SAFE GEOLOGIC STORAGE OF CAPTURED CARBON DIOXIDE: *TWO DECADES OF DOE'S CARBON STORAGE R&D PROGRAM IN REVIEW*

April 13, 2020

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Suggested Citation:
"Safe Geologic Storage of Captured Carbon Dioxide – DOE's Carbon Storage R&D Program: Two Decades in Review," National Energy Technology Laboratory, Pittsburgh, April 13, 2020.

This report was prepared by MESA for the U.S. DOE NETL. This work was completed under DOE NETL Contract Number DE-FE0025912. This work was performed under MESA Task 2130.104.003.001.

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EXECUTIVE SUMMARY

Carbon capture, utilization, and storage (CCUS) is widely regarded as a necessary component in the global effort to reduce carbon dioxide (CO_2) emissions to the atmosphere in a cost-effective way. A key question about the viability of CCUS with respect to protection of human health and the environment is how to ensure that CO_2 injected in deep geologic reservoirs is securely stored. Geological storage of CO_2 has been a natural process in the Earth's upper crust for hundreds of millions of years. While this provides supporting evidence that CO_2 can be securely and safely contained in the deep subsurface, it is vitally important that the technical means exist to identify suitable sites and monitor stored CO_2 to verify secure containment. The U.S. Department of Energy (DOE) has invested more than $1 billion during the past two decades through its Carbon Storage Research and Development (R&D) Program to develop the technologies and capabilities for widespread commercial deployment of geologic storage. This investment has made DOE a leader in this worldwide effort.

CCUS projects supported by DOE and other organizations around the world, which in 2019 injected more than 25 million metric tons of CO_2, have shown no adverse impacts to human health or the environment. And no DOE supported project has observed migration of CO_2 outside of the intended storage reservoir or confining cap rock. Increasing years of experience and a preponderance of successful projects will promote even further confidence in secure storage for operators, regulators, insurers, financial institutions, environmental groups, and the public.

The assurances we can make today about the secure storage of CO_2 in deep geologic reservoirs are based on: (1) a foundation of nearly five decades of oil and gas industry experience injecting CO_2 into oil- and gas-filled formations; (2) the 20 years of technology advancements made from R&D programs like DOE's Carbon Storage Program; (3) field-testing campaigns, such as the Regional Carbon Sequestration Partnerships (RCSPs) that have validated monitoring tools and strategies and developed best practices; (4) improved understanding of the physics, chemistry, and mechanics involved throughout the life of a CCUS project, which has served as the foundation for new risk assessment and management tools; and (5) the growing number of CCUS demonstration and commercial projects worldwide that promote learning-by-doing. This paper is a review of these elements and how they contribute to the increasing confidence that geologic storage of capture CO_2 can be a safe enterprise on a broad scale.

1 INTRODUCTION

One of the great challenges facing the world today is the need to reduce global greenhouse gas (GHG) emissions and thereby mitigate the potential impacts of climate change without provoking undue detriment to global economies. The United Nations' Intergovernmental Panel on Climate Change (IPCC) laid out estimates of the reductions needed by 2050 among various emitting sectors to limit global temperature increase to 1.5°C (2.7°F) [1]. One potential reduction option is called carbon capture, utilization, and storage (CCUS).

CCUS comprises capturing carbon dioxide (CO_2) from any source (e.g., fossil-fueled power plant, industrial process, direct air capture, biomass combustion and conversion); compressing it to a liquid-like state; transporting it via pipeline, ship, truck, or other means; and injecting it underground, either in deep reservoirs at a site suitable for secure geologic storage or in oil/gas fields for CO_2-enhanced oil recovery (EOR). There are a variety of technologies for capturing CO_2 from industrial sources, but the main challenge for capture has been, and continues to be, reducing the cost [2]. The United States already has more than 4,000 miles of pipelines for transporting a variety of liquids and gases; consequently, transporting CO_2 is not viewed as a technical challenge. For more than four decades, the United States has been using CO_2 to enhance production from oil fields that became depleted following primary production and subsequent water flooding. Over this time, more than 600 million metric tons of purchased CO_2 have been used in the southwest U.S. Permian Basin alone [3]. These decades of experience provide strong evidence of the technical feasibility of geologic storage, which uses compression and injection technologies virtually identical to those used for CO_2-EOR.

The Earth's geology provides key pieces of evidence that CO_2 can be securely and safely contained in the deep subsurface. Geological storage of CO_2 has been a natural process in the upper crust for hundreds of millions of years, resulting in accumulations of CO_2 alone or in combination with other fluids such as hydrocarbons. Studies of oil and gas fields indicate that hydrocarbons and other gases and fluids, including CO_2, can remain trapped for millions of years [4, 5]. Moreover, 85% of the CO_2 used for EOR in the United States is extracted from natural geologic sources (e.g., McElmo Dome) [6], where CO_2 generated from thermogenic and biogenic processes has accumulated for millennia, even millions of years. However, the mass of CO_2 used for CO_2-EOR per year is substantially smaller than the 5.2 billion metric tons (2018 data) emitted in the United States each year from industrial processes, electricity generation, vehicles, home heating, and all the other forms of energy production or conversion [7].

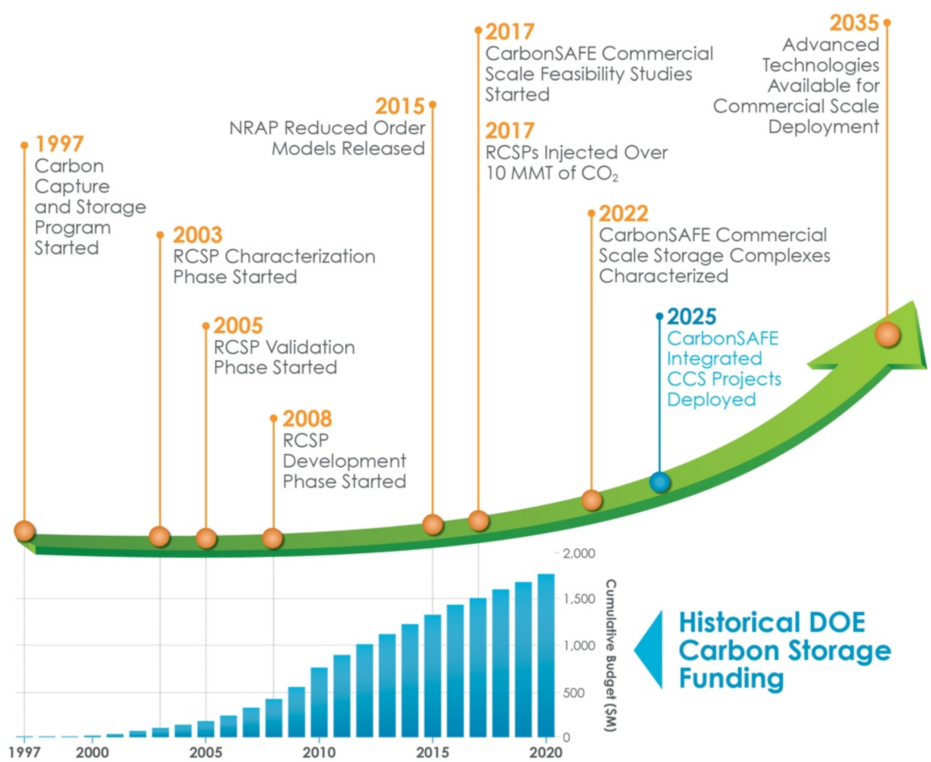
With this understanding, the U.S. Department of Energy (DOE) has supported research on CCUS for more than two decades—in cooperation with domestic and international partners—to address the challenges posed by CCUS deployment at the scale needed to meet reduction targets such as the 1.5°C (2.7°F) scenario. Specifically, DOE's Office of Fossil Energy (FE) initiated what was then called the Carbon Sequestration Program in 1997, as public interest grew about the world's rising CO_2 emissions and the potential impacts of climate change. Indeed, the world shared a similar concern, and this prompted IPCC to issue the *Special Report on Carbon Capture and Storage* ("Special Report") in 2005 that assessed the technical, scientific, and socio-economic implications of capturing CO_2 and storing it in natural underground reservoirs [8]. The

Special Report, which served as a consensus document of more than 100 authors from 30 countries (including multiple prominent DOE-supported U.S. researchers), asserted that commercial technologies, including CO_2-EOR, acid gas disposal, and natural gas storage, provided a substantial knowledge base for transport and underground storage of CO_2. The Special Report further asserted there were no major technical or knowledge barriers to the adoption of geological storage of captured CO_2. More importantly, the report identified key technology gaps that would need to be addressed if worldwide CCUS deployment is to be realized. DOE's Carbon Storage Program sought to fill these key gaps by developing, demonstrating, and verifying the approaches and technologies needed to ensure safe and secure storage of captured CO_2. What follows are highlights of the advancements in CCUS technology that DOE and its partners have made as evidence that geologic storage is a viable and safe approach to reducing CO_2 emissions.

2 Technology Advancements to Ensure Secure Storage

DOE's Carbon Storage Program has been leading the worldwide effort to develop the tools and methods necessary to ensure safe and secure geologic storage of captured CO_2. The Carbon Storage Program's success is attributed to 20+ years of investments in a diverse portfolio of applied research projects (Exhibit 2-1). These projects developed and advanced technologies that address the overarching technical challenges of geologic storage to achieve technology readiness for widespread commercial deployment.

Exhibit 2-1. Cumulative investment and milestones toward achieving technology readiness for widespread commercial-scale deployment



Key players are the universities, national laboratories, geological surveys, other research institutions, and various industry members that have been at work for two decades advancing technologies that reduce risk, are cost-effective, and achieve permanent geologic storage of CO_2. By harnessing the expertise and intellectual capacity of these institutions, the research and development (R&D) funded by the program has greatly increased the collective understanding of the effectiveness of available technologies and how CO_2 behaves in a variety of potential carbon storage settings, including saline formations, oil reservoirs, natural gas reservoirs, unmineable coal seams, basalt formations, and organic-rich shales. More information on the Carbon Storage Program, which includes project factsheets, is available on the National Energy Technology Laboratory's (NETL) website at: https://netl.doe.gov/coal/carbon-storage.

2.1 Field Testing Leads to Improved Understanding of CO_2 Behavior and Storage Resources

Perhaps the best-known endeavor of the Carbon Storage Program is the Regional Carbon Sequestration Partnership (RCSP) Initiative. The RCSP Initiative began in 2003 with the Characterization Phase (Phase I), which focused on collecting and analyzing data on potential CO_2 reservoirs and assembling resources to test CO_2 storage in the field. The initiative culminated in the development of a standard, consistent methodology for assessing geologic reservoirs and estimating the volumes of CO_2 that could be stored. This methodology has been applied in a series of widely acclaimed Carbon Storage Atlases for the United States and portions of Canada [9]. Part of the RCSP initiative was to identify and capture best practices from each of the field projects; these are captured in a series of DOE Carbon Storage Program Best Practice Manuals (BPMs) [10].

The Validation Phase (Phase II) of the RCSP Initiative included 19 small-scale field projects, during which more than 1.0 million metric tons of CO_2 were safely injected. The projects were performed across numerous potential storage settings, including eight projects in depleted oil and gas fields, five in unmineable coal seams, five in clastic and carbonate saline formations, and one in basalt.

These small-scale tests provided the foundation for the Development Phase (Phase III) field projects, which began in 2008. Results provided a more thorough understanding of plume movement and permanent storage of CO_2 in a variety of geologic storage formations. Experience and knowledge gained from these projects helped support regulatory development and commercial deployment of geologic storage. The formations tested are considered regionally significant and are expected to have the potential to store hundreds of years of CO_2 emissions from stationary sources. More than 11 million metric tons of CO_2 were stored in geologic formations via RCSP large-scale field projects, with no indications of negative impacts to either human health or the environment.

The success of the partnerships in validating secure storage at their respective sites was largely based on the deployment of new or improved monitoring technologies. Technology research by the partnerships and their partner organizations, such as the national laboratories, targeted demonstration of robust and reliable monitoring systems. An example is the repeat of 3D seismic (4D seismic) at the Plains CO_2 Reduction (PCOR) Partnership's Bell Creek site in North Dakota, which provided images that correlated with changes in CO_2 saturation and pressure [11]. The PCOR Partnership is also attempting to use surface seismic as a real-time monitoring tool by the installation of a scalable, automated, semi-permanent seismic array (SASSA) at the Bell Creek site [12]. Another prime example is fiber-optic seismic sensing technologies, which should provide higher resolution than conventional geophone arrays [13]. To date, surveys were recorded after injection of CO_2 in several projects by using a distributed acoustic sensing (DAS) fiber-optic system [14, 15, 16, 17, 18, 19]. These efforts have shown promise at lowering costs while improving the ability to monitor and verify the behavior of the injected CO_2.

Improvements in monitoring and characterization, when combined with advanced computation, has led to improvements in models and simulations, increasing the ability to understand and predict subsurface conditions and plume behavior. Improved measurements of injection rate and volume, reservoir fluid pressure, CO_2 saturations by pulsed-neutron logs, and CO_2 plume mapping by time-lapse seismic have proved useful for calibrating reservoir simulations. Reservoir models at the Southeast Regional Carbon Sequestration Partnership's (SECARB) Citronelle site and the Midwest Geological Sequestration Consortium's (MGSC) Illinois Basin–Decatur Project (IBDP) site were accepted by the U.S. Environmental Protection Agency (EPA) for use to delineate the Area of Review during of all phases of these CO_2 injection projects. Numerical simulations for the IBDP site have reduced the uncertainty about the location of the CO_2 plume; simulation results reasonably matched field measurements. This increases confidence that the simulations are representative of the system's behavior.

Intelligent monitoring systems (IMSs) combined with artificial intelligence and machine learning have been identified as current and future research areas for carbon storage. IMSs incorporate new strategies and optimized sensor systems that reduce operational risks by enabling integration of data/measurements in real time. Different components of IMSs are being tested at field test sites, an important first step in reducing the risk of leakage or reducing the time to detection of leaks using autonomous monitoring, enhanced surveillance techniques, and user-friendly, web-based technologies. For example, University of North Dakota researchers worked with the SaskPower Aquistore project in Canada to develop new IMS workflows to automate the integration of monitoring measurements and reservoir simulations with algorithms for visualization and real-time decision-making support [20]. Researchers in the Industrial Carbon Capture and Storage (ICCS) project headed by Archer Daniels Midland Company (ADM) built an innovative, permanent DAS seismic monitoring network, combined with real-time data processing, to feed reservoir flow and geomechanical models [21]. The RCSP IBDP project implemented a dedicated high-speed network for acquiring operational and monitoring information in real time, including alarm points on pressure, injection rate, temperature, and microseismic data streams [22]. These advancements in monitoring technologies have been integral to ensuring that injected CO_2 will remain securely stored and provide early detection of plume migration behavior that would warrant mitigation measures.

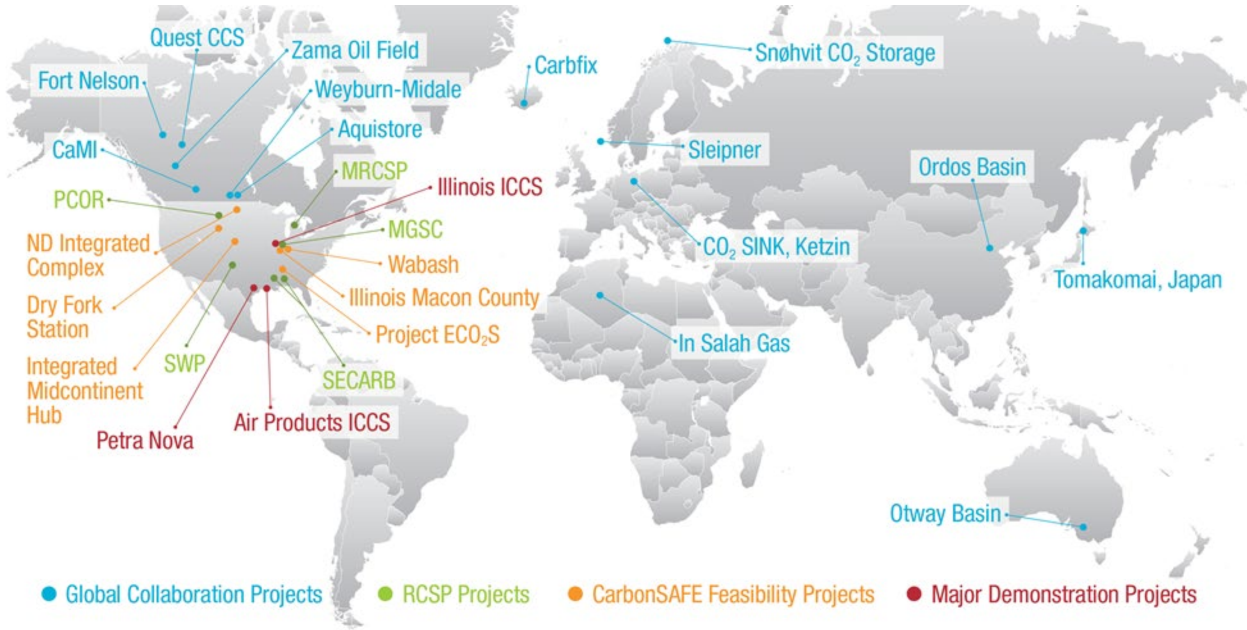
2.2 Risk Assessment and Management Tools Lead to Safer and More Secure Operations

Analysis of the risks associated with large-scale CO_2 storage will be a necessity through all stages of operation. Understanding risks and their evolution through the life cycle of a project is integral to the selection of technologies for site-screening and characterization, safe and continuous operations, and all monitoring activities. In recognition of the importance of quantitatively assessing and managing subsurface environmental risks, NETL leads the National Risk Assessment Partnership (NRAP) as a research collaboration that also includes Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL) [23]. NRAP also engaged with a stakeholder group to ensure they addressed the risk-related issues that mattered most. Through 10 years of research, NRAP substantially improved our capability to model how drivers of risk evolve over time at individual storage sites. NRAP developed a suite of open-source tools, which are available to the public, for assessing and managing risks. NRAP published a large body of work on findings, perhaps most notably in a special issue of the International Journal of Greenhouse Gas Control [24]. NRAP's work will significantly improve industry's ability to select secure storage sites, operate safely, and efficiently manage storage operations.

2.3 Learning-by-Doing: Growth in Projects Worldwide Leads to More Confidence in Secure Storage

In 1996, the world's first large-scale storage project was initiated by Statoil (now Equinor) and its partners at the Sleipner Gas Field in the North Sea (offshore Norway). Sleipner remains the world's longest-running geologic storage project, injecting about 1 million metric tons of CO_2 per year through a single well drilled into the saline Utsira Formation. All evidence from monitoring activities indicates the CO_2 remains securely stored [25]. In 2008, Statoil began operation of a similar project at the Snøhvit field in the southern Barents Sea (also offshore Norway). To date, more than 22 million metric tons have been injected at Sleipner and Snøhvit storage facilities [26]. Other major international geologic storage projects initiated in the last 20 years include the Weyburn-Midale CO_2 Monitoring and Storage Project located in Saskatchewan, Canada; the commercial In Salah saline formation project located in Algeria; the Ketzin pilot saline formation injection project located in Germany; and the Otway depleted gas reservoir carbon capture and storage (CCS) demonstration project located in Australia. DOE's Carbon Storage Program has played a role in these projects and brought the lessons learned back to the United States. A map summarizing DOE's large-scale U.S. storage projects and global collaborations is provided as Exhibit 2-2. Having operated for years and in some cases decades, these projects have experienced no adverse environmental or health and safety impacts. The positive performance of these projects has no doubt given some additional assurance to Chevron in their 2019 launch of the CO_2 storage component of the Gorgon liquified natural gas project, the largest CO_2 storage project to date, injecting as much as 4 million metric tons of CO_2 per year in a deep geologic storage reservoir located in western Australia [27].

Exhibit 2-2. Map depicting locations of major U.S. DOE/NETL projects and global collaborations



In 2015, the International Energy Agency Greenhouse Gas R&D Program (IEAGHG) updated their position on the status of science and technology underpinning CCUS in a Special Issue of the International Journal of Greenhouse Gas Control [28]. The Special Issue comprised a collection of 17 peer-reviewed papers, which cover areas where significant CCS R&D progress was made in the 10 years since release of the IPCC Special Report. More than 100 authors participated, using more than 3,000 references to support their work. Special Issue conclusions related to geologic storage included the following:

- Storage in saline formations is a safe and secure option.
- Significant progress has been made in technologies for monitoring and verification, both onshore and offshore.
- There is common agreement on the ability of available techniques to test and demonstrate containment and conformance.
- The surface expression of leaks, should they occur, would be in the form of small isolated areas, and impact on groundwater would be limited both in severity and spatial extent.
- A consolidation and expansion of scientific knowledge enables more accurate assessment and management of potential impacts, risks, and costs.

In recent years, large-scale integrated projects have continued to come online, generating experience and knowledge at commercial scale for integrated CCUS systems with different types of CO_2 sources and storage in different geologic settings.

In the United States, with support from DOE's Industrial Carbon Capture and Sequestration (ICCS) Program, the Illinois Industrial CCS Project began operation in 2017, being one of the first CCUS projects to successfully complete the new EPA Class VI permitting process. The project is demonstrating an integrated system for collecting CO_2 from ADM's ethanol production plant in Decatur, Illinois, and injecting up to 3,000 metric tons per day into the Mount Simon sandstone reservoir. The project built upon the extensive geologic and operational knowledge base provided by the IDBP project. As part of the monitoring program, ADM is also field testing advanced seismic technologies being developed through DOE's Carbon Storage Program. Cumulative current stored volume is 1.71 million metric tons.

In Port Arthur, Texas, an ICCS project headed by Air Products & Chemicals started operations in 2013. The project captures up to 1 million metric tons of CO_2 per year from steam methane reformers used for hydrogen gas production. The CO_2 is transported via the Denbury Green Pipeline to Denbury's West Hastings oilfield for storage in conjunction with EOR operations. Cumulative current stored volume is 6.08 million metric tons.

The Petra Nova project, supported by DOE/FE under the Clean Coal Power Initiative (CCPI), began operations in 2017 near Houston, Texas (Exhibit 2-3). This integrated project incorporates the world's largest operating post-combustion CO_2 capture system applied to an existing unit at the coal-fueled W.A. Parish Generating Station. The system can capture up to 1.6 million tons of CO_2 per year and transport it to the West Ranch Oil Field in Jackson County, Texas, for storage in conjunction with EOR. Cumulative current stored volume is 3.73 million metric tons.

Exhibit 2-3. Petra Nova CCS (Thompsons, Texas) – operations began in 2017

Internationally, DOE continues to support U.S. scientist participation to advance research in carbon storage. In Saskatchewan, Canada, the Aquistore project started injection into a deep saline reservoir in 2015. Aquistore is an integral component of SaskPower's Boundary Dam Integrated CCS Demonstration project, which involves post-combustion capture from a coal-fueled power plant and transport via pipeline to an oilfield for EOR, with additional saline storage at the Aquistore site. As part of the monitoring program, advanced fiber-optic DAS lines were deployed. This has encouraged additional development and testing at other sites.

In 2016, the Japanese government began injection into a large-scale integrated CCS demonstration project in the Tomakomai area, Hokkaido Prefecture. Over the next three years, 300,000 metric tons of CO_2 captured from the hydrogen gas production unit of an oil refinery were injected and stored in offshore deep saline formations beneath the Tomakomai port. To advance monitoring at the site and test novel technologies, DOE-supported U.S. researchers acquired and validated an ultra-high-resolution 3D marine seismic technology dataset. Post-injection monitoring is ongoing.

A comprehensive review of the 19 active, international integrated CCS projects has been prepared by the Global CCS Institute and can be found at: https://www.globalccsinstitute.com/resources/global-status-report/. This report also details the four large-scale projects under construction and the 28 under planning and site assessment.

3 CONCLUSION AND FUTURE DIRECTIONS

Prior to DOE's R&D efforts to advance CCUS technologies, the oil and gas industry had been safely injecting fluids, including CO_2, into the subsurface in association with petroleum production in the United States and abroad for more than four decades. Oil and gas industry experience has been crucial, providing a solid foundation for adapting existing technologies and pointing the way to new technologies and capabilities needed for secure geologic storage of CO_2. DOE's field test sites, such as RCSP injection projects, have served as the primary platform for the development and validation of technologies and operational best practices. Similarly, DOE's CCPI projects, such as Petra Nova, achieved their own successes, in part by capitalizing on learnings from RCSP projects, as well as industry oil and gas experience. Results of projects around the world, large and small, that promote learning-by-doing, along with DOE's in-house efforts under NRAP, have improved the ability to understand and manage risks, which is essential for ensuring secure storage and protection of human health and the environment. CCUS projects supported by DOE and other organizations around the world, which have injected more than 25 million metric tons of CO_2 in 2019 alone [29], have shown no adverse impacts to human health or the environment. And with increasing years of experience comes more confidence for operators, regulators, insurers, financial institutions, environmental groups, and the public.

To date, the Carbon Storage Program efforts have served primarily to confirm the initial conclusions of the original IPCC Report, that billions of tons of CO_2 can be stored in geologic formations safely and securely across the country and the globe. New tools have been produced to enable operators and developers to identify where and how much CO_2 can be safely stored, and at the same time determine what formations are unsuitable for large-scale carbon storage.

Efforts within the storage component of CCUS continue to focus on technologies and methods to reduce operational risks and costs and increase efficiencies to make commercial-scale storage economical. Based on nearly two decades of DOE-sponsored research, development, and demonstration, the Carbon Storage Program launched the Carbon Storage Assurance Facility

Enterprise (CarbonSAFE) Initiative in 2016 to demonstrate how the experience of the past 20 years can be applied to certify commercial-scale safe storage, culminating in one or more fully characterized and permitted storage complexes with capacity to store 50+ million metric tons of CO_2. CarbonSAFE continues into its third phase this year, and selected projects will apply all that has been learned to further reduce technical risk, uncertainty, and cost.

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