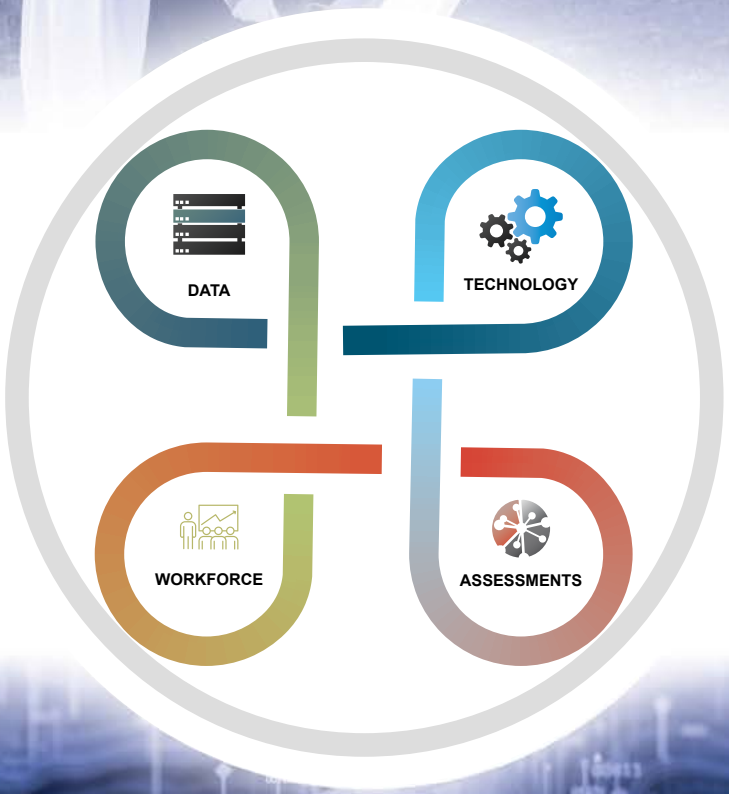
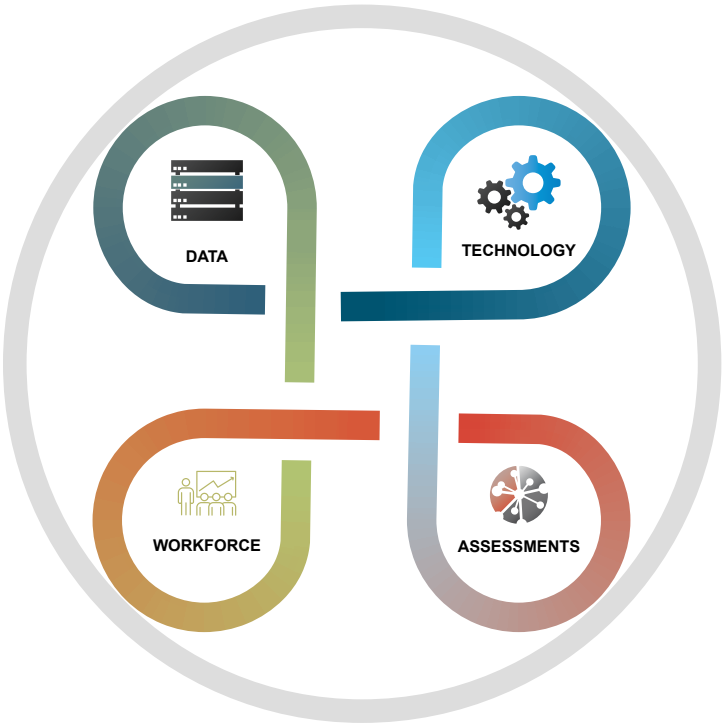


American Resources for a Secure Future:

A National Cooperative Subsurface Assessment Program

National Petroleum Council | 2026



American Resources for a Secure Future:

A National Cooperative Subsurface Assessment Program

Committee on Resource Assessment

Scott Tinker, Chair

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National Petroleum Council 2026

NATIONAL PETROLEUM COUNCIL

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U.S. DEPARTMENT OF ENERGY

Chris Wright, Secretary

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■

PREFACE

I. NATIONAL PETROLEUM COUNCIL

The National Petroleum Council (NPC) is an organization whose sole purpose is to provide advice to the federal government. After successful cooperation during World War II, President Harry Truman requested this federally chartered and privately funded advisory group to be established by the Secretary of the Interior to represent the oil and natural gas industry's views to the federal government by advising, informing, and recommending policy options. Today, the NPC is chartered by the Secretary of Energy under the Federal Advisory Committee Act of 1972, and the views represented are broader than those of only the oil and natural gas industry.

NPC members, about 200 in number, are appointed by the Energy Secretary to assure well-balanced representation from all segments of the oil and natural gas industry, from all sections of the country, and from large and small companies. Members are also appointed from outside the oil and natural gas industry, representing related interests such as large consumers, states, Native Americans, and academic, financial, research, and public interest organizations and institutions. The NPC promotes informed dialogue on issues involving energy, security, the economy, and the environment of an ever-changing world.

II. STUDY REQUEST

On June 30, 2025, Secretary of Energy Chris Wright requested that the NPC undertake a Future Energy Systems study to provide advice on ensuring the availability of affordable, reliable, and secure energy for U.S. consumers and allies (Appendix A). The study was designed with a number of subcomponent deliverables. Two have already been published.[1] In subsequent communications, the Department of Energy (DOE), in collaboration with the Department of the Interior (DOI), asked the NPC to provide an appraisal of the potential value to industry of a new and expanded national resource assessment program (Appendix A). Such an effort, funded and guided by federal legislation, would engage state geological surveys, the U.S. Geological Survey (USGS), the Marine Minerals Administration (MMA)[2], and the DOE to gather data and conduct assessments for oil and gas and other subsurface resources (e.g., geothermal; critical minerals; pore space for hydrogen, natural gas, and carbon; coal; groundwater). The DOE emphasized that it did not expect the NPC to conduct the resource assessment studies.

III. STUDY SCOPE

This study considers the value of conducting resource assessments across federal, Tribal, state, and private lands, both onshore and offshore. Its scope encompasses a wide range of subsurface resources, although it does exclude shallow groundwater aquifers, which are assessed using different technology and involve different stakeholders than those represented in this study. This study considers the following subsurface resources: oil and gas, utility-scale geothermal energy, essential minerals, coal, geologic hydrogen, dynamic subsurface storage, and permanent subsurface storage.

1 National Petroleum Council, *Reliable Energy: Delivering on the Promise of Gas-Electric Coordination*, December 3, 2025, https://gas-electric.npc.org/; National Petroleum Council, *Bottleneck to Breakthrough: A Permitting Blueprint to Build*, December 3, 2025, https://permitting.npc.org/.

2 The MMA was formerly the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

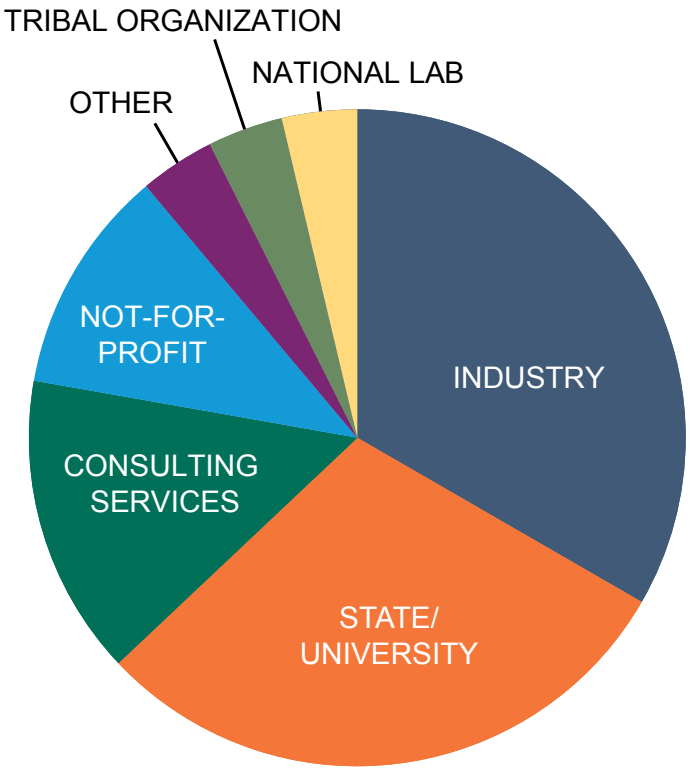


Figure P-1. *Representation by Sector on the Study Committee, Coordinating Subcommittee, and Task Groups*

IV. STUDY GROUP ORGANIZATION

The study was directed by a study committee composed of senior leaders from the industries of oil and gas, critical minerals, geothermal, hydrogen, geologic carbon storage, and groundwater, along with representatives from state agencies, universities, Tribal organizations, consulting services, and public interest and nonprofit organizations. The coordinating subcommittee oversaw the development of scope areas, supported by task groups focused on specific technical and policy issues. This structure is designed to ensure that a broad range of expertise and perspectives are incorporated into the analysis, deliberations, and recommendations of the NPC (Figure P-1).

Participants in this study contributed in a variety of ways, ranging from work in all study areas, to involvement in a specific topic, to reviewing proposed materials. Involvement in these activities should not be construed as a participant's or their organization's endorsement or agreement with all the statements, findings, and recommendations in this report. Additionally, while U.S. government participants provided significant assistance in the identification and compilation of data and other information, they did not take positions on the study's recommendations.

V. REPORT STRUCTURE

The report is organized into three chapters following an executive summary and summary of resource-specific findings and recommendations.

1. The Value of Publicly Available Subsurface Data and Resource Assessments
2. Synthesis of Publicly Available Subsurface Data and Assessments
3. Cross-Sectoral Recommendations

Resource-specific recommendations are developed in Chapter 2 and cross-sectoral recommendations are developed in Chapter 3. ■

EXECUTIVE SUMMARY

The United States' energy future—from geothermal, nuclear, wind, solar, and hydropower to oil and natural gas—depends on the subsurface. Yet despite its strategic importance, the subsurface remains one of the nation's most undercharacterized assets. As demand grows for secure domestic energy, critical minerals, storage capacity, and water resources, the United States will need renewed investment in understanding and managing its subsurface assets to help industry identify and de-risk new opportunities, while ensuring robust environmental stewardship. A comprehensive national subsurface assessment effort will require sustained investment in data (acquisition, management, and sharing), robust assessments, technology development, and a qualified workforce (Figure ES-1).

OVERARCHING RECOMMENDATION:
The NPC recommends that Congress authorize and appropriate a National Cooperative Subsurface Assessment Program that builds on existing federal and state agency authorities for resource assessments, data acquisition and management, technology development, and workforce capacity to strengthen the nation's ability to holistically evaluate subsurface resource

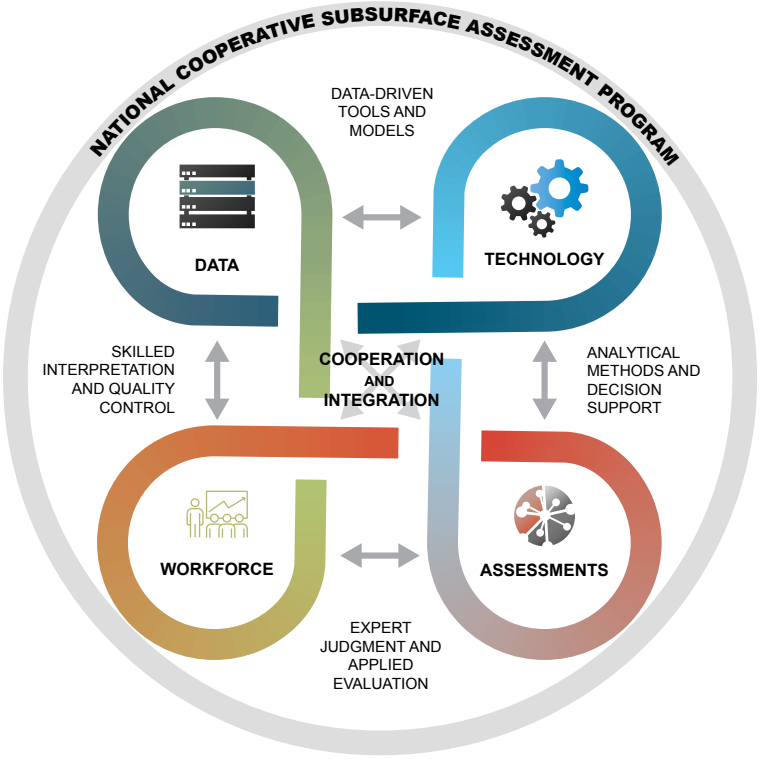


Figure ES-1. *Cooperative and Integrated Data, Technology, Workforce, and Assessments Are Key Pillars of a National Cooperative Subsurface Assessment Program*

potential and support a secure energy and economic future.

High-quality subsurface datasets are essential for assessments, yet many remain fragmented, inconsistently preserved, or inaccessible across agencies, states, industry, and academia. Modern frameworks for standardized data collection, digital preservation, interoperability, and sharing are needed to maximize their long-term value. Because many resources—such as oil and gas systems, storage potential, geothermal resources, and minerals in produced water—can overlap within the same subsurface regions (Figure ES-2), integrated assessments focused on characterizing a volume of Earth, rather than a single resource, can support multiple energy sectors (Table ES-1). Preserving these valuable datasets enables ongoing use, improves efficiency, and supports future research and development.

Equally important is the continued advancement and deployment of technologies—including advanced seismic, remote sensing, and geophysical imaging; field, laboratory, and well-based methods; 3D modeling and 4D simulation; and high-performance computing, artificial intelligence, and machine learning—which can significantly improve the resolution, efficiency, and predictive capability of subsurface assessments. These tools require a workforce skilled in geology, geophysics, engineering, data management, and modeling, including the ability to interpret seismic, well, sensor, and satellite data; integrate large datasets; evaluate uncertainty and risk; and translate technical results for policy and resource decisions.

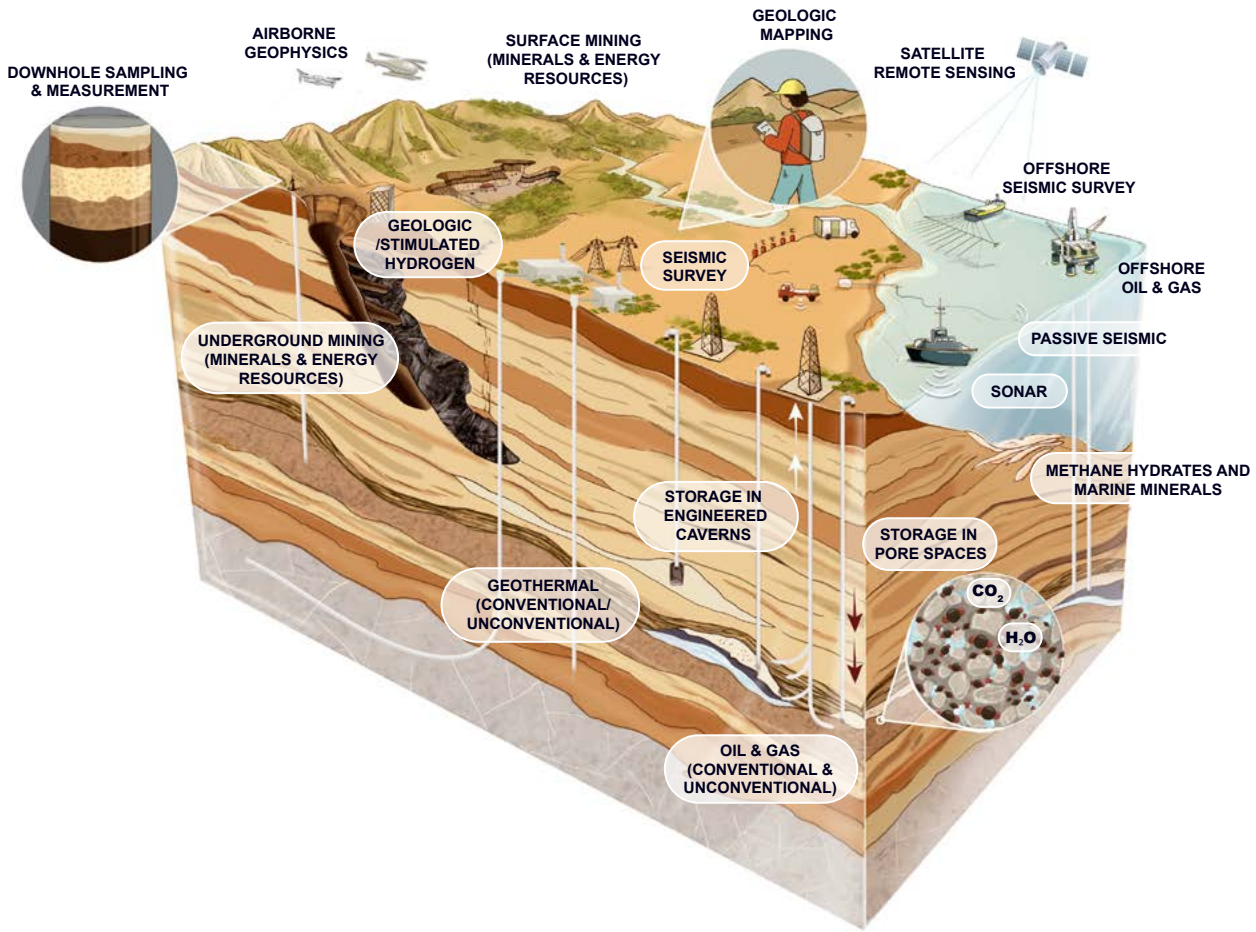


Figure ES-2. *Illustration of Resources in the Subsurface, Plus the Methods Used to Characterize Them*

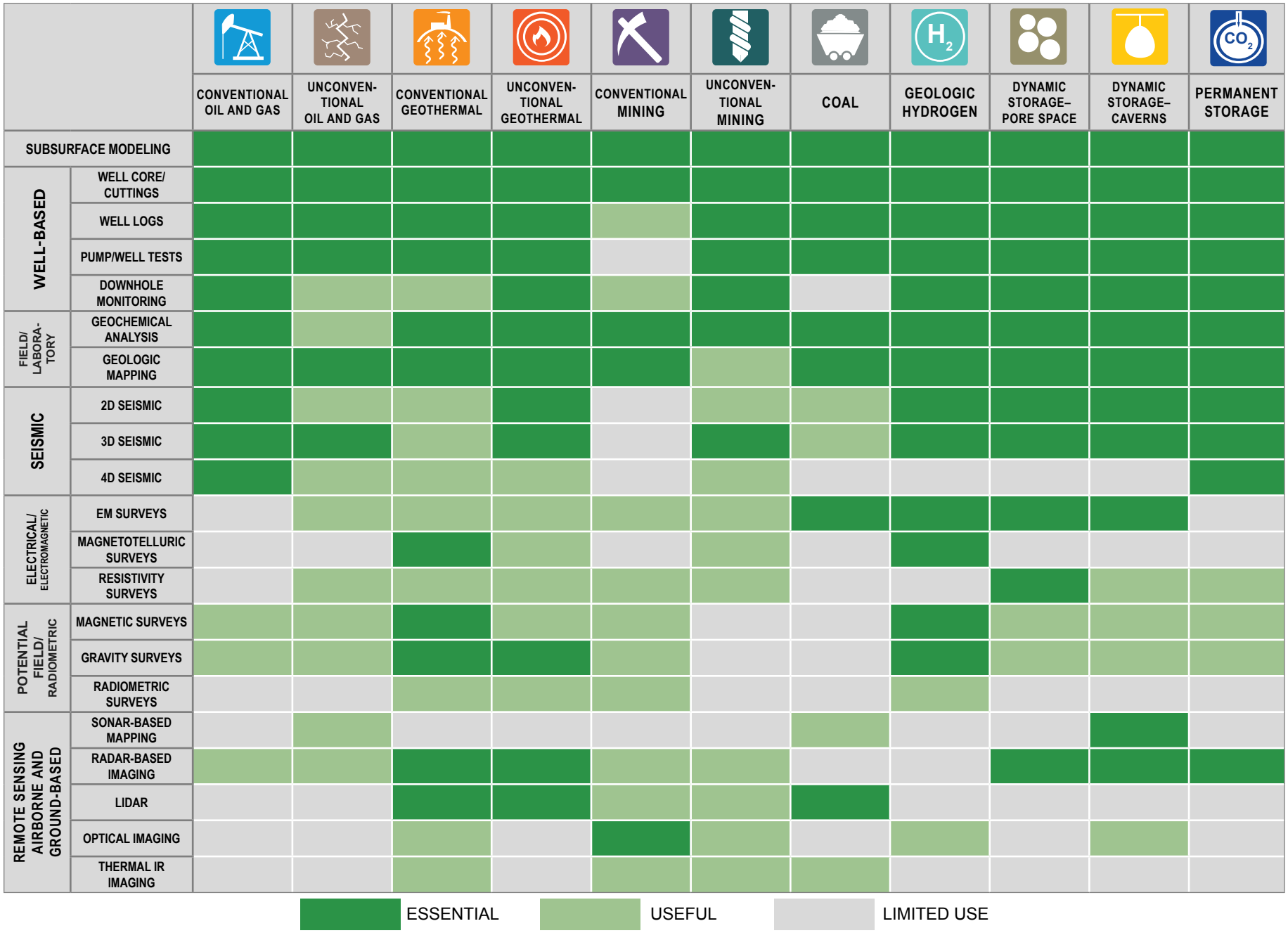


Table ES-1. *Current Importance of Subsurface Characterization Methods for the Resources Discussed in This Report*

Together, integrated data systems, advancing technologies, a qualified workforce, and robust assessments can accelerate discovery, reduce uncertainty, lower costs, and improve decisions by policymakers, industry, and the public. The scale of the opportunity is substantial: Extractive industries contributed roughly $384 billion,[3] or about 1.2% of U.S. GDP, in 2025, while subsurface resources provide more than 80% of the nation's energy needs and essential feedstocks for manufacturing, infrastructure, defense, and advanced technologies. A modern national program would help convert fragmented and underused data into actionable insight, enabling coordinated planning for resource development, storage, infrastructure siting, and environmental stewardship. Without it, the nation risks data loss, duplicative investment, slower resource identification, higher development uncertainty, and missed opportunities to fully realize the economic, energy security, and environmental value of the U.S. subsurface. This may ultimately weaken U.S. competitiveness in the global race for industrial and technological leadership.

I. STUDY BACKGROUND

At the request of the Department of Energy (DOE), in collaboration with the Department of the Interior (DOI), this study examines the value of publicly available subsurface resource assessments across federal, Tribal, state, and private lands, both onshore and offshore. It considers a range of resources—including oil and gas, geothermal energy, essential minerals, coal, geologic hydrogen, and subsurface storage—and identifies gaps in current federal and state assessment efforts, as well as opportunities to strengthen or expand programs.

In the United States, subsurface resource assessments are conducted by both public institutions and private industry, each serving distinct but complementary roles. Publicly available assessments are led primarily by government entities—including the U.S. Geological Survey (USGS), the Marine Minerals Administration (MMA)[4], and state geological surveys—which generate foundational geologic data and regional-scale resource evaluations. Land management and other regulatory agencies, such as the Bureau of Land Management (BLM) and various state oil and gas regulators, may also produce assessments, often drawing heavily on the underlying datasets created by the geological surveys. The U.S. Energy Information Administration (EIA) plays a complementary role by aggregating and reporting reserves and production data to inform markets, policy, and planning. In parallel, federal science and technology agencies—including DOE and its national laboratories, NASA, the National Science Foundation (NSF), and NOAA—advance the scientific understanding, tools, and technologies that support resource characterization and development. Industry builds on this public foundation through targeted, high-resolution assessments of specific basins, plays, and prospects.

The interaction between public data and private analysis is therefore critical: Publicly available datasets and assessments reduce uncertainty, accelerate prospect evaluation, and enable more efficient capital deployment. Together, this ecosystem of public and private assessment supports more informed, efficient, and innovative resource development across sectors, and advances the United States' energy independence.

FINDING: Government-produced subsurface assessments tend to focus on data generation, data compilations, and static resource assessments. These provide foundational value for a wide range of stakeholders by reducing uncertainty, enabling informed decision-making, and supporting safe and efficient resource development.

FINDING: Government resource assessments are most useful in the early stages of resource exploration or where new concepts or technologies open opportunities for revitalizing resource development.

3 Federal Reserve Bank of St. Louis, Federal Reserve Economic Data (FRED), https://fred.stlouisfed.org/graph/?g=1Um3C.

4 The MMA was formerly the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

II. KEY GAPS IN THE CURRENT U.S. SUBSURFACE ASSESSMENT SYSTEM

Despite world-leading capabilities in geologic science, data collection, and resource evaluation, the United States lacks a coordinated, integrated approach to understanding its subsurface resources at a national scale. This report identifies several cross-cutting gaps that limit the nation's ability to fully characterize, assess, and develop its subsurface resources, including:

- Need for integrated decision-relevant framework and holistic multiresource assessments: Federal and state entities produce valuable subsurface data and assessments under distinct mandates, methods, and update cycles. These efforts provide essential views of different parts of the resource system, but they are not consistently integrated into a unified decision-relevant framework. Additionally, multiresource assessments that evaluate colocated resources as part of a broader subsurface system remain rare.
- Gaps in baseline datasets, legacy data preservation, and public-private data integration: Key baseline datasets—such as regional geologic mapping; geophysical surveys; drilling, coring, and downhole logging; and geochemistry—remain incomplete or uneven across regions. At the same time, valuable legacy subsurface datasets are at risk of loss and high-resolution industry data (e.g., seismic data) are not always systematically incorporated into public assessments (with the exception of MMA's assessments of the Outer Continental Shelf), limiting a complete national view of subsurface resource potential.
- Limited data standardization and interoperability: Subsurface datasets are often stored in incompatible formats with inconsistent naming conventions, identifiers, and quality standards. This creates significant barriers to integrating data and reduces the overall utility of publicly available information.
- Misalignment with evolving technologies and emerging resources: Assessment methodologies and data collection efforts have not consistently kept pace with advances in extraction technologies, sensing capabilities, and emerging resource opportunities.
- Limited subsurface workforce: Modern subsurface assessments increasingly depend on a limited number of professionals who can combine subsurface expertise with quantitative skills in data science, modeling, geospatial analysis, and uncertainty evaluation.

Together, these gaps highlight a central challenge: The United States possesses extensive subsurface data and strong analytical capabilities, but lacks the integrated, modernized, and coordinated framework needed to fully realize the value of its subsurface resources.

III. TOWARD A NATIONAL COOPERATIVE SUBSURFACE ASSESSMENT PROGRAM

Establishing a National Cooperative Subsurface Assessment Program will require a phased approach that progresses from near-term priorities to a fully integrated national capability. As shown in Figure ES-3, initial efforts should focus on assessing emerging resources, strengthening foundational data and analytical capabilities, and improving coordination across federal and state organizations. Over time, these efforts can support holistic, multiresource assessments that provide a more comprehensive understanding of the nation's subsurface and inform decisions related to energy security, economic competitiveness, resource development, and environmental stewardship.

RECOMMENDATION: The NPC recommends that Congress establish a long-term planning process within the White House Office of Science and Technology Policy (OSTP) that convenes federal agencies involved in subsurface resources, alongside a Federal Advisory Committee Act (FACA) committee chartered by OSTP, DOE, and DOI, and representing Tribal governments, state geological surveys, industry, academia, and other stakeholders. The planning process should incorporate the FA-

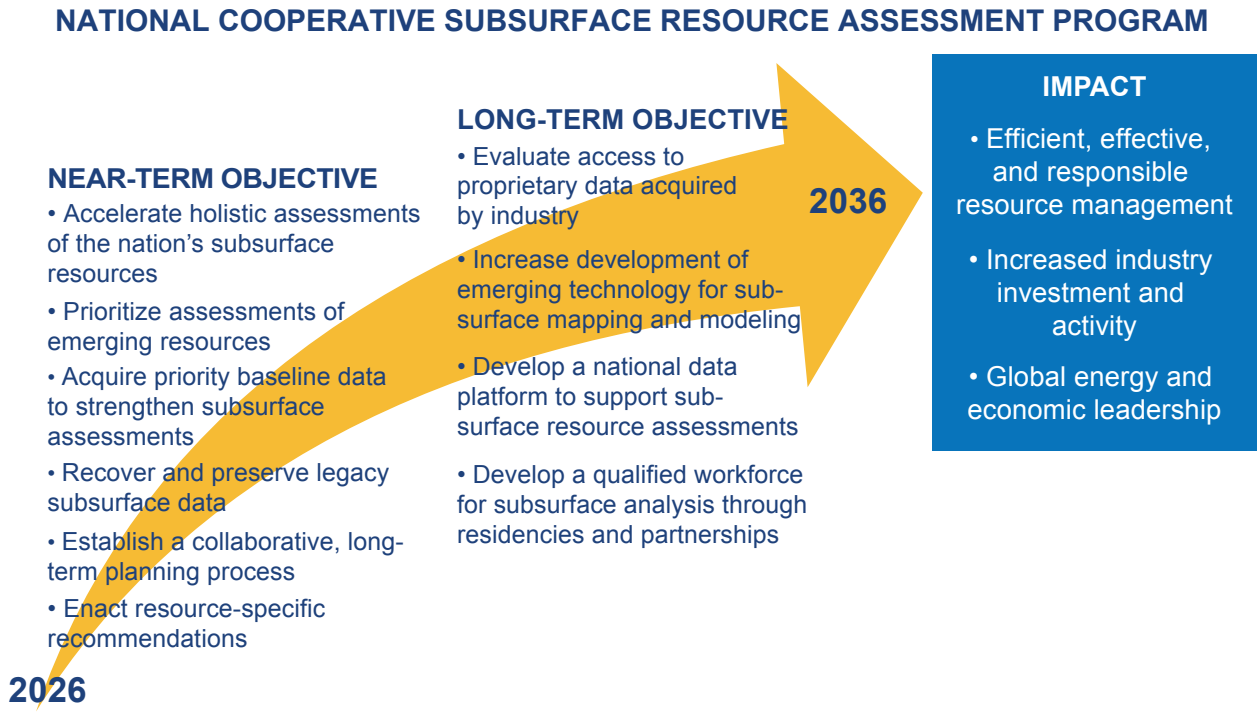


Figure ES-3. *Goals to Implement the Ultimate Vision of Establishing a National Cooperative Subsurface Assessment Program*

CA's input to identify national subsurface resource assessment priorities—including opportunities for holistic, multiresource assessments—and recommend funding, as well as periodically update priorities and recommended actions to maximize the relevance, impact, and timeliness of assessment activities.

A. Data

Data are the foundation of any subsurface assessment program. A holistic approach depends on integrating diverse datasets—including well logs, geophysical surveys, core samples, geochemical analyses, and remote sensing data—into accessible, standardized, and interoperable systems. Because these data are costly to acquire and often fragmented across agencies and industry, improved data preservation, standardization, and sharing are essential. A coordinated data ecosystem enables cross-jurisdictional analysis, supports advanced modeling and machine learning applications, and allows data collected for one resource to inform the assessment of others, significantly improving efficiency and reducing duplication of effort.

RECOMMENDATION: The NPC recommends that Congress authorize and appropriate dedicated, ongoing funding for a coordinated federal-state data acquisition initiative—led by the USGS with DOE, MMA, and state geological surveys partners—to close critical gaps in baseline subsurface data.

The initiative should prioritize:

- Nationally consistent, geophysical mapping (airborne magnetic, radiometric, gravity, and targeted seismic where appropriate).
- Strategic drilling, coring, and downhole logging to calibrate and validate geophysical interpretations.
- Standardized geochemical, mineralogical, and metallurgical sampling and

analysis (including produced water chemistry where relevant).

- Rapid publication of quality-controlled data and metadata in interoperable public repositories.

RECOMMENDATION: The NPC recommends that Congress fund a National Data Portal to ease access to interoperable public repositories for subsurface data. This portal, designed in consultation with an Office of Science and Technology Policy National Data Task Force, would be implemented by the USGS. The task force of key federal agencies—with input from academia, industry, state, Tribal, and federal stakeholders—would establish data standards and governance processes to optimize public data access to enable resource development and management.

RECOMMENDATION: The NPC recommends that Congress:

- Increase annual funding to the USGS National Geological and Geophysical Data Preservation Program (NGGDPP) to the originally authorized $30 million per year.
- Reduce the state matching requirement to 25%.
- Fund an Office of Science and Technology Policy National Data Task Force to develop a data preservation and recovery strategy that builds on the NGGDPP and establish best practices and budget recommendations for collecting, preserving, and serving data from industry and public sources.

RECOMMENDATION: The NPC recommends that the DOI commission a focused review of state, federal, and select international policies governing industry sharing of proprietary subsurface data—including well, seismic, and other geophysical data—to identify best practices and develop recommendations. The review should also evaluate incentives for early data release, giving due consideration to research and development and commercial investments and intellectual property rights, and impacts on operators and data/information service companies.

B. Technology

Advances in technology are critical to enabling holistic subsurface assessments. Emerging tools—including artificial intelligence and machine learning, advanced sensing technologies such as quantum and fiber-optic systems, and high-performance computing—are transforming how subsurface data are collected, integrated, analyzed, and visualized. These technologies will enable the production of 3D Earth models that provide an essential framework for integrating geologic, geophysical, geochemical, and engineering data to characterize resource distribution, evaluate uncertainty, identify colocated opportunities, and support more reliable assessments. At the same time, continued research is needed to better understand fundamental subsurface processes, such as fluid-rock interactions and reservoir behavior under varying conditions. Together, technology integration and innovation enhance the accuracy, scale, and speed of assessments, enabling a more comprehensive evaluation of both conventional and emerging subsurface resources.

RECOMMENDATION: The NPC recommends that DOE, in coordination with USGS, increase investment in emerging technologies, through both public/private partnerships and direct research and development (R&D) funding, to improve resource extraction technologies and subsurface resource mapping and modeling. Such investments should support new technologies, such as miniaturizing and ruggedizing existing technologies; developing new sensing technologies; improving drilling and recovery technologies; advancing hydraulic

fracturing and stimulation technologies; advancing 3D models; and leveraging artificial intelligence and machine learning capabilities to capitalize on the full potential of current and future resource data.

C. Assessments

A holistic subsurface assessment program evaluates the subsurface as an integrated resource system rather than as isolated commodities. Across the United States, multiple existing and emerging resources—oil and natural gas, geothermal energy, critical minerals, hydrogen, helium, and subsurface storage—often coexist within the same geologic frameworks. A comprehensive approach leverages shared datasets, advanced technologies, and coordinated institutional capabilities to assess these resources together, improving efficiency, reducing uncertainty, and enabling optimized development. Such a program requires alignment across assessments, data infrastructure, technology innovation, and clearly defined roles and responsibilities to fully realize the strategic value of the nation's subsurface.

RECOMMENDATION: The NPC recommends that the USGS and MMA, working in collaboration with the state surveys, accelerate the development of holistic, multiresource assessments that leverage DOE technology and pilot project support, advanced 3D subsurface maps and models, artificial intelligence, and emerging sensor integration.

While the long-term objective should be a holistic national subsurface assessment program, full implementation will require continued progress in data, methods, governance, and interagency coordination. Emerging resource assessments are a necessary near-term step toward that vision because resources such as geologic hydrogen, methane hydrates, unconventional critical minerals, and subsurface storage systems remain undercharacterized, lack standardized methods, and depend on evolving technologies and limited field data. A national program should prioritize these resources to reduce geologic uncertainty, expand baseline data, and connect resource potential to technical feasibility, processability, and system-level integration. Where appropriate, the program should integrate pilot tests and test wells to improve understanding of resource characteristics, reduce development uncertainty, and validate assessment methods. Doing so would accelerate early-stage validation, improve investment confidence, and help position emerging resources to support energy security, supply chain resilience, and future energy needs.

RECOMMENDATION: The NPC recommends that the DOI prioritize national assessments of emerging resources and collaborate with the DOE and state surveys to integrate emerging and existing technologies into these assessments. Current emerging resources include unconventional sources of critical and essential minerals, methane hydrates, and geologic hydrogen, as well as subsurface porous media storage capacities for oil and gas, hydrogen, carbon dioxide, and wastewater management. Establishing assessment priorities for emerging resources should include consideration of data availability to allow for adequate subsurface characterization and understanding of the key mechanisms governing the distribution and recoverability of the resource.

D. Workforce

Emerging resources and advanced, data-intensive assessment methods will require a more modern and interdisciplinary subsurface workforce. Resources such as geologic hydrogen, unconventional critical minerals, and subsurface storage systems demand skills beyond traditional geoscience and petroleum engineering, including data science, advanced modeling, and integrated systems analysis. Technologies such as artificial intelligence, machine learning, high-resolution sensing, and 3D modeling further increase the need for professionals who can work across geoscience, engineering, and digital domains. Coordinated efforts across academia, government, and industry will be needed to modernize curricula, expand training, transfer knowledge from

the existing workforce, and build capabilities aligned with emerging resource opportunities. Without this effort, workforce limitations could become a bottleneck to both emerging resource assessments and broader subsurface modernization. The following recommendation complements the workforce development directive [section 7002(k)] in the Energy Act of 2020, but with a focus on subsurface skill development.

RECOMMENDATION: The NPC recommends that DOI and DOE coordinate with NSF, academic institutions, state geological surveys, national laboratories, and private-sector partners to identify priority subsurface analytical skillsets. They should then establish a residency program linking universities to professional practice while expanding fellowship and internship opportunities focused on developing these competencies. These steps will send a signal to universities that these skills are highly valued and create the durable pipeline of highly skilled early-career geoscientists and advanced computational analysts essential for progressing national priorities in resource extraction and storage.

IV. RESOURCE-SPECIFIC RECOMMENDATIONS

Many subsurface data types, technologies, and assessment frameworks apply across resource systems, but assessments for individual resources often emphasize different data types, methodologies, and technologies. Because each resource is currently supported by distinct federal and state initiatives, gaps in data availability, methodological consistency, technology integration, and decision-relevant assessment also vary by resource. Table ES-2 summarizes the sector-specific recommendations in this report to address those gaps for oil and gas, geothermal, essential minerals,

Resource	Summary of Resource-Specific Recommendations
Oil and Gas	Develop Methodologically Consistent Oil and Gas Assessment System
	Improve Assessments of Produced Water as a Resource
	Advance Unconventional Oil and Gas Pilot Projects
	Continue the Long-Term Methane Hydrates Test Site
Geothermal	Increase Access to Deep Wells and Demonstrations
	Increase Collection of Well and Laboratory Data
	Advance Material Science Research for Superhot Conditions
Essential Minerals	Establish a Coordinated National Minerals Program
	Implement a Unified Framework for Assessments
Coal	Revise and Develop New Assessments
Geologic Hydrogen	Authorize and Fund a National Geologic Hydrogen Program
	Assess Helium Resources Associated with Hydrogen Discoveries
Dynamic Storage	Complete a Nationwide Assessment
	Expand Screening Datasets
	Execute an R&D Program to Quantify and Mitigate Containment Risks
Permanent Storage	Assess National Storage Capacity for Produced Water
	Continue Funding Carbon Storage Demonstration Projects

Note: See Chapter 2 for more details.

Table ES-2. *Summary of Sector-Specific Recommendations*

coal, geologic hydrogen, dynamic storage, and permanent storage. These recommendations are developed in greater detail in Chapter 2.

V. INDICATIVE INVESTMENT AND EXPECTED RETURN

Rigorous estimation of required appropriation levels and economic analyses of the recommendations presented in this report were beyond the scope of this study. However, development and implementation of the National Cooperative Subsurface Assessment Program will require a holistic approach linking advanced data acquisition and management, development of new technologies, new approaches to resource assessment, and investment in workforce development. This will require significant coordinated upfront investment. Some high-cost elements include drilling and testing deep wells, acquisition of high-resolution remote sensing data, building and operating the pilot tests sites needed to develop advanced technology, and support for workforce development. All these elements are critical because it is the combination that will support rapid advancement of U.S. domestic energy and mineral supplies, and subsurface storage.

Based on funding levels for similar programs—and indicative costs for data acquisition, field pilot projects, staffing, and other capital-intensive components—we estimate that the total of the recommendations would require new appropriations from $500 million to more than $1 billion per annum. Although this investment would be significant, the combined expected value return to the federal government would be on the order of 10x to >50x, based on comparison with similar resource-focused initiatives.[5] State and industry benefits would be in addition to this. The return of investment multiple and timing will vary depending on the resource, resource maturity, technological capability, and market conditions. However, it is reasonable to expect 5x–10x returns within 10 years and higher returns over the course of 20 years as resources are developed and revenues generated.

As analogous indicators of expected return on investment, Geoscience Australia commissioned Deloitte to conduct an analysis of the value of government investment in precompetitive data in 2021–2022 to support subsurface resource exploration and extraction and calculated that the investment of $AU 151 million in new data acquisition and facilitated provision of legacy data returned $AU 5.5 billion in resource exploration value and $AU 70.5 billion in resource extraction (minerals and oil and gas).[6] A report published by the American Geosciences Institute analyzed the return on investment of geologic mapping in the United States from 1994–2019 and estimated that the investment of $1.99 billion during this period fostered $20.61 billion[7]—more than a 10x multiplier in value.

Beyond direct economic returns, the recommendations would lead to more secure value chains for energy, minerals, and subsurface storage in the United States; further strengthen U.S. leadership in subsurface resource exploration and production; grow and evolve capabilities for the future to keep pace with rapid advancements in technology; and address concomitant needs for a highly skilled workforce for subsurface assessment.

VI. SUMMARY

The subsurface underpins the nation's energy system, mineral supply chains, infrastructure, and long-term economic prosperity. Yet much of its potential remains incompletely understood. A National Cooperative Subsurface Assessment Program, as outlined in this report, would help transform fragmented data and assessments into a comprehensive understanding of the nation's subsurface resources, enabling better decisions about development, storage, environmental stewardship, and future investments. By acting now, the United States can strengthen its energy security, enhance economic competitiveness, and ensure responsible management of one of its most valuable strategic assets. ■

5 Deloitte Access Economics, *The Economic Value of Government Precompetitive Geoscience Data and Analysis for Australia's Resources Industry*, prepared for Geoscience Australia, 2023, 9; American Geosciences Institute, *Economic Analysis of the Costs and Benefits of Geologic Mapping in the United States of America* (2025), https://www.americangeosciences.org/static/pdf/GeoMapAnalysis.pdf.

6 Deloitte Access Economics, *The Economic Value of Government Precompetitive Geoscience Data and Analysis for Australia's Resources Industry*, prepared for Geoscience Australia, 2023, 9.

7 American Geosciences Institute, *Economic Analysis of the Costs and Benefits of Geologic Mapping in the United States of America* (2025), https://www.americangeosciences.org/static/pdf/GeoMapAnalysis.pdf.

SUMMARY OF RESOURCE-SPECIFIC FINDINGS AND RECOMMENDATIONS

The Executive Summary describes the cross-cutting case for a National Cooperative Subsurface Assessment Program and identifies common data, technology, assessment, and workforce needs that apply across the nation's subsurface resources. This section summarizes the resource-specific findings and recommendations developed in Chapters 1 and 2, showing how those shared needs vary across oil and gas, geothermal, essential minerals, coal, geologic hydrogen, dynamic storage, and permanent storage.

I. CONVENTIONAL AND UNCONVENTIONAL OIL AND GAS

Onshore and offshore oil and gas resources remain the largest and most economically significant subsurface assets in the United States. Estimated in-place resources range from 2 to 4 trillion barrels of oil and tens of thousands of trillion cubic feet of gas, including conventional and unconventional accumulations and emerging resources such as methane hydrates in Alaska's North Slope (Prudhoe Bay) and in the Gulf of America. Public-sector assessments led by USGS, MMA[8], and EIA have helped characterize these resources and associated coproduced resources such as helium and produced water, while DOE has accelerated the development of assessment and extraction technologies through R&D and field demonstrations.

Given the scale of the resource base, even modest improvements in assessment quality can affect production, investment decisions, and energy security. However, current federal and state assessment efforts remain fragmented, vary in scope and methodology, and are not consistently updated to reflect rapid technological advances—particularly in unconventional systems. Thus, they do not provide an integrated, decision-relevant view of national resource potential.

FINDING: The United States has world-leading geologic assessment and data capabilities but lacks a coordinated, frequently updated, and methodologically consistent framework across agencies to translate them into a comprehensive, decision-relevant view of oil and gas resource potential from undiscovered resource to proven reserves.

RECOMMENDATION: The NPC recommends USGS, MMA, and DOE work toward coordinating existing methodologies into a comprehensive and methodologically consistent oil and gas assessment system that links undiscovered technically and economically recoverable resources, contingent resources, and reserves for both the onshore and offshore.

RECOMMENDATION: The NPC recommends DOE support unconventional oil and gas reservoir pilot projects to advance recovery technology and to inform USGS's technical recoverable assessments.

RECOMMENDATION: The NPC recommends DOE continue funding and support for the long-term methane hydrate production test site at Prudhoe Bay. The site's unique infrastructure, well-characterized subsurface data, proven hydrate resources,

8 The MMA was formerly the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

and instrumented wells provide an unparalleled platform to advance commercial production methods and establish methane hydrates as a significant global resource.

RECOMMENDATION: The NPC recommends USGS continue improving the assessment of produced water as a resource for beneficial reuse by quantifying formation-specific volumes and constituents.

II. CONVENTIONAL AND UNCONVENTIONAL GEOTHERMAL

Geothermal energy represents a potentially vast, largely untapped domestic resource capable of providing reliable, low-carbon baseload and dispatchable power at scale. Unconventional geothermal technologies such as enhanced geothermal systems (EGS) and more novel technologies such as superhot geothermal could significantly expand the accessible resource base, increasing its potential contribution to the U.S. energy mix. Technology development and deployment and resource assessments of conventional and unconventional geothermal are critical to identifying viable locations, reduce exploration risk, and accelerate development projects. However, existing federal and state efforts remain limited by a lack of access to geographically distributed, privately owned deep wells; incomplete, low-resolution, and inconsistent data; uneven geographic coverage; and relatively low levels of sustained funding. These limitations constrain federal and state agencies' ability to fully characterize the scale and quality of the resource and to support rapid deployment.

FINDING: Many recent geothermal resource assessments have continued to rely on previously compiled datasets with inconsistent resolution and coverage, rather than incorporating substantial new data. A major update to underlying datasets will be required to advance the geothermal industry.

FINDING: Basic research, development, and deployment are needed to further advance the unconventional geothermal industry. This could occur through the development of public-private partnerships.

RECOMMENDATION: The NPC recommends DOI and DOE increase the acquisition of thermal, hydraulic, mechanical, and chemical data through drilling of new research wells and from wells of opportunity (e.g., oil and gas wells planned for abandonment, orphaned wells under state/federal oversight) and support laboratory and demonstration-scale testing under high-pressure/high-temperature conditions across diverse geologic settings.

RECOMMENDATION: The NPC recommends DOI and DOE consider assuming ownership of, or creating a program that enables access to, a limited number of distributed deep wells for core and fluid collection, instrumentation, monitoring, potential deepening, and additional demonstrations of unconventional geothermal technologies.

RECOMMENDATION: The NPC recommends DOE and NSF advance material science research and demonstrations to develop drilling capabilities and processing equipment in superhot conditions.

III. CONVENTIONAL AND UNCONVENTIONAL ESSENTIAL MINERALS

Essential minerals—including critical minerals needed for energy technologies, manufacturing, defense, and advanced industrial supply chains—represent an increasingly important component of the U.S. subsurface resource base. Although the United States has substantial domestic resources and a robust cross-agency capacity for geologic assessment, many conventional mineral systems remain undercharacterized, while

unconventional resources—including produced waters, geothermal brines, mine tailings, coal combustion residuals, acid mine drainage, and offshore mineral systems—have only recently begun to receive systematic evaluation. Public resource assessments help identify prospective regions, reduce exploration risk, and strengthen supply chain resilience. However, current federal and state efforts remain fragmented across programs, commodities, and jurisdictions, resulting in uneven data coverage, limited interoperability, inconsistent integration of mineralogical and metallurgical data, and insufficient attention to unconventional resource pathways. These gaps limit the nation's ability to fully evaluate domestic essential mineral potential, including where resources exist, whether they are recoverable, and how they could contribute to future supply.

FINDING: The United States maintains strong geologic assessment capabilities for essential minerals but lacks a unified regularly updated national framework that integrates geologic, geochemical, hydrological, and metallurgical considerations into a decision-relevant view of domestic supply potential.

RECOMMENDATION: The NPC recommends policymakers, USGS, DOE, state geological surveys, and industry partners establish a coordinated national minerals program by 2029 that restores the integrated capabilities once housed in the former U.S. Bureau of Mines—linking geologic assessment, extractive metallurgy, mineral processing research, and pilot-scale demonstration.

This program should:

- Expand the Earth Mapping Resources Initiative to produce national-scale prospectivity maps using integrated geologic, geophysical, geochemical, and mineral systems modeling.
- Launch a national mineralogy and metallurgy program that requires all federally funded essential minerals projects to include early stage mineralogical characterization and bench-scale metallurgical testing.
- Establish at least three multisite mineralogical and metallurgical testbeds to benchmark extraction performance across conventional and unconventional feedstocks.

RECOMMENDATION: The NPC recommends USGS, in coordination with DOE and state geological surveys, implement, by 2028, a unified national framework for minerals assessment and processing. This framework should publish resource specific assessment playbooks that define sampling protocols and minimum dataset requirements—including geologic, geophysical, geochemical, drilling, mineralogical, metallurgical, geotechnical, and environmental data—for each resource maturity stage.

IV. COAL

Coal represents one of the most extensively characterized and historically significant subsurface resources in the United States, with a large and well-documented resource base that could support supply for centuries under current assumptions. Federal and state assessment efforts—led primarily by the USGS, the EIA, and state geological surveys—have produced comprehensive datasets on coal quantity, quality, and distribution, making coal one of the most mature resource assessment domains. These assessments continue to provide value by informing land management, supporting legacy operations, and increasingly identifying opportunities for new uses, including critical mineral recovery from coal and coal waste streams. However, as market conditions shift and coal's role in the energy system evolves, federal and state initiatives have increasingly deprioritized large-scale resource reassessment and modernization of legacy datasets. This creates a growing gap between the extensive historical knowledge base and the need for updated, integrated assessments that

reflect emerging technologies, new use cases such as underground coal gasification, and changing economic conditions.

FINDING: Mature, comprehensive historical databases of coal resources would benefit from updates to reflect modern analytical techniques and emerging priorities, including critical mineral recovery from coal and waste streams.

RECOMMENDATION: The NPC recommends USGS, in coordination with DOE for technology development, work with states to revise and/or develop new assessments to better characterize the quality and composition of undeveloped coal resources. Such assessments will provide greater opportunity to determine the suitability of utilizing remaining coal resources for emerging market opportunities.

V. GEOLOGIC HYDROGEN

Geologic hydrogen has the potential to become a new, large-scale source of low-carbon energy, with early studies suggesting that natural hydrogen-generating systems may be widespread, and in some geologic provinces, associated with other resources such as helium. Although still at an early stage, initial public-sector mapping efforts, including a high-level prospectivity analysis of the continental United States, have begun to define areas of potential and highlight the scale of the opportunity. In this context, resource assessments are essential to establish the fundamental geologic framework, reduce uncertainty, and guide early exploration. However, current federal and state efforts remain limited in geography and scope, lack dedicated authorization and funding, and are not yet supported by standardized methodologies or integrated, quantitative datasets, constraining the ability to evaluate resource potential at a national scale.

FINDING: While a high-level qualitative prospectivity assessment of the continental United States has been completed, the USGS has not yet completed prospectivity assessments for Hawaii or U.S. offshore geological hydrogen resources. The association of geologic hydrogen and helium resources in certain geologic settings may warrant integrated assessments of both resources.

FINDING: Existing assessments for the contiguous United States remain largely qualitative and could be improved with further research and rigorous quantitative methods.

RECOMMENDATION: The NPC recommends Congress authorize and fund a national program for geologic hydrogen research, assessment, development, and demonstration. Modeled after the Methane Hydrate Research and Development Act, the program would support DOE-led technological development and field demonstrations and USGS-led resource assessment of both conventional and unconventional (stimulated) geologic hydrogen, in partnership with state geological surveys, research institutions, and industry.

RECOMMENDATION: The NPC recommends that USGS should consider assessing potential helium resources that might be associated with hydrogen discoveries, as more exploration data from geological hydrogen wells drilled in the United States becomes available. Currently the USGS national assessment of recoverable helium resources includes only those found in known natural gas resources.

VI. DYNAMIC STORAGE IN POROUS MEDIA AND CAVERNS

Dynamic subsurface storage resources—including natural gas,[9] hydrogen, and other energy carriers—are critical to enabling a reliable and

9 NPC, forthcoming report on natural gas storage (December 2026).

flexible energy system, particularly as variable generation increases. The United States has substantial existing storage capacity and significant potential for expansion within suitable geologic formations. Resource assessments are central to identifying suitable sites, evaluating performance characteristics, and supporting infrastructure development. The USGS has already developed a probabilistic method for quantifying dynamic storage of natural gas. However, current assessments are limited in geographic extent. Further, these assessment efforts are largely derived from legacy oil and gas data and are not consistently tailored to storage-specific performance requirements, which limits their effectiveness in supporting future system needs. Additional research is also needed to study containment of hydrogen and other energy resources, such as thermal energy, in dynamic storage reservoirs.

FINDING: USGS has developed a probabilistic methodology for quantifying dynamic storage, but its method and data sources are incomplete and the analysis has not yet been applied across the United States.

FINDING: Additional research is needed to study containment of hydrogen in dynamic storage reservoirs, including research on biogeochemical reactions and loss of containment through caprock, faults, fractures, or leaky wells.

RECOMMENDATION: The NPC recommends USGS complete the nationwide assessment of dynamic subsurface storage resources currently in progress. This work should standardize the probabilistic methodology, clarify data inputs and quality requirements, and apply the methodology at scale across the United States. USGS should publish a transparent inventory of assessed coverage and remaining data gaps.

RECOMMENDATION: The NPC recommends USGS and state surveys, in partnership with research institutes, expand existing salt and storage screening datasets into a national, GIS-based layer with location-specific depth, thickness, impurity, and geomechanical properties to improve early-stage site screening and reduce development risk.

RECOMMENDATION: The NPC recommends DOE, working with USGS, national labs, state surveys, and industry, fund an applied R&D program to quantify and mitigate hydrogen containment risks in dynamic storage reservoirs and deliver field-validated best practices for site screening, monitoring, and integrity management.

VII. PERMANENT STORAGE

Permanent subsurface storage of fluids associated with energy production represents one of the largest potential uses of subsurface pore space in the United States. Produced water—generated from oil and gas operations across every major producing basin—is a significant resource that can be treated for beneficial reuse[10] with residual brines managed through subsurface injection and permanent storage. New treatment technologies, combined with integrated water management systems, currently help minimize freshwater use in the oil and gas industry, and in the future, afford the opportunity to supplement the supply of freshwater for other uses such as agriculture, combined-cycle power generation, and cooling. Carbon dioxide shares many of the same storage conditions and containment requirements. Realizing permanent subsurface storage opportunities depends on robust resource assessments to characterize storage capacity, injectivity, and long-term containment. While DOE, USGS, and other federal and state agencies have made progress in developing regional assessments and demonstration projects (e.g., CarbonSAFE and the Regional Carbon Sequestration Partnerships), underlying datasets remain fragmented and uneven in resolution and coverage, with limited integration across jurisdictions.

10 NPC, forthcoming report on the beneficial reuse of produced water (December 2026).

These gaps, combined with a limited number of demonstration projects in emerging storage play types—including organic shales, basalt formations, and unmineable coal seams—constrain the development of a comprehensive, decision-relevant understanding of national permanent storage potential. These gaps increase technical risk, uncertainty, and cost for permanent storage.

FINDING: Current regional- and basin-level storage assessments, for both produced water and carbon management, require more site-specific subsurface data to improve resolution and coverage while addressing formation-specific risks. Key data needs include additional 3D seismic surveys and well data, such as those provided by the CarbonSAFE demonstration program.

FINDING: Produced water storage capacity is a critical national resource supporting oil production and represents a major gap in national-level storage assessments. Leveraging subsurface characterization work already underway for carbon dioxide storage assessment can help address this gap. However, there is still a critical need to assess pore pressure variability and compressibility within deep and shallow produced water intervals, particularly in regions such as the Permian Basin, among other key basins across the United States.

RECOMMENDATION: The NPC recommends that Congress provide funding for USGS to conduct a comprehensive national assessment of subsurface storage capacity in saline aquifers, depleted reservoirs, and other suitable formations for produced water. This effort should build on existing datasets and methodologies.

RECOMMENDATION: The NPC recommends that Congress continue to fund DOE programs such as CarbonSAFE that reduce technical risk, uncertainty, and cost for commercial carbon dioxide storage in saline aquifers, while also supporting and providing new funds for demonstration programs that combine carbon dioxide storage with enhanced hydrocarbon recovery. Within CarbonSAFE, DOE should also increase focus on emerging storage play types such as basalts, unmineable coal seams, shales, and composite confining systems. ■

CHAPTER 1 |
THE VALUE OF PUBLICLY AVAILABLE SUBSURFACE DATA AND RESOURCE ASSESSMENTS

I. INTRODUCTION

What value do subsurface assessments provide to industry and other stakeholders, and how does that value vary across resource type and maturity? This chapter addresses this question by outlining the data and analytical methods used to characterize the subsurface and highlighting how those assessments are used to support decision-making across different resource types and development stages.

A. Subsurface Resources

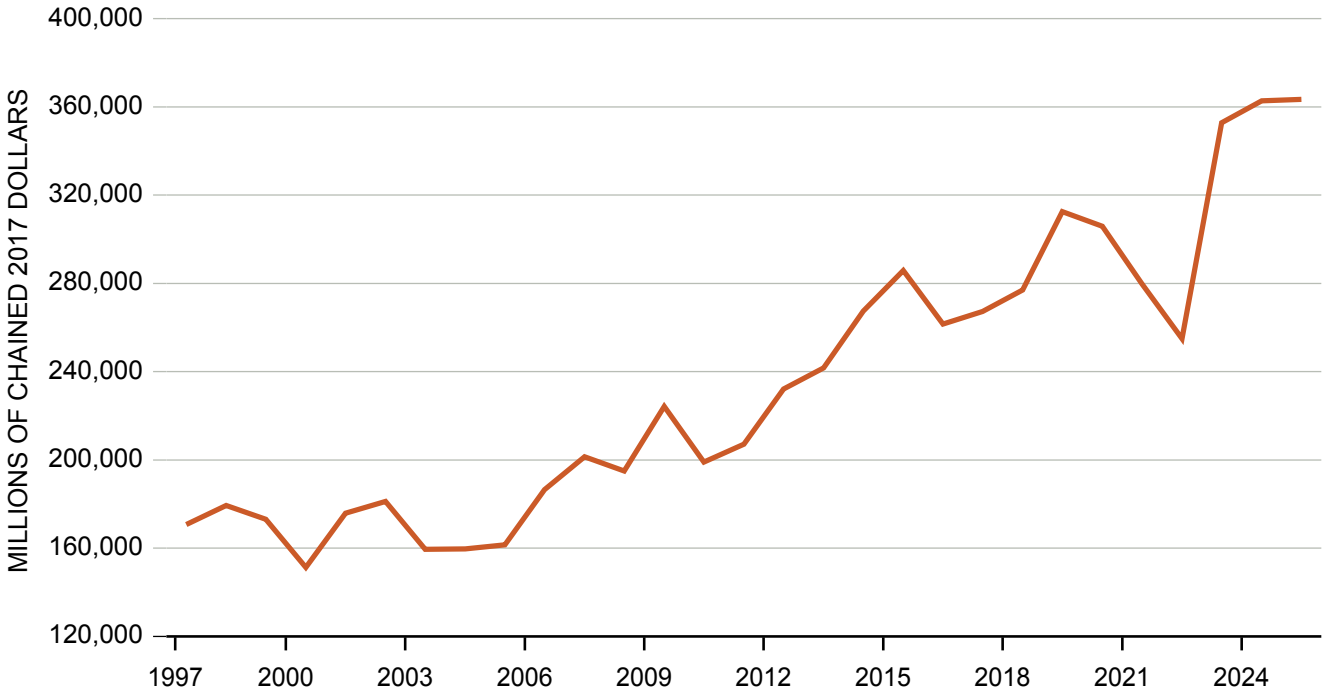
Subsurface resources are broadly defined as the suite of commodities and capacities that are beneath the Earth's surface and require drilling or mining for their utilization. This definition encompasses traditional resources—such as oil and gas, coal, and essential minerals—that have been developed for more than a century, as well as emerging or revalued resources, including hydrogen, mine tailings, and deep saline groundwater. Extractable subsurface resources also include thermal energy that is generated and trapped in the subsurface and can be harnessed for utility-scale geothermal power generation.

These extractive industries are a major part of the United States' economy, contributing more than $384 billion (2017 dollars) or 1.2% to the United States' gross domestic product in 2025 (Figure 1-1).[11] Subsurface resources provide more than 80% of the nation's energy needs, and oil, gas, and minerals are essential feedstocks for manufacturing.

Not all subsurface resources are extracted, however. The term also encompasses pore space and underground voids that have the potential to serve as storage reservoirs, whether for temporary applications (e.g., chemical energy storage or fluid management) or permanent sequestration (e.g., carbon dioxide and wastewater).

In this report, resource maturity is classified into five stages, reflecting the progression from initial evaluation to long-term development and reassessment. "Frontier" refers to early-stage areas with limited data where the presence of a working resource system is unproven and assessments focus on high-uncertainty "rank wildcat" opportunities. "Emerging" describes areas where a resource system has been identified but remains incompletely defined, with assessments aimed at delineating the extent of the system and reducing uncertainty. "Developing" applies to areas undergoing active appraisal and initial development, where increasing data availability supports more refined estimates of resource distribution, recovery or storage potential, and project design. "Mature" denotes well-established producing areas with extensive data and operational history, where assessments focus on optimizing

11 Federal Reserve Bank of St. Louis, Federal Reserve Economic Data (FRED), https://fred.stlouisfed.org/graph/?g=1Um3C.



Source: U.S. Bureau of Economic Analysis via FRED®. 2026.

Figure 1-1. *Real Gross Domestic Product from Extractive Industries (Mining, Quarrying, Oil and Gas Extraction) in the United States from 1997 to 2025*

recovery, managing decline, and identifying remaining or bypassed resources. "Revitalizing" captures the reevaluation of previously developed or overlooked resources using new technologies, improved data, or changing economic conditions, reflecting the potential to unlock additional value from resources once considered uneconomic or technically inaccessible.

B. Subsurface Data, Technology, and Workforce

In contrast to surface features, which can often be directly observed, subsurface resource characterization usually relies on limited direct sampling supplemented by a range of indirect data. Direct measurements include geologic mapping, well logs, core and drill cutting sampling, geochemical analysis, and pump tests. Indirect methods for subsurface imaging include seismic, gravity, resistivity, and magnetic surveys. Radiometric, radar, optical, hyperspectral, infrared imaging, laser ranging (LiDAR), and multibeam sonar surveys complement subsurface techniques providing data from the Earth's surface. Emerging technologies such as artificial intelligence and machine learning (AI/ML) and quantum sensing may help improve future resource assessments by enabling more sensitive subsurface measurements, better integration of complex datasets, reduced uncertainty, and more timely decision-relevant insights. Further description of subsurface technology can be found in Appendix B.

Collecting these complex datasets demands expert judgment and significant investment in training and human capital. These evaluations are performed either by broadly skilled geologists or specialized teams spanning fields such as petrophysics, stratigraphy, geophysics, and geomechanics, often supported by engineers for project execution.

C. Subsurface Assessments

Subsurface assessments are defined as the systematic integration and analysis of one or more datasets to produce quantitative estimates of the presence, location, geometry, internal properties, composition, or structural integrity of a subterranean geological resource. Subsurface assessments are produced by both governmental bodies (state, federal, and Tribal) and industry. Industry-produced resource assessments are optimized to support decisions on specific assets or specific areas. Government assessments are often regional in scale and conducted without direct commercial incentives. They provide neutral, objective benchmarks, often for regional- or national-scale decisions.

The type of subsurface assessment approach varies with resource type, asset maturity, data quality and availability, and the business or resource management questions relevant to each stage of development. Because acquiring direct measurements of subsurface properties is inherently difficult and often costly, government and industry organizations have developed sophisticated analytical approaches that combine diverse datasets to systematically constrain uncertainty and improve confidence in resource evaluations before doing extensive direct data acquisition campaigns.

Regardless of industry or application, subsurface assessments can be organized into four categories reflecting progressively greater data requirements and analytical sophistication:

1. **Data Compilations:** Aggregated datasets—such as bottomhole temperatures from legacy wells, geochemical assays, regional well log databases, cuttings, and core samples—form the foundation of subsurface assessment. Though often underestimated, these compilations can yield powerful and actionable insights at the region- or play-scale,[12] sometimes even opening new plays.
2. **Static Model Interpretations:** Compiled data are used to construct interpretive geologic models, including 2D and 3D maps and cross sections of geologic units of interest, buried structural features, fault offset analyses, and seal integrity or thickness maps. These models provide the spatial framework for all subsequent assessment stages.
3. **Static Volumetric and Property Assessments:** Data compilations—including well logs, test data, pressure versus temperature data, and geophysical surveys—and static model interpretations are routinely integrated to estimate how much of a resource exists underground. At this stage, 3D models are used to represent the shape and structure of the subsurface and to map how key properties vary across it. These models help estimate characteristics such as porosity, permeability, fluid content, and, in the case of mineral resources, ore grade—providing a spatially detailed picture of the resource in place. Static assessments can be carried out using either deterministic or probabilistic approaches. Deterministic methods produce a single best estimate, while probabilistic methods account for uncertainty and generate a range of plausible outcomes.
4. **Dynamic Simulations:** The technical viability of a subsurface asset can ultimately only be determined through simulation. Computer models—built from earlier geologic data—are used across oil and gas, geothermal, and carbon storage projects to estimate how a reservoir will perform over time, including how fluids will flow, how pressure will change, how much of a commodity can be recovered or stored, and how injected fluids will move underground. These models simulate different operating and economic scenarios to understand a range of possible outcomes. Because key reservoir properties are never known with complete certainty, simulations typically account for uncertainty and produce a range of results rather than a single answer.

Assessments have distinct objectives and outputs that depend on asset maturity and data availability, and can be broadly categorized into a three-tiered evaluation hierarchy:

12 A play is an area with similar geological characteristics that make it promising for a particular type of resource, such as oil, gas, minerals, or geothermal energy.

1. **In-Place Characteristics:** For both extractive and storage assets, in-place characteristics—such as resource presence, geometry, depth, internal rock properties, and mineral composition—are defined first. Although new data are continuously acquired to reduce uncertainty and refine estimations, the original in-place volume and compositional characteristics of a subsurface asset are generally treated as fixed. Government-produced assessments of in-place characteristics are critical for a broad, regional perspective of resources. They are also essential for resources that are emerging. Government-funded scientific research on in-place characteristics often informs play-opening data acquisition and industry assessments.
2. **Technical Recovery or Storable Quantities:** This stage quantifies the portion of a resource that can be recovered, or the capacity that can be stored, in the case of dynamic or permanent storage (Table 1-1). While early estimates may rely on recovery or storage factors from analogous operations, robust assessments must account for both subsurface conditions and the availability of extraction or storage technologies. These estimates are typically expressed as model-derived ranges rather than single values and can accommodate dynamic changes as production or injection progresses. Unlike in-place resource volumes, which are fixed by geology, recovery and storage factors can change substantially with technological advancement. The role of government-produced information for technical recovery or storage capacity is more limited for mature resources, but still essential for realizing the near- and long-term potential of emerging resources.
3. **Commercial Recovery or Storage Capacity:** The final stage of the resource evaluation hierarchy is commercial recovery or storage capacity (Table 1-1). In addition to characterizing the resource size and technical recoverability or viability for storage, commercial assessments must account for dynamic external conditions. These variables include current and future commodity prices, revenue generation forecasts, regulatory requirements, capital availability, and market demand, and collectively determine whether a technically achievable project can be economically or operationally brought to production or service. While government-produced data and research may impact resource management and regulatory compliance, industry assessments of commerciality often drive investment.

An illustration of the progression of this resource evaluation hierarchy comes from unconventional oil and gas development in the United States. Decades of drilling activity targeting conventional formations identified low-permeability, hydrocarbon-rich units—commonly organic-rich shales, siltstones, and sandstones—that had been penetrated and logged but generally dismissed as nonproductive. Although these units were known to contain vast quantities of oil and gas, the resource base was considered technically unrecoverable because of the extremely low permeabilities that inhibited hydrocarbon fluid flow.

The production potential of these unconventional tight oil and gas reservoirs was not fully appreciated until the advent and commercial scaleup of hydraulic fracturing from directional and horizontal wells. As drilling and completion technologies advanced in tandem through the 1990s and 2000s, immense volumes of hydrocarbon resources that had previously been classified as unrecoverable were reclassified as active production targets, fundamentally reshaping U.S. energy supply projections. Even with these industry-changing technological advances, the fraction of hydrocarbons that can be economically extracted from unconventional reservoirs remains modest. Estimated technical recovery factors in most unconventional tight oil plays are less than 10% of original oil in place—underscoring the degree to which vast in-place resources can remain stranded even in actively producing fields and the potential size of the target from improved subsurface assessments.[13, 14]

13 Lauren C. Burrows et al., "A Literature Review of CO_2, Natural Gas, and Water-Based Fluids for Enhanced Oil Recovery in Unconventional Reservoirs," *Energy & Fuels* 34, no. 5 (2020): 5331–5380, https://doi.org/10.1021/acs.energyfuels.9b03658.

14 J.J. Sheng, "Critical Review of Field EOR Projects in Shale and Tight Reservoirs," *Journal of Petroleum Science and Engineering* (2017).

		Resource Evaluation Hierarchy		
		In-Place Resource Characteristics	**Technical Recovery or Storage Quantities**	**Commercial Recovery or Storage Capacity**
Assessment Objectives		• Derive an estimate of resource size and characteristics • Quantify principal subsurface uncertainties (e.g., depth, 3D extent, porosity, permeability, reservoir pressure, fluid saturation, thermal conductivity, geothermal gradient, mineral composition, or ore grade)	• Derive estimates of recoverable (or storable) resource size ranges based on in-place resource characteristics as well as current or foreseeable technologies and engineering best practices	• Derive the economically viable recoverable (or storable) resource size based on technical recovery (or storability), factoring in commodity prices, regulatory requirements, revenue generation forecasts, capital availability, and market demand
Key Assessment Outputs	**Resource Extraction**	• Original oil or gas in place (hydrocarbon resources) • Geothermal gradient and heat in place (utility-scale geothermal energy) • Ore body size, depth, and elemental concentrations (critical minerals and coal)	• Estimated recoverable oil or gas (hydrocarbon resources) • Estimated recoverable thermal content and nameplate MW electrical (MWe) output (utility-scale geothermal energy) • Estimated recoverable tonnage (critical minerals and coal)	• Economic chance of success, return on investment, discounted rate of return for the project (for extraction projects) • Consumer price impact (for utilities projects)
	Storage and Disposa	• Original storage capacity and fluid saturation • Salt deposit depth, thickness, and pressure • Seal capacity and seal interval evaluation	• Estimated storage capacity	
Role and Relative Impact of Government Research and Resource Assessmen		• Critical for emerging resources • Critical for regional resource assessments • Government scientific research often informs play-opening data acquisition and industry assessments	• Critical for emerging resources • Moderate for industry assessments of established resources	• Data and interpretations impact regulatory compliance and resource management • Industry assessments of commerciality drive investment decisions
Relative Role of Technological Advancements		• High for detection and characterization of resources	• High for recovery or storability efficiency gains	• High for current and accurate estimations of commercial recovery factor

Table 1-1. *Resource Evaluation Hierarchy*

FINDING 1-1: Static assessments of in-place resources are the foundation of publicly available long-term, cross-sectoral data. When conducted rigorously and supported by robust datasets, these assessments can remain valuable for generations, enabling diverse industries to explore the subsurface as technologies evolve and new pathways emerge for technically and economically recoverable resources.

FINDING 1-2: Data collected for conventional resources often provide benefits to emerging resources at a later date.

II. CROSS-SECTORAL VALUE OF GOVERNMENT-PRODUCED SUBSURFACE DATA AND ASSESSMENTS

Government-produced subsurface data and resource assessments support a broad ecosystem of users, including government agencies, industry, financial institutions, academia, think tanks, and the public. Across these groups, such data inform decisions related to exploration, investment, regulation, infrastructure development, and public policy.

Different stakeholders rely on these assessments in distinct but complementary ways. Industry users depend on government data for a credible, independent baseline of the nation's resource endowment. These assessments reduce subsurface uncertainty, inform exploration strategies, and support long-term capital allocation. By providing publicly available, geoscience-based estimates and maintaining foundational datasets, federal, state, and Tribal agencies help de-risk early-stage investment—particularly in frontier or underexplored areas where private data are limited. They also enable benchmarking and validation of proprietary models, giving companies, investors, and lenders a common reference point for decision-making. Public subsurface assessments impact companies differently depending on the company's size, capital structure, and risk tolerance. For example, more than 85% of domestic onshore oil and 90% of domestic onshore gas production is generated by independent companies[15]—a diverse mix spanning small private companies operating a handful of wells, mid-sized companies managing regional portfolios, and large independents with multibasin, multiplay exposure. Independents operate with more focused asset portfolios than the large, multinational oil and gas companies: They depend on the assets they choose to pursue, making subsurface assessments the basis for foundational business decisions. For small independents, which often operate in established lower-cost basins with limited acreage and narrow margins for error, public assessments help de-risk near-wellbore decisions, validate type curves, and support reserve-based lending.

Government agencies use subsurface data and assessments for land management, permitting, and long-term planning. Planners, regulators, and health, safety, and environmental professionals rely on subsurface assessments to ensure safe and effective development of resources, particularly in applications such as geologic storage (e.g., carbon storage, hydrogen, and natural gas storage in porous formations or salt caverns). Meanwhile, communities, landowners, and nongovernmental organizations depend on accessible credible information to understand both economic opportunities and environmental risks.

Beyond their stakeholder-specific uses, subsurface data have significant cross-sectoral value. Many regions host multiple existing and emerging resources in proximity. For example, oil and natural gas systems may coincide with geothermal resources, subsurface storage opportunities, and minerals contained in produced water.[16] Similarly, ultramafic and granitic formations may host critical minerals, geother-

15 Rystad Energy, *Economic Impact of US Independent Operators* (American Exploration & Production Council, August 2025), https://axpc.org/wp-content/uploads/2025/09/Rystad-Energy-Economic-Impact-of-Independent-Operators-August-2025.pdf.

16 Produced water is the largest byproduct of oil and gas production—water that naturally exists in subsurface formations or is injected during operations and then returns to the surface along with hydrocarbons. It often contains salts, hydrocarbons, metals, and other chemical constituents, even naturally occurring radioactive materials, making it both a management challenge and a potential resource (https://www.gwpc.org/topics/produced-water/).

mal potential, natural and stimulated geologic hydrogen, and helium.

As a result, the geological, geochