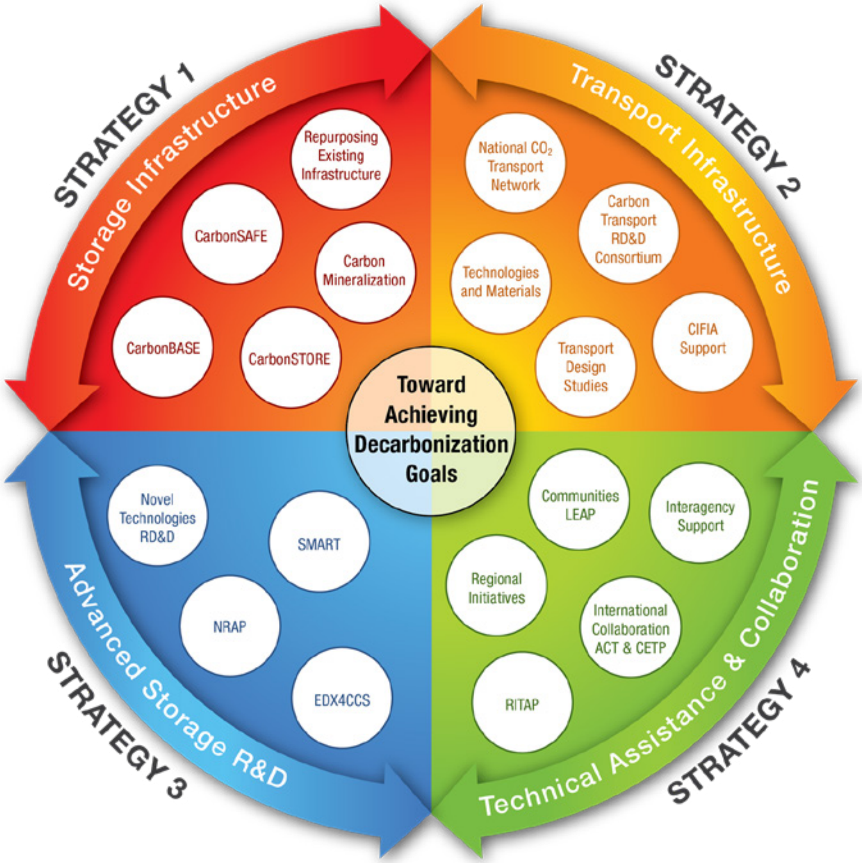
The SRMS combines certainty in the estimate of CO_2 storage capacity with the maturity of a project that is ultimately intended to inject and store CO_2. The use of specific terms to describe combinations of storage capacity certainty and project maturity helps clarify differences between CO_2 storage estimate methods and certainty of storage estimates, while improving communication between stakeholders that will promulgate CO_2 storage (SRMS, 2017).

All DOE storage projects will be reporting using the SRMS, where applicable. As seen in Appendix A, the phases of Carbon Storage Assurance Facility Enterprise (CarbonSAFE) projects easily correlate to the SRMS, with the most common category being Contingent Resources (Phase II/III). The project activities funded by the CarbonSAFE Initiative serve to remove the contingencies that will ultimately lead to the classification of capacity.

2. Technical Plan

The technical plan describes the four strategies mentioned in Section 1.2 and provides details of the various RD&D initiatives that will be pursued to meet the CT&S Program's goals. The plan includes both BIL-funded and base program-funded activities (Exhibit 2-1) that are integrated as a holistic approach to achieving the goals.

Exhibit 2-1. CT&S Program's technical plan with various ongoing and planned RD&D initiatives



2.1. Strategy 1 — Expanding Storage Infrastructure

The storage infrastructure strategy focuses on five interfacing initiatives: Carbon Basin Assessment and Storage Evaluation (CarbonBASE), CarbonSAFE, Carbon Storage Technology Operations and Research (CarbonSTORE), Carbon Mineralization, and Repurposing Existing Infrastructure. The CarbonSAFE Initiative focuses on developing multiple, new large-scale storage facilities throughout the United States. The base program-funded CarbonSTORE Initiative will focus on accelerating the development of commercial-ready storage technologies that can be tested and validated at sites with relevant infrastructure and geologic settings, and at operating-scale storage sites, potentially including CarbonSAFE sites. The base program-funded CarbonBASE Initiative will focus on addressing basin-scale considerations related to the expansion of CarbonSAFE and industry-led CO_2 storage deployment to ensure the safe and efficient management of storage resources and de-risk future storage deployment by developing storage resource management tools.

In combination, these initiatives link the expansion of pore space **utilization** (CarbonSAFE) with pore space **assessment** of future sites and basin-scale resource management (CarbonBASE) in parallel with technology advancements that improve **performance** at lower cost and lower risk (CarbonSTORE). The program's comprehensive strategy will also include evaluating the potential for repurposing existing oil and gas infrastructure that is suitable for CO_2 storage injection or monitoring. Evaluating the potential to repurpose infrastructure will identify opportunities where CCS and CDR can leverage investments already made by the oil and gas and other related industries. The following subsections provide additional details on each of these initiatives.

2.1.1. Expanding CarbonSAFE

The CarbonSAFE Initiative began in 2016 to facilitate development of commercial-scale storage facilities, each with the capacity to store more than 50 million MT of CO_2, from conception to construction. The CarbonSAFE Initiative has been carried out in a phased approach representing the different stages of development in a storage project. Specifically, this includes Phase I — Integrated CCS Prefeasibility; Phase II — Storage Complex Feasibility; Phase III — Site Characterization and Permitting; Phase III.5 — National Environmental Policy Act (NEPA), FEED Studies, and Storage Field Development Plan Only; and Phase IV — Construction. As shown in Exhibit 2-2, these phases are designed to advance a storage project by working with the community, industry and other stakeholders to formulate a multidisciplinary team to characterize, permit and construct a project.

In the first six years of implementation, the CarbonSAFE Initiative completed 19 projects (13 Phase I; six Phase II) and initiated five Phase III projects. Over a five-year period encompassing Fiscal Year (FY) 2022 through FY 2026, the BIL will expand and accelerate the CarbonSAFE Initiative by investing a total of $2.5 billion for Carbon Storage Validation and Testing (Section 40305). The funding is targeted for the development of new or expanded large-scale carbon storage projects and associated CO_2 transport infrastructure. In FY 2023, DOE selected 11 new Phase II projects and nine Phase III projects, with 40 projects across all CarbonSAFE Phases anticipated through FY 2026. Exhibit 2-3 shows the locations of the current CarbonSAFE Phase I, Phase II and Phase III projects, as well as transport FEED studies across the United States. The CT&S goals for 2030, detailing targeted commercial injectivity, capacity, and contingent resources (Exhibit 1-2), will be supported by CarbonSAFE projects. This involves detailed characterization of locations where sufficient subsurface data may not currently be available, addressing site-specific technical challenges related to different geologic settings, progressing into offshore storage settings, and consideration of unconventional storage options (e.g., basalts). These efforts will be informed by the results of storage resource assessments that will be implemented by other elements of the CT&S Program, including CarbonBASE.

Exhibit 2-2. Activities and deliverables of the CarbonSAFE Initiative

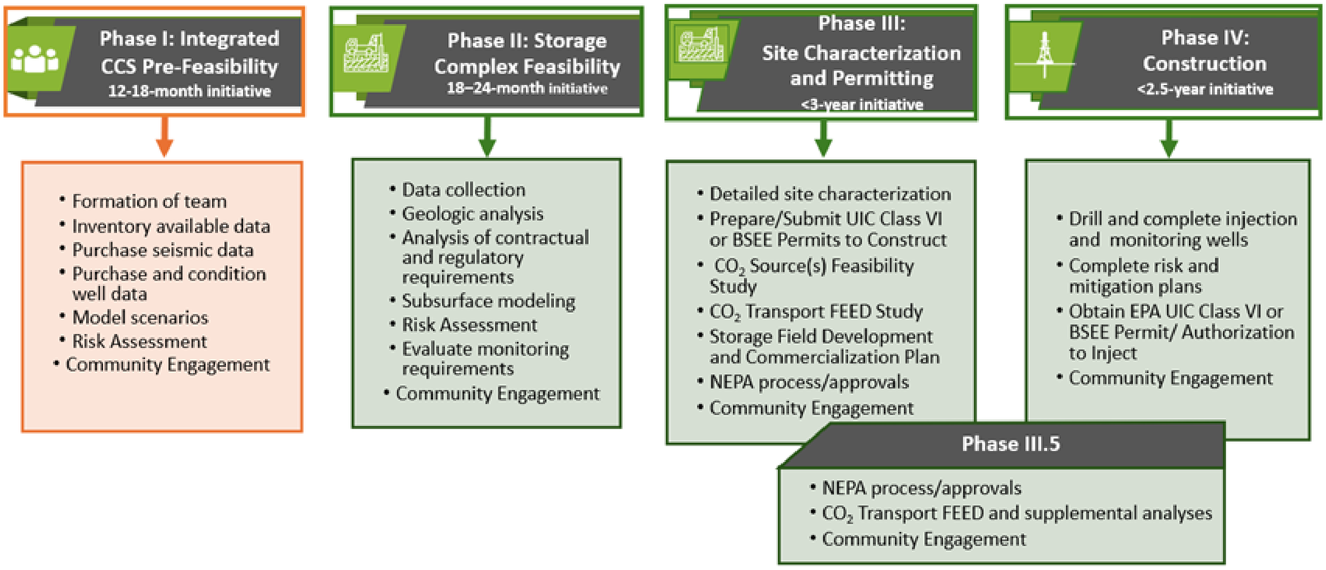
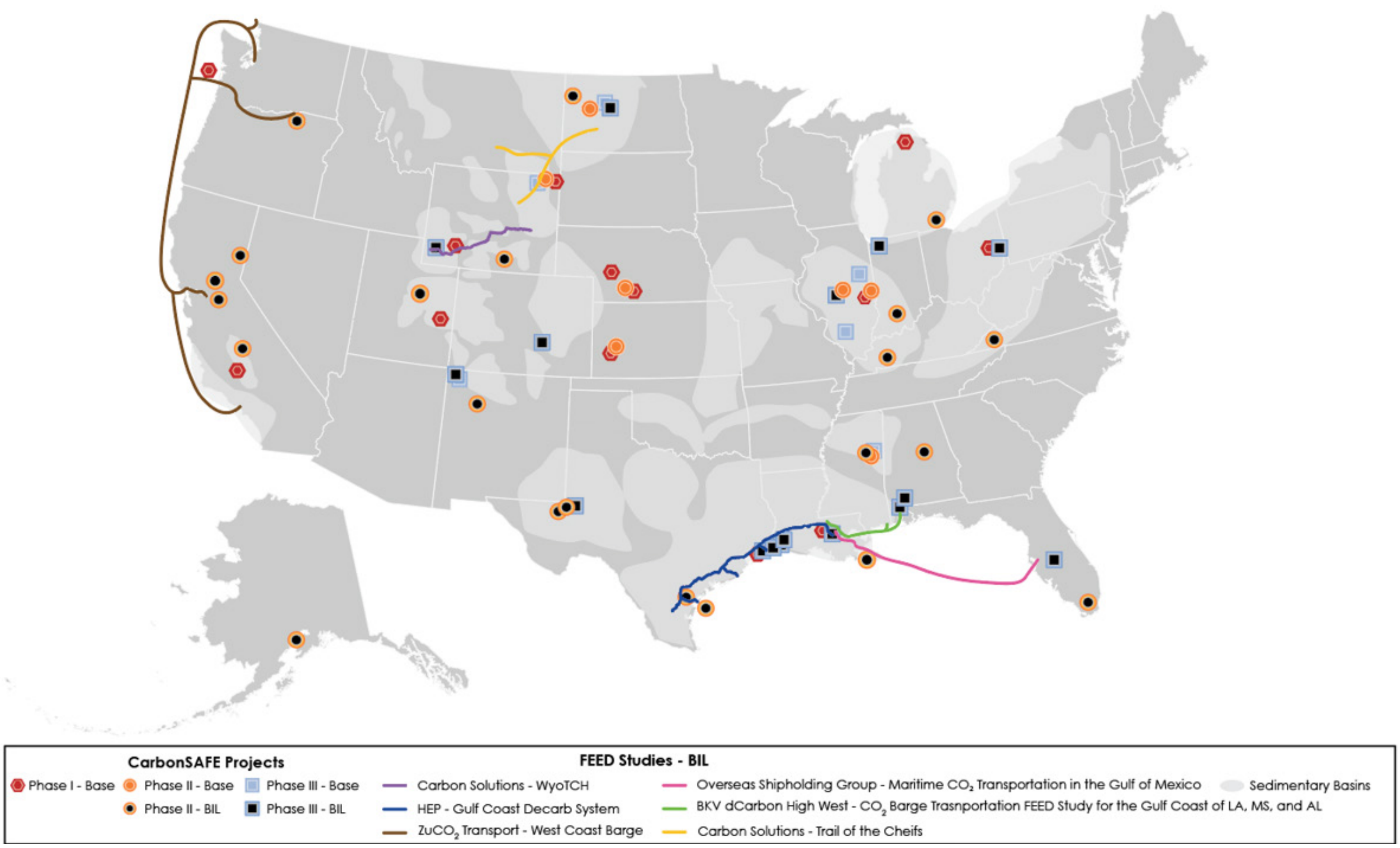


Exhibit 2-3. Map of the contiguous United States depicting sedimentary basins; FEED pipeline studies; and locations of CarbonSAFE Phase I, II and III projects



The portfolio of characterized and permitted storage facilities developed through the CarbonSAFE Initiative will facilitate regional approaches for decarbonization across the United States. As noted in Section 1.3.1, the CarbonSAFE Initiative is aligned with implementing the SPE SRMS (UNECE, 2023)(SPE, 2017) to classify the commercial potential of storage projects and quantify and categorize storage resource estimates. For further explanation regarding the intersectionality between the CarbonSAFE Program and SRMS classification, refer to Appendix A: Relationship Between CarbonSAFE and SRMS.

Across the nation, the CT&S Program's CarbonSAFE facilities will support foundational regional infrastructure for the development of economic geologic storage projects in diverse geologic settings and understudied regions, including offshore opportunities during the Validation Phase and Activation Phase.

2.1.2. Establishing CarbonSTORE Facilities

With the implementation of CarbonSAFE and a growing number of independent, industry-led CCS and CDR projects, DOE-FECM recognizes an opportunity to leverage carbon storage sites and associated infrastructure for testing storage performance and validating next-generation, lower-cost technologies, such as real-time monitoring of pressure evolution; pressure interference; and their effects on injectivity, storage efficiency and induced seismicity risk. In 2025, DOE-FECM plans to launch a multiyear, field-based RD&D initiative called Carbon Storage Technology and Operations REsearch (CarbonSTORE) that will establish a series of field laboratories in different geologic settings to (1) facilitate enhanced data gathering for new technology development, (2) accelerate emerging technology validation, and (3) provide real-world performance feedback for operational improvements and optimization.

These CarbonSTORE facilities may be aligned with CarbonSAFE projects, other CCS projects, or sites with relevant infrastructure and geologic settings (i.e., depositional environments). Through this approach, DOE-FECM expects to enable storage performance evaluation and technology validation at-scale and thereby fast-track technology deployment. The tools and technologies that can be tested at CarbonSTORE facilities will support safe and efficient operations of commercial geologic CO_2 storage facilities in diverse geologic settings, which is a key component to de-risking future carbon storage projects.

2.1.3. Developing CarbonBASE

The scale-up of CCS will necessitate deploying secure geologic CO_2 storage in diverse geologic settings across multiple basins throughout the United States. Multiple storage projects, including CarbonSAFE projects, are currently in development across a range of promising storage basins. One of the challenges associated with storage scale-up is relying on available, often disparate data to identify and select multiple geologic storage sites within a basin. Additionally, as numerous individual and hub-scale projects become operational within a basin, consideration must be given to the safe and efficient utilization of available carbon storage resources, along with other subsurface uses in the basin.

To address potential limitations associated with data availability and accessibility, as well as new challenges that may arise with the deployment of multiple CCS and CDR with storage projects in a single basin, DOE-FECM is establishing a new initiative called the Carbon Basin Assessment and Storage Evaluation (CarbonBASE).

The key objectives of CarbonBASE are to:

- Strategically collect, interpret and share critical information and data for multiple basins.
- Develop tools for managing carbon storage resources across entire basins to help:
    - Inform project siting.
    - Inform policy development.
    - Build public trust and confidence.
- Develop and install basin-wide monitoring systems to assess basin-scale influences of multiple storage projects operating simultaneously (CEQ, 2022).
- Provide expertise and tools to help regional stakeholders enable a basin- or region-specific system of governance for their carbon storage resources.

Meeting these objectives is expected to require multistakeholder partnerships that span multistate regions. The data and tools developed through multiple CarbonBASE Partnership projects will assist project developers in selecting storage sites, support consideration of basin-scale interactions of projects, and provide a system for monitoring and managing subsurface CO_2 storage resources within basins. Additionally, data generated by CarbonBASE projects will be publicly accessible to enhance transparency and build stakeholder confidence in geologic storage. The CarbonBASE Initiative will also promote the identification and utilization of crosscutting and collaboration opportunities with other DOE program offices.

2.1.4. Carbon Mineralization Storage

Carbon storage through mineralization represents another approach to achieving permanent, safe and secure CO_2 storage. Carbon dioxide mineralization involves the reaction of CO_2 with abundant minerals, such as olivine and serpentine, to form stable carbonate minerals such as magnesite, dolomite and calcite. Carbon dioxide mineralized into a solid form following injection represents another permanent form of CO_2 storage (National Academies of Sciences, 2019). Carbon dioxide mineralization storage may be accomplished through ex situ or in situ processes. In situ processes involve circulating CO_2 bearing fluids in suitable rock formations, such as basalts, in the subsurface. Ex situ processes involve reacting CO_2 with solid reactants at the surface.

Pilot in situ projects like CarbFix Silverstone in Iceland have demonstrated that CO_2, as a saturated mixture in water and injected into basaltic rock, can be mineralized within two years of injection (Matter, et al., 2016). Additionally, the Wallula Pilot Project in Washington demonstrated the rapid mineralization of 1,000 MT of liquid-phase CO_2 injected into a basalt formation (McGrail, et al., 2017). While these results are promising, in situ CO_2 mineralization has not yet been deployed and demonstrated at large scale. Within CarbonSAFE, CarbonSTORE and CarbonBASE, the CT&S Program will support RD&D to help advance CO_2 mineralization storage by investing in studies to better understand the relevant geochemical and geomechanical processes, as well as to develop or adapt modeling and monitoring tools as needed. The goal of these efforts is to ensure modeling and monitoring tools can accurately represent fluid, chemical and petrophysical dynamics in an in situ CO_2 mineralization storage project. This goal is critical for geologic storage projects in reactive rock formations with an expected high rate of mineralization to have modeling and monitoring solutions.

CT&S Program objectives specific to demonstrating CO_2 mineralization as viable in situ and ex situ CO_2 storage options at scale include:

- Improving understanding of the interaction between carbonated fluids and geological formations, which can affect the integrity and permeability of the storage site.
- Improving understanding of the thermodynamic conditions suitable for mineralization.
- Evaluating induced seismicity and containment risk as compared to conventional storage reservoirs.
- Developing methods to calculate storage capacity in fractured basalts and approaches to determine associated storage capacity within the SRMS framework.
- Evaluating monitoring technologies and approaches most effective in basalts and similar reactive rock-type conditions, particularly for potential storage reservoirs without a caprock seal.
- Developing, testing and verifying modeling and monitoring methodologies and tool sets.

Similar processes are involved in both in situ and ex situ mineralization and as RD&D efforts proceed, the CT&S Program continues to integrate with the DOE-FECM CDR Program's RD&D on ex situ CO_2 mineralization coupled with value-added byproducts. The DOE-FECM CDR MYPP includes additional details on areas of coordination between both programs for CO_2 mineralization.

2.1.5. Repurposing Infrastructure for CO_2 Storage Onshore and Offshore

Meeting the national CO_2 emissions reduction goals will require the development of national-scale CCS infrastructure. The existing national oil and gas infrastructure, including transport pipelines and wells, represents an opportunity to facilitate the development of the required CCS infrastructure. Reusing or repurposing existing infrastructure for CO_2 storage could offer financial benefits through cost-savings and has the prospect of expediting CCS deployment. Additional potential benefits include avoiding further land disturbances and minimizing environmental impacts associated with developing new infrastructure projects. However, reusing existing infrastructure presents challenges such as determining its availability and compatibility with expected operational conditions and environments, and in ensuring its safety and long-term integrity as part of CCS infrastructure. Repurposing research needs were first identified through a DOE-sponsored event entitled "Carbon Transport and Storage R&D Priorities for Repurposing Infrastructure Workshop" in 2022, and further identified in a DOE-sponsored 2023 workshop on this topic entitled "Workshop on Applied Research for CO_2 Transport." Additional information is available within both workshop summary reports.

2.2. Strategy 2 — Strategic Planning and R&D for CO_2 Transport Infrastructure

The role of CO_2 transport in carbon management is connecting regions of capture with areas of storage. In the context of DOE-FECM's broad strategic portfolio, the role for the carbon transport program is to ensure optimal integration with other large-scale DOE initiatives. From an economic standpoint, strategies pursued can enable benefits in the form of a robust CO_2 transport and storage industry offering accessible, well-paying jobs. Exhibit 2-4 lists the priority research and development (R&D) areas the CT&S Program will support going forward in the order they were presented within the workshop's summary report.

Exhibit 2-4. Priority transport R&D topics

- **Transport Studies**
    - Evaluate and identify potential manufacturing and supply chain constraints for transport and storage materials of construction.
    - Continuously consolidate existing research into an open repository for CO_2 transport data and models.
- **Leak Detection, Impurities and Emergency Response**
    - Advance the development of digital and physical tools for metering CO_2 for monitoring, reporting and verification.
    - Conduct longer-term research to evaluate the impact of impurities have on fluid behavior, corrosion and material performance at bench and pilot scales.
    - Research and advance the development of digital and physical leak detection and monitoring capabilities for CO_2 and impurities.
    - Research and advance the development of tools to assess risk exposure to CO_2 with impurities for stakeholders and community applications (e.g., first responders, repair crews and the public).
    - Research and advance the development of improved dispersion modeling tools relative to existing tools to support the development of transportation system design and emergency response to potential accidental releases to the environment.
- **Repurposing Existing Infrastructure**
    - Support and advance the development of industry standards and best practices for CO_2 service material qualification and testing.
    - Support and advance the development of industry standards and best practices for potential transport and storage infrastructure repurposing.
- **Multimodal Transport and Intermodal Hubs**
    - Develop and advance techno-economic analysis tools that incorporate multimodal and intermodal transportation modes.
    - Advance the development of at-scale, coastal and international CO_2 marine shipping design and operations.
    - Research and evaluate the economic feasibility of CO_2 marine shipping by U.S. inland waterways.

2.2.1. National-Scale CO_2 Transport: Approaches, Optimization, Conceptual Plan

The activities described under this subsection will utilize DOE-FECM program funds and will support effective execution of BIL transport programs. The program will conduct detailed studies to develop an optimal conceptual plan for a robust, safe and efficient national-scale CO_2 transport infrastructure by leveraging multiple modes of transport. New infrastructure will be required to support a national-scale CO_2 transport network and may include CO_2 transport by a variety of modes, such as pipeline, railways, trucks and ships. Based on the unique attributes and scale of each region within the United States, proposed tools and studies support the evaluation and customization of unique carbon transport networks. These networks will enable regional- to national-scale optimization and support meaningful stakeholder engagement on the tradeoffs between transportation modes. Because there is some uncertainty in siting future storage and capture developments, transport networks will continue to adjust and evolve, requiring thoughtful, periodic updates to tools and studies.

From an economic point of view, pursued strategies should maximize benefits in the form of a robust CO_2 transport and storage industry offering high-paying jobs made accessible to communities. Tools such as techno-economic analyses (TEAs) and life cycle assessments (LCAs) will contribute to the optimization of both environmental and economic returns. Ongoing tool development and analyses are needed and should provide refined useful insights and inform future strategic initiatives.

The LCA and TEA studies, which will evaluate each transport mode, can additionally clarify national and regional carbon capture, utilization and storage (CCUS) policies. A coordinated and proactive communication and engagement strategy utilizing LCA and TEA study results will support addressing public concerns throughout CO_2 transport infrastructure development.

This MYPP is informed by the DOE-FECM Roadmap for CO_2 Transport Fundamental Research Workshop (hereafter the "Transport Workshop") held in February 2023 (DOE-FECM, 2023). Approximately 100 individuals from federal agencies, industry, academia, nongovernmental organizations (NGOs), national laboratories and other stakeholders gathered to share their independent views on identifying:

- Near-term challenges and RD&D areas of interest.
- Potential participants in ongoing and future RD&D efforts.
- Whether a CO_2 Transport Research Consortium would advance CCUS deployment and remove potential barriers to future success.

The following key needs were identified and have been integrated into the MYPP strategy:

- Development of a CO_2 Transport Research Consortium that coordinates RD&D efforts and facilitates communication among stakeholders.
- Compilation and curation of information in an open-access platform to facilitate gap analyses.
- Acceleration of experimental and modeling R&D efforts to keep pace with the timeline for demonstration projects and at-scale deployment.
- Creation of pathways to engage and grow the workforce.
- Collaboration and engagement with the public.

DOE-FECM CT&S program funding will be key in resolving these technical and non-technical challenges through proactive work and outreach. Examples of potential strategies include leveraging and amplifying DOE-FECM's technical assistance, coordination, and collaboration efforts; and actively coordinating research and outreach with other key Federal agencies such as the Department of Transportation, Department of the Interior, and Department of Homeland Security through interagency working groups. These working groups amplify the ongoing outreach led through regional initiatives, and planning and supporting future outreach with industry and academia through the proposed transport RD&D consortium. Transport funding actions under the DOE-FECM program aims to lower business risk and build synergies between private and public sectors. They will also enhance transport activity effectiveness by generating awareness that historical barriers to transportation infrastructure development are addressed.

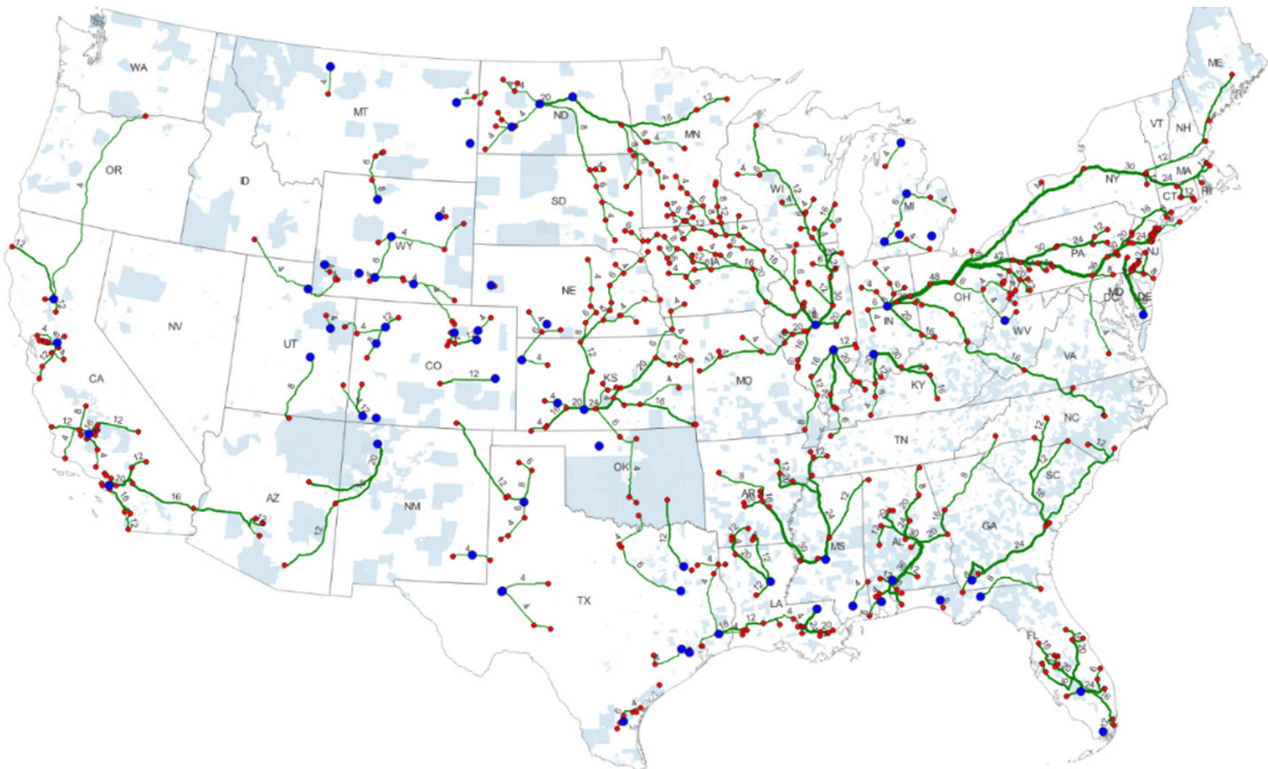
The CT&S Program will inform and interact with the two task forces on CCUS permitting that were tasked by Congress with identifying priority pipelines and to investigate opportunities for permitting reform (DOE, July 2, 2024). At the May 2024 kickoff of these task forces, the CT&S Program presented information about priority pipelines and how modeling efforts through DOE-FECM can assist in establishing them (DOE, May 2024). The task forces also learned about the federal financing opportunities available through DOE-FECM to project developers from the BIL provisions for transport FEED studies and loans and grants for construction.

2.2.2. Support for Pipeline Design and Multimodal Hub Development

DOE-FECM program funding will support CO_2 transportation system design and development of multimodal hubs. The planning of a national pipeline network presents challenges in optimizing the network design for cost, size, connectivity between sources and sinks, and other factors. Publicly available models are being developed to evaluate the performance and cost of CO_2 pipeline infrastructure under specific CCS scenarios. For example, the National Energy Technology Laboratory (NETL) CO_2 Transport Cost Model (Morgan, Guinan, & Sheriff, 2022) calculates diverse cost scenarios for a single point-to-point pipeline. It allows users to adjust values for input variables such as CO_2 mass flow rate, pipeline length, project duration and financial inputs to match their project requirements. The model can also calculate costs in real (i.e., constant) or nominal (i.e., escalated) dollars.

Los Alamos National Laboratory's SimCCS evaluates financial risk and determines optimal investment solutions, including pipeline infrastructure design for implementing CCS technologies. To date, DOE-FECM program funding of SimCCS models has been used in conceptualization studies for both regional-scale (EFI, 2020) (LEP, 2021) (Ma, Chen, & Pawar, 2023) (Ellett, Middleton, Stauffer, & Rupp, 2017) and national-scale CO_2 transport development (Abramson, McFarlane, & Brown, 2020). These models can provide useful forecasts on the size and scale of future carbon transport development activity. A recent study estimated that one possible future network totaling 28,547 miles of CO_2 pipelines is plausible to achieve net-zero goals by midcentury (Exhibit 2-5) (Chen, 2022). Carbon transport modeling and associated forecasts can be further refined through model improvements such as adding multimodal transportation applications and further LCA and TEA analyses.

Exhibit 2-5. High-removal scenario — pipeline infrastructure in 2050



Source: Los Alamos National Laboratory (Chen, 2023)

In the future, DOE-FECM program funds will support studies and projects to facilitate and optimize a robust, national-scale CO_2 transport network. The near-term goal for 2030 is to expand the nation's capability to transport 65 million MT of CO_2 annually. The long-term goal for 2050, aligned with a net-zero GHG emissions strategy by midcentury, is to ensure the capability to transport one gigaton of CO_2 per year.

Carbon dioxide is typically in either a liquid, dense-phase, or a supercritical state during transportation. Liquid CO_2 transport by insulated tanker trucks, rail, barges and ships is technically feasible and has the potential to complement CO_2 pipeline transport to achieve 2050 goals. Multimodal transportation options can allow for greater source-to-sink flexibility and scale to connect potentially geographically isolated CO_2 providers to transportation and storage sites over time. Given these potential advantages, multimodal transportation modes can provide additive utility by unlocking new CCUS value chain possibilities that may not be otherwise practical.

Although not currently in use in the United States for CO_2 transport, barging and coastal shipping may prove to be viable transport alternatives where waterways are available. One such example is in coastal states with potentially large geologic resources (e.g., Texas, Louisiana and Alaska) where local and internationally sourced CO_2 may be stored more cost-effectively through economies of scale. Preliminary analysis for both rail and truck transport analyzed separately suggests that rail may represent a good alternative for longer-distance transport (Holubnyak & Quillinan, 2022). Truck transport may be best applied for delivering CO_2 from a source over relatively short distances as a link to other transport infrastructure, such as a train or pipeline. There is additional interest in dual- or multiuse transport carriers that are capable of transporting CO_2 and other low-carbon energy products such as hydrogen or ammonia.

Multimodal designs may also increase technical complexity in a system design. Those technical complexities — such as CO_2 stream mixing, impurities management, and impact to materials and operations — will continue to be an area of active research. Carriers may require a new class of container to be developed. DOE-FECM program funds will support additional work to commercially integrate multimodal transport into regional CCUS hubs, including (1) advancement of containers to transport CO_2 safely and economically, (2) implementing TEA/LCA along with risk analysis, (3) system network design and optimization, and (4) innovations in business models.

DOE-FECM program funds will be key in deploying CO_2 infrastructure at scale and will require cross-sector coordination both within and outside of DOE. The solution involves the formation of a research consortium focused on transport as described in this MYPP. Consortium activities will support coordination within DOE and with other federal agencies, such as but not limited to the U.S. Department of Transportation, the U.S. Department of the Interior, the U.S. Department of Commerce and the U.S. Environmental Protection Agency (EPA).

Insights gained from these studies and initiatives, such as the intended research consortium, can then inform the optimization of industry standards and best practices, as well as help develop the supporting regulations where necessary. Standards bodies include, but are not limited to, the Association for Materials Protection and Performance, the American Society of Mechanical Engineers, the American Petroleum Institute (API), Process Industry Practices, and the International Organization for Standardization.

Ultimately, the various modeling studies described in this section are supporting the advancement of project planning into FEED studies. The funding of FEED studies for regional-scale anthropogenic CO_2 pipeline projects was expanded to address other surface transportation mode projects, such as rail, barge, ship and truck, and can be intertransport and have multimodal hubs.

Multimodal pre-FEED studies are being funded and will support the development of infrastructure that facilitates transfer and temporary storage of CO_2 in regional and national CO_2 transportation networks. Such facilities will allow CO_2 streams with different physical characteristics (such as temperature and pressure) and trace impurities to be efficiently integrated into the transport networks and accommodate variations in flow rates and capacities among different transport modes.

Pre-FEEDs and then completed FEED studies can expedite future participation in the Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) program of loans and grants.

2.2.3. Cost-Effective Technologies and Materials for New, Repurposed and Safe CO_2 Transport

Technologies, best practices and specifications for CO_2 pipeline infrastructure require updates and further standardization to facilitate the efficient design, construction and operation of a national-scale CO_2 pipeline network that incorporates varying anthropogenic sources of CO_2. The existing oil and gas pipeline infrastructure represents a huge investment, which, if repurposed for anthropogenic CO_2 transport, can accelerate widespread CCUS deployment. Design improvements for both repurposed and new pipelines will require additional laboratory- and field-testing. There are four RD&D areas, elaborated on in high-priority transport R&D topics (Exhibit 2-4), that relate to pipeline performance challenges that DOE-FECM program funds will address through the considered transport consortium.

- **Impacts of CO_2 Stream Impurities on Metallurgy and Transport Efficiency**: Understanding the effects of impurities and various combinations with CO_2 (e.g., nitrogen [N_2], oxygen [O_2], hydrogen [H_2], carbon monoxide [CO], argon [Ar], sulfur oxides [SO_X], etc.) is necessary to account for issues that cause corrosion and performance of a transport system (Peletiri, Mujtaba, & Rahmanian, 2019).[1]
- **Fracture Propagation**: Studies are needed to update the Battelle Two-Curved Method (Maxey, November 1974) model and design guidelines encompassing different fluid compositions for CO_2, natural gas and other fluids at different conditions as required to take into consideration advancements in worldwide steelmaking, as well as the decompression behavior of CO_2.
- **Dispersion Modeling**: Current dispersion modeling software tools need to be updated to accurately model the complex physical processes associated with plume development and movement, as well as other variables such as pipeline characteristics, operating pressures, release rate, local terrain and meteorology.
- **Leak-Detection Methods and Emergency Response Protocols**: Detection methodology of supercritical CO_2 leaks from a pipeline requires refinement due to the phase change associated with the thermodynamic properties. Improved thermodynamic models, including various impurities effects, and sensing and measuring technologies can enhance leak-detection capabilities of CO_2 pipelines.

The DOE-FECM Transport Workshop provided valuable insights, including the intended need for a CO_2 Transport Research Consortium, consisting of a broad spectrum of participants involving labor, community, academia, industry and other partners. DOE FECM plans to support RD&D activities to investigate and address aforementioned topics while being cognizant of and collaborative with other federal agencies and industry-led research efforts. Additionally, in fulfilling one of the key recommendations from the "Transport Workshop," DOE-FECM aims to establish a CO_2 Transport RD&D Consortium, which is further discussed in the following section.

2.2.4. Carbon Transport Research, Development and Demonstration Consortium

In fulfilling one of the key recommendations from the "Transport Workshop," DOE-FECM aims to establish a Carbon Transport Consortium. This consortium is intended to identify initiatives for carbon transport RD&D efforts (e.g., pipeline, rail, truck, ship and barge transportation); facilitate communication among stakeholders; and compile and curate information in an open-access platform.

The consortium aims to connect disparate research activities within the CO_2 transport space and accelerate RD&D efforts across various modes of transportation, accelerate knowledge sharing between stakeholders, and leverage best practices from past federal research efforts to ensure success. Examples of successful research consortiums include DOE's Office of Energy Efficiency and Renewable Energy (EERE) H2@Scale and associated consortium (H-MAT, HyBLEND, etc.), and DOE-FECM's Subsurface Hydrogen Assessment, Storage and Technology Acceleration.

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[1] Additional information about the generation of impurities from flue gas carbon capture can be found at http://co2quest.eu/wp-content/uploads/2017/04/quality_guidelines.pdf.

As part of the consortium, RD&D activities funded through the DOE-FECM program should progress simultaneously with work from other agencies, and engagement from industry. Educational materials and a community and stakeholder communications plan should be developed and implemented to promote public awareness and provide venues for public consultation and engagement. Effective public requires providing practical opportunities for community and local stakeholder input and engagement should be the responsibility of all future consortium parties and requires constructive coordination as identified at the DOE-FECM Transport Workshop. Additionally, future communication efforts may leverage and build upon existing resources (e.g., the American Petroleum Institute's [API] Recommended Practice 1185 titled "Advancing Stakeholder Engagement through Two-Way Communication") and DOE-FECM's Societal Considerations and Impacts materials. The consortium is intended to comprise a range of organizations, including but not limited to:

- Federal agencies
- State agencies
- National laboratories
- Academia
- NGOs
- National or international standards bodies
- Industry owners and facility operators
- Service providers and equipment vendors
- Trade associations
- Manufacturing entities (e.g., pipe fabricators)
- Labor unions
- Tribal Nations
- Alaska Native Corporations
- International entities

The following benefits could be realized through the consortium:

1. **Work sharing and reduced costs**: The consortium would facilitate the sharing of resources and responsibilities across organizations. This would support cost reductions and time savings as new knowledge and technologies are developed.
2. **Increased national lab visibility**: The consortium would provide an opportunity for various DOE national laboratories to increase awareness surrounding their work product.
3. **Improve success**: The consortium would bring together professionals working toward mutual goals, resulting in better collaboration and cooperation among members.
4. **Growing network of knowledge**: The consortium would grow a network of quality connections and knowledge by providing:
    - Increased access to experts
    - Increased access to organizations
    - Increased access to peer-reviewed knowledge and data
    - Increased access to multimodal transport companies

The consortium will create opportunities to attract new members over time, bringing expertise to fill identified R&D gaps. DOE-FECM will use the consortium to solve the technical challenges identified for all modes of carbon transport.

One key action for the consortium will be to review the gaps identified from the 2023 Applied RD&D CO_2 Transport Workshop for their relevance toward safety regulation and policy issues, as well as with standards-developing organizations and for technology needs. Connecting relevant research to key end-users will support consortium efforts to effectively plan for both knowledge and technology transfer activities. For example, research coordination with API regarding "Impacts of CO_2 Stream Impurities on Metallurgy and Transport Efficiency" can aid in their efforts to evaluate allowable impurities for CO_2 pipelines. This goal can be supported through a diverse consortium membership grown over time and through a systematic plan to transfer research outputs into the hands of the most relevant end-users. These are the entities that can directly apply research results for use into new or revised standards or through technology improvements in the market.

2.2.5. CIFIA Loans and Grants for Transportation Infrastructure Construction

The objective of the CIFIA Program is to financially enable the growth of large-capacity common carrier CO_2 transport infrastructure, supporting up to 80% of the construction costs. The CIFIA-based build-out of infrastructure over this MYPP period is designed to fill the current and future demands necessary for connecting regions of capture with areas of storage. The CIFIA team will continue routine dialogue with the transport industry and other stakeholders regarding the capacity, cost and route modeling capabilities at the DOE and national labs.

The successful execution of funded programs — such as Carbon Dioxide Infrastructure Finance and Innovation Act (CIFIA) Loans, Future Growth Grants, and CCUS demonstration- and pilot-scale projects — depends on the efficient and effective collaboration of offices across DOE, including DOE's Loan Programs Office (LPO) and OCED. Collaboration between DOE-FECM and LPO are framed through an internal memorandum of understanding (MOU) to support CIFIA Loans and Future Growth Grants. OCED support is provided through participation in coordination with project execution and technical and nontechnical knowledge sharing as needed.

The first release of the Future Growth Grants NOFO occurred in May 2024. Grants are now available for base projects that meet the CIFIA Program eligibility requirements, including documentation of how the expanded project can be designed to add excess capacity that has not yet been contracted into the transport system. For a pipeline, this could mean adding inches to the initially planned diameter or having a more extended system by adding laterals. For barges, this could mean designing for a larger capacity vessel than originally planned or running more vessels at a higher frequency.

Future Growth Grants provide a unique opportunity for collaboration since, after the award, they are executed in three phases that address issues relevant on an interagency basis.

2.3. Strategy 3 — Carbon Storage Advanced R&D

2.3.1. Performance and Integrity Technologies

The advanced R&D strategy is focused on investing in a diverse portfolio of next-generation technology development projects, ranging from early-stage proof-of-concept projects to applied field laboratory research that advances low-cost, high-performance technologies for eventual commercial adoption in storage projects. Going forward, the CT&S Program will continue to employ its iterative strategy of advancing technologies by leveraging both CT&S Program-funded projects and other field initiatives, which will serve to (1) provide field-validated and commercial-ready technologies applicable for diverse geologic settings, and (2) develop the knowledge base, technical data, and experience that can be used by storage developers and operators. Advancements in fiber-optic sensing, high-performance computing and simulation, risk assessment methods, and machine learning applications are all being leveraged for the planning, construction and operation phases of carbon storage projects. Section 2.3.2 provides additional details on three key initiatives that are advancing the frontiers of machine learning and data science applications to transform existing operations.

The outcome of addressing key priority R&D areas will be a suite of advanced tools and technologies for a wide range of site-specific applications that can provide numerous options to accommodate a range of complex storage geologic settings.

The objective of the advanced R&D strategy over the next 10 years is to support the goals in Exhibit 1-2 through the development of tools and technologies that facilitate accelerated deployment of large-scale geologic CO_2 storage projects and hubs while ensuring effective resource utilization, operational safety and long-term integrity. A key component of this strategy will be to utilize dedicated field sites established through the CarbonSTORE Initiative and available CarbonSAFE sites for at-scale testing and validation of novel technologies and to perform crosscutting research that can accelerate the development of field-ready technologies. Exhibit 2-6 lists the priority R&D areas that the CT&S Program will support going forward, leveraging the current state of science the CT&S Program has already established from prior investments, which are described in *Appendix B: Key Advancements in Individual Technologies*.

Exhibit 2-6. Priority advanced storage R&D topics

- **Developing Novel Technologies and Approaches**
  - Basin-scale decision support tools and models to assess project performance and to manage storage resources safely and efficiently.
  - Technologies to improve storage efficiency at individual project scale and basin scale.
  - High-resolution, real-time monitoring technologies and intelligent monitoring systems (IMSs) for CO_2 plume monitoring and leak detection.
  - Low-cost well materials and systems that meet or exceed well-integrity standards in harsh environments (e.g., high pressure, temperature, total dissolved solids and CO_2 concentration).
  - Technologies and approaches to quantify and verify CO_2 storage efficiency and containment in fractured basalts.
  - Geophysical monitoring technologies to measure and/or infer in situ dynamic pressure in fractured basalts.
  - Technologies to characterize resources for ex situ CO_2 mineralization storage.
  - Studies on collecting data on mineralization kinematics and thermodynamics (for in situ and ex situ), field injectivity, and geomechanics of key subsurface reservoirs suitable for in situ CO_2 mineralization.
- **Advancing Technologies and Approaches**
  - Tools and methods for continuous, accurate, high-resolution measurement of evolving stress-state away from the wellbores.
  - Tools and technologies to significantly improve detection and characterization of faults.
- **Validating Technologies and Approaches**
  - Field demonstration and validation of tools and methods to detect pressure evolution, pressure interference and effects on injectivity at an individual project scale and basin scale.
  - Field demonstration and validation of methods for pressure management, including brine extraction.
  - Field demonstration and validation of tools for forecasting induced seismicity risks.
  - Development of CO_2 plume stabilization indicators and field-testing through optimized sensor networks.

2.3.2. NRAP, SMART and EDX4CCS

National Risk Assessment Partnership (NRAP), Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART), and Energy Data eXchange (EDX) for CCS (EDX4CCS) have the potential to facilitate deployment of more commercial-scale storage facilities. Combined, these efforts are developing tools and technologies that can be used to (1) reduce the overall risks of geologic CO_2 storage projects (NRAP), (2) control storage site operations in near-real time to improve safety and efficiency (SMART), and (3) facilitate management of data and knowledge that is primarily developed through the CT&S Program (EDX4CCS).

NRAP was initiated in 2010 with an overall objective of developing defensible science-based methodologies and computational platforms to quantify, inform, manage and mitigate risks at geologic CO_2 storage sites.

NRAP has developed and released a set of first-of-its-kind tools and workflows to quantify risks and support decisions related to site characterization, effective monitoring design, safe site operations, permanent site closure and post-injection site care. NRAP-developed tools are being applied as part of multiple CarbonSAFE and industry-led projects. Over the next five years, NRAP will be developing technologies and tools to (1) characterize evolution of hydrologic and geomechanical risks when multiple projects are deployed across a geologic basin and to effectively manage them to ensure safe operations, (2) support efficient and adaptive risk-based monitoring designs at project and basin scales, (3) assess long-term liability to inform project investment decisions, and (4) support risk-based decisions for transitioning Underground Injection Control (UIC) Class-II wells to Class-VI wells.

The SMART project was launched in 2019 to leverage advanced machine learning techniques and big data analysis methods to transform the ability to make timely and effective decisions related to operations, visualization and management of CO_2 storage reservoirs. Over next five years, SMART will focus on three key areas:

- **Virtual Learning**: Develop a computer-based experiential learning environment to enhance an intuitive understanding of CO_2 storage field operations and facilitate field development strategies during the project's pre-injection phase.
- **Real-Time Visualization**: Develop tools and workflows that enable dramatic advances in visualizing key subsurface features and fluid flow, providing faster speeds and enhanced detail compared to traditional approaches.
- **Real-Time Forecasting**: Develop tools and workflows to transform reservoir management by enabling rapid, near-real-time analysis of monitoring data and information.

The SMART tools will be publicly released and are expected to be applied to upcoming storage projects, including CarbonSAFE projects.

Building on decades of investment, EDX4CCS was initiated in 2022 with an overall objective of providing an advanced, strategic, CCS-specific data infrastructure system to drive efficient and rapid deployment of CCS efforts.

Going forward, EDX4CCS will focus on both accelerating and expanding access to critical datasets and interpretive resources. Developments will prioritize data identification and integration, development of geospatial tools, and visualization and communication resources.

The CT&S Program will utilize NRAP, SMART and EDX4CCS to develop key technologies that will improve performance while reducing the risks associated with geologic CO_2 storage at a single project, as well as basin-scale, and will underpin future infrastructure development required for accelerated deployment of carbon storage and transport projects to meet net-zero emissions goals.

2.4. Strategy 4 — Strengthening Carbon Transport and Storage Through Technical Assistance, Coordination and Collaboration

The objectives of the CT&S Program have continually been to develop the tools, experience and expertise in the geologic storage of captured CO_2 that will enable a safe, successful and responsible CCS industry. After two decades of investment in the RCSPs, DOE-FECM is now firmly positioned to leverage the accumulated knowledge and experience for establishing a regional technical assistance initiative in support of launching a variety of carbon management industries, including geologic storage of captured CO_2. The CT&S Program will issue funding opportunities to select technical assistance projects that range from basin-scale storage resource management to education and outreach.

A key component of the CT&S Program's success has been its strong partnerships and collaborations within DOE, as well as with other federal agencies, governments, industry, NGOs and the public. This MYPP considers the essential support from and coordination with interagency and international partners. The sections below describe the technical assistance initiatives the CT&S Program will implement and the domestic and international partnerships it will continue to foster and grow to leverage opportunities that help achieve the goals in Section 1.2.

2.4.1. Technical Assistance Initiatives

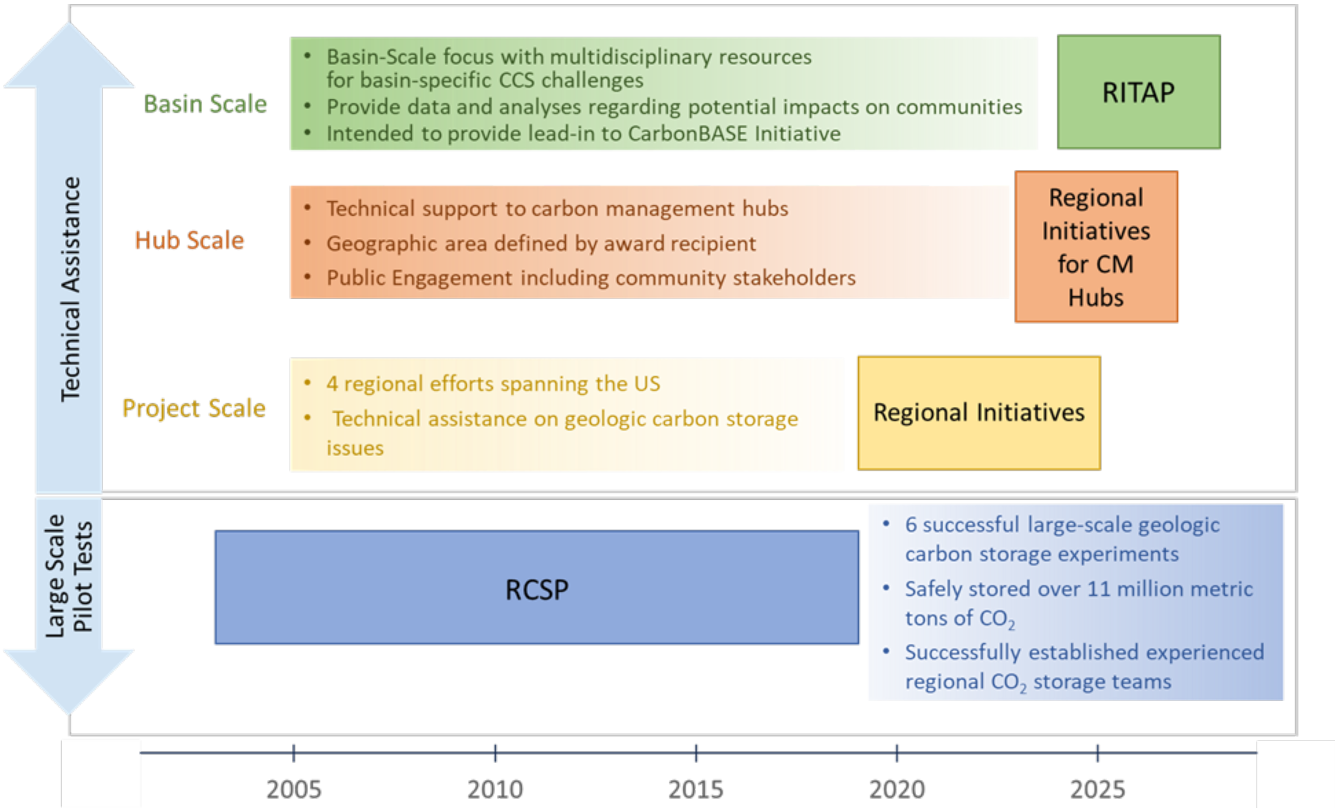
Regional Initiatives

DOE's RCSP Initiative began in 2003, continued through 2019, and was highlighted by six successful large-scale geologic carbon storage field tests that safely and collectively stored more than 11 million MT of CO_2.

DOE transitioned the long-running RCSP Program into the Regional Initiatives that leverage the expertise and experience developed by the RCSPs. In 2020, DOE awarded four projects under this initiative. These Regional Initiative projects all have a common overall objective — to provide a broad range of technical, procedural, and engagement assistance to CCS stakeholders across the United States.

In 2023, DOE-FECM launched the Regional Initiative for Technical Assistance to Accelerate CCUS Deployment to meet the growing demand for technical assistance. The newly selected projects under this initiative provide technical and stakeholder support for large-scale storage facilities and regional carbon management hubs. Additionally, some projects under this initiative are conducted by state geologic surveys, focusing on compiling and analyzing geological data to facilitate the development of future storage facilities or carbon management hubs within their respective states.

Exhibit 2-7. Evolution of Regional Carbon Sequestration Partnerships/Initiatives



DOE-FECM established the Basin-Scale Regional Initiative for Technical Assistance Partnerships (RITAP) in 2024 to provide technical assistance on the unique challenges of monitoring and managing storage resources within a single geologic basin or subbasin. Examples of challenges at the basin scale include:

- Pressure interference among neighboring storage facilities.
- Pore space and mineral rights conflicts.
- Transportation rights-of-way.
- Diverse regulatory jurisdictions.

The RITAP projects aim to ensure that local insight is engaged in the utilization and management of storage resources and that best practices are followed.

Communities LEAP

DOE's Communities Local Energy Action Program (Communities LEAP) offers technical assistance to communities pursuing strategies for planning and investing in energy transition pathways, which could include CCS. DOE-FECM participated in the inaugural pilot of Communities LEAP, launched in 2021, by providing technical assistance to two communities in California. Participation continues in Communities LEAP Cohort 2, through which multiple DOE programs are enabling technical assistance to 30 communities in support of their clean energy-related economic development efforts (DOE, n.d.). The technical assistance DOE-FECM enables through Communities LEAP is helping these communities better understand the opportunities and impacts of CCS projects being considered in their region. DOE-FECM plans to continue participating in future Communities LEAP technical assistance grant announcements and will explore the potential of integrating or coordinating this activity with the Regional Initiatives.

To address energy-transition-related challenges in Central California's Kern County, the county's Planning and Natural Resources Department partnered with the Communities LEAP pilot to explore the idea of a business park on former agricultural and other disturbed land near CCS sites with the goal of attracting and streamlining permitting for new carbon capture and clean energy companies that could help meet California's emission reduction goals, create jobs for residents and generate new tax revenue for the county. (DOE, July 17, 2024).

2.4.2. Interagency Coordination and Support

Collaborations between U.S. government agencies and within various DOE offices are crucial to the success of the CT&S program. Historically, partnerships with other agencies have enhanced DOE's ability to develop and deploy carbon management technologies successfully. In addition, DOE-FECM's leadership in interagency coordination on CCS policy, permitting, regulatory issues and external stakeholder engagement facilitates alignment and efficiencies across federal agencies. DOE is continually working on building and maintaining these cross-agency relationships. One example is through land use and transport topic teams, which meet bimonthly to share technical information and expertise and collaborate through working with other departments on CCS; another example is supporting EPA through the Federal Technical Assurance Program (FTAP). Exhibit 2-8 details the CT&S Program's ongoing efforts in interagency coordination to facilitate information exchange and promote alignment on the evolving policy, legal and regulatory aspects of CT&S projects.

Exhibit 2-8. Collaborative roles of U.S. agencies/organizations involved in CO_2 transport and storage

Federal Agency	Office	Engagement Activity
Environmental Protection Agency	Water Office; UIC Program	Inform the regulatory development process with lessons learned from RD&D. Leverage DOE national laboratories' expertise in support of the UIC Class VI Program to provide technical and capacity-building support to EPA and regional permit writers.
	Air Office	Inform the regulatory development process with lessons learned from RD&D.
Department of Transportation	Pipeline and Hazardous Materials Safety Administration	Support R&D on material integrity and safe operations of pipelines and the shipment of CO_2 transport via truck, train and ship.
	Federal Railroad Administration	Support R&D on the safe operations of CO_2 transport via rail.
	Federal Highway Administration	Support R&D on the safe operations of CO_2 transport via truck.
	Maritime Administration	Support R&D on the safe operations of CO_2 transport via waterways.
Department of Agriculture	United States Forest Service	Provide guidance, best practices and tools to assess the project and plan development in or near sensitive environments. Inform the regulatory development process with information exchanged in the interagency topic teams for land management and CO_2 transport; facilitate information exchange about storage facility and pipeline siting and permitting issues.
Department of the Interior	Bureau of Ocean Energy Management and Bureau of Safety and Environmental Enforcement	Provide data needed to set up an offshore CO_2 infrastructure and resource system. Inform the regulatory development process with lessons learned from RD&D and information exchanged in the interagency topic teams on land management and CO_2 transport.
	Bureau of Land Management	Inform on carbon storage processes, infrastructure, regulations, etc. Co-chair interagency land management topic team.
	United States Geological Survey	Cooperation on storage resource assessments.
Department of Defense	Army Corp of Engineers	Assist with transport project design, permitting and deployment to assess impacts on major wetlands and rivers. Facilitate information exchange on permitting issues.
Department of Homeland Security	Customs and Border Patrol, Coast Guard	Provide guidance on domestic and international cargo transport among U.S. ports.
Department of Commerce	National Institute of Standards and Technology	Develop benchmark materials, measurements, data and models and unify standardizations for design, materials and multimodal transport and storage.

Federal CCS Workforce Capacity-Building

DOE-FECM provides capacity-building support to all federal agencies involved in CCUS. For EPA's UIC Class VI Program, DOE-FECM provides regular and ongoing technical and capacity-building support. DOE-FECM leverages the expertise of national laboratories to provide technical assistance to the EPA UIC Program, including evaluation of subsurface modeling (i.e., to evaluate the delineated Area of Review around CO_2 injection wells) and review of geologic site characterization. In addition, DOE plans to continue to support EPA and other agencies as needed by sharing in-depth technical knowledge and expertise gained through DOE's CCUS research, development, demonstration and deployment (RDD&D) programs; Regional Initiatives; and demonstration projects. In 2022 and 2023, DOE-FECM delivered one multiday in-person training and 10 virtual trainings to federal staff responsible for permitting, right-of-way approvals and other requirements associated with CCUS project implementation. DOE-FECM is currently planning additional training moving forward.

Interagency Information-Sharing and Collaboration

DOE-FECM coordinates government-wide efforts to enhance CCUS interagency communication and collaboration. DOE-FECM has led active engagement with more than 160 CCS contacts from 10 federal agencies and initiated discussions and ongoing collaboration on focused CT&S topics such as land management, CO_2 transport development and offshore infrastructure. The teams are developing interagency tools to communicate processes, facilitate coordination and track the progress of CCS projects. DOE-FECM's interagency coordination efforts will facilitate more efficient use of agencies' resources, reduced redundancy, leveraged expertise and more effective implementation of federal CCS requirements.

2.4.3. International Engagement and Collaboration

DOE-FECM engages with international partners to advance CCS technology and demonstrations. International collaboration on CT&S projects promotes global standardization and engineering practices for the CO_2 transport and geologic storage-related activities. These collaborations include multilateral and bilateral partnerships and participation of U.S. scientists in major CCS field projects worldwide.

2.4.4. Tribal Consultation and Engagement

Tribal Nations and Alaska Native Corporations play an important role in helping the United States meet its energy security while working to develop their vast energy, critical minerals and materials, and carbon management potential. DOE-FECM is committed to inviting tribal nations and Alaskan Native Corporations to consult in the earliest stages and throughout the decision-making process as articulated in U.S. Department Of Energy Policy On Consultation And Engagement With Federally Recognized Indian Tribes And Alaska Native Claims Settlement Act Corporations. Tribal consultation will be held on a government-to-government basis whenever there is a DOE action with potential impacts on tribal interests and will maximize opportunities to seek consensus wherever possible.

2.4.5. Domestic Engagement and Collaboration

DOE-FECM's domestic engagement objective is to support carbon management project implementation in the United States by closing the knowledge gap that exists between industry and the public. To achieve this, DOE-FECM provides scientific information on carbon management, including on specific DOE-funded projects that have been selected. DOE-FECM also connects and facilitates constructive relationships among industry, state and local governments, Tribes, land owners, communities, labor and workforce development institutions, economic development entities, and environmental organizations.

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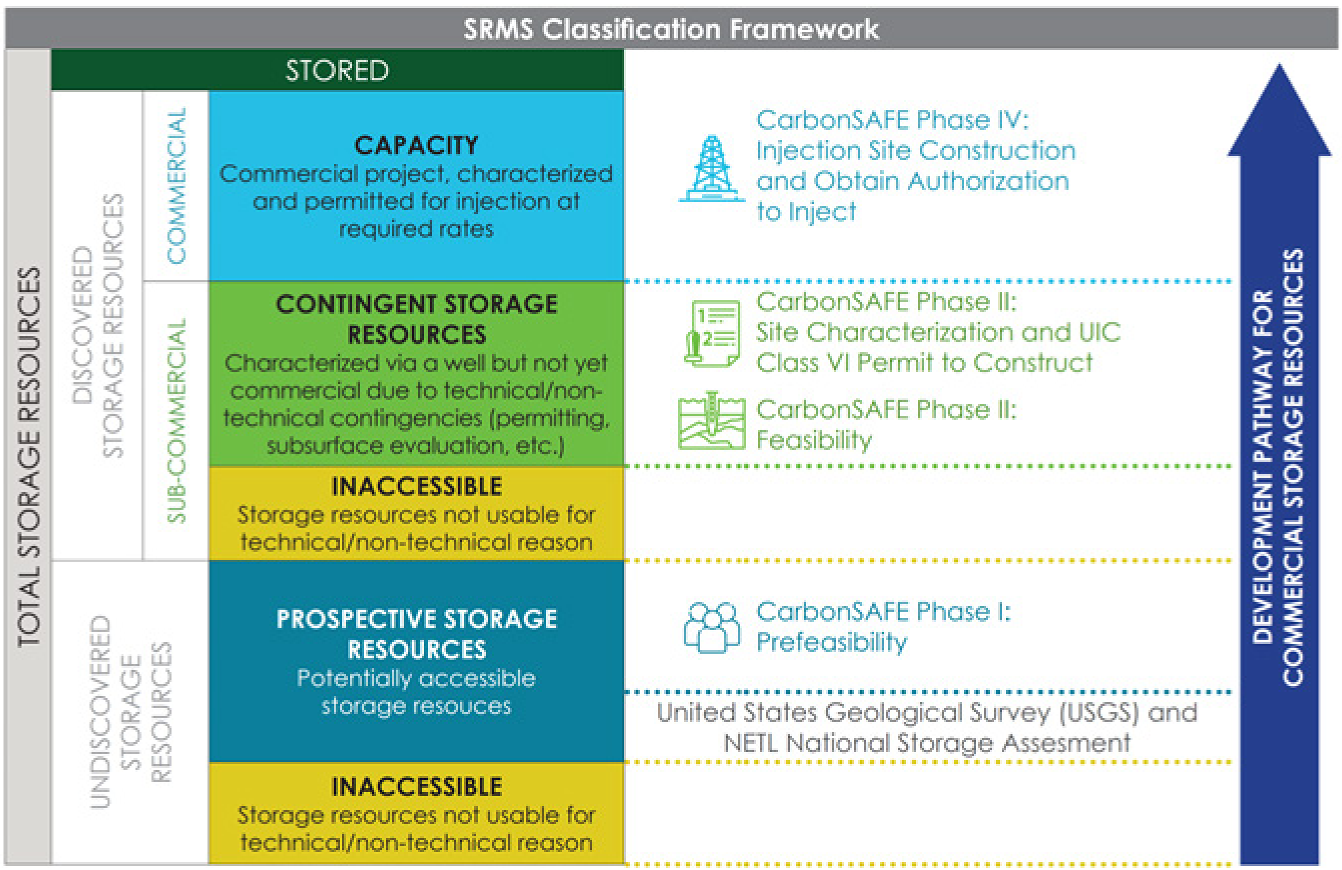
Appendix A: Relationship Between CarbonSAFE and SRMS

The correlation between Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Phases and their CO_2 Storage Resources Management System (SRMS) classification is shown in Exhibit A-1. The SRMS is source-agnostic and is intended to be used for carbon dioxide (CO_2) storage into saline aquifers and depleted oil and gas reservoirs.

Exhibit A-1. CO_2 SRMS



Adapted from SRMS (UNECE, 2023) (SPE, 2017)

Appendix B: Key Advancements in Individual Technologies

Exhibit B-1. Key technology advancements in advanced storage R&D

Federal Agency	Engagement Activity
Environmental Protection Agency	**Advanced Simulators** • Development of reservoir simulators that more accurately model hydrologic and geochemical processes, including the detailed physics and chemistry of the interplay between CO_2-plume migration and CO_2 trapping, and effects of fractures in different geologic settings. • Development of guidelines on the required level of complexity in reservoir simulators. • Development/evaluation of upscaling approaches. **Fit-for-Purpose Modeling Tools** • Development of modeling tools that enable more realistic modeling of (1) the effect of pressure increases on storage efficiency, (2) optimum well placement for reservoir pressure management, (3) cost-effective analysis of well-pressure gauge data. • Development of the Enhanced Analytical Simulation Tool for CO2 storage capacity estimation and uncertainty quantification. • Development of data-constrained reservoir models for managing CO2 storage reservoirs in the presence of brine extraction. **Reduced-Order Models** • Development and testing of (1) simplified physics-based modeling, (2) statistical learning-based modeling, and (3) reduced-order method-based modeling approaches for more computationally efficient prediction of injection well and formation pressure buildup, as well as other reservoir processes. **Joint Inversion** • Development and validation of joint inversion methods to integrate monitoring data (e.g., seismic, electromagnetic [EM], pressure and petrophysical data) and link to simulations. **Storage Resource and Storage Efficiency** • New modeling-based estimates of storage capacity, and optimization of storage, in stacked saline and unconventional reservoirs. • Development of regional and site-specific storage resource estimates. • Improved understanding, from laboratory testing and modeling, of the detailed physics of the interplay between CO_2-plume migration and CO_2 trapping. **Geophysical Technologies** • Multiple advances in seismic technology for plume monitoring (acquisition, processing and analysis), including: ▫ Development and field-testing of seismic distributed acoustic sensing technology. ▫ Development and field-testing of sparse array seismic monitoring (scalable, automated, semipermanent seismic array). ▫ Development of advanced seismic analysis of seismic data from large arrays. ▫ Development and field-testing of orbital vibrator seismic sources. • Development and field-testing of a charged wellbore casing controlled source EM tool. **Intelligent Monitoring Systems** • Development of new workflows, algorithms and hardware to improve intelligent monitoring systems applications in geologic storage. ▫ Development of a framework for data integration, assimilation, and learning for geologic carbon storage.

Federal Agency	Engagement Activity
Secure Storage (focus outside of reservoir)	**Seismic Technologies** • Development of the Spatial Temporal-Densely Connected Convolutional Neural Network for detecting small leak signals over large areas in the subsurface. • Field validation and deployment of an ultra-high-resolution 3D marine seismic technology. **Nonseismic Technologies** • Development of an integrated seismic/EM monitoring system for leakage detection. • Development of distributed strain sensing to monitor subsurface strain. • Development and field-testing of a pressure-based inversion and data assimilation system for detecting CO_2 leakage from storage. **Joint Inversion** • Ongoing work to integrate geophysical measurements, including seismic, EM and strain, coupled with joint inversion and modeling, to detect leakage in the subsurface above the storage complex. **Advanced Simulators** • Development of advanced coupled process numerical simulators that model (1) geomechanical changes/potential failure of the caprock, (2) geomechanical deformation of the fracture system, and (3) complex chemistry while considering interactions of natural fractures. • Development of a geomechanical screening tool to assess geomechanical processes and conditions related to CO_2 storage, including faults, fractures and damaged caprock. **Storage Resource and Storage Efficiency** • Characterization/evaluation of geomechanical properties of potential storage complexes. **Surface-Based, Atmospheric Monitoring** • Development of the Greenhouse Gas Laser Imaging Tomography Experiment system. • Development of a ground-based sensor network and airborne sensor system for directly detecting and quantifying seepage of CO_2 into the atmosphere.
Subsurface Stress	**Seismic Technologies** • Advances in technologies to improve the sensitivity of microseismic detectors and reduce uncertainty in locating events. • Improved microseismic processing/analysis methods. • Fundamental theoretical, laboratory and small-scale field laboratory studies (e.g., Mont Terri) of the relationship between the frictional properties of faults/fractures and changes in permeability resulting from aseismic and seismic slip. **Advanced Simulators** • Development of advanced coupled process numerical simulators capable of simulating initiation and propagation of fractures, stress-dependent fracture flow, and aseismic and seismic slip of faults. • Development of a methodology/workflow to predict presence of faults that are susceptible to movement due to fluid injection. • Development of data integration methods to reduce uncertainty in estimation of stress changes. **In Situ Stress Measurement** • New methods to estimate in situ stresses using borehole deformation in combination with numerical simulation and machine learning techniques.
Wellbore Integrity	**Wellbore Integrity Studies** • Evaluation of critical factors in the cement carbonation process and validation of proper well construction procedures, well design and well logging/testing. • Postmortem studies of legacy well records to evaluate the quality of data contained and develop indicators for the potential of well integrity issues. **Novel Wellbore Materials** • Development of materials and deployment methods for remediating wellbores with hydraulic integrity issues. • Development of new mineralization and biomineralization precipitation technologies capable of sealing near-wellbore leakage pathways. **Sensors** • Development of new sensors that are being designed to be embedded in the well.

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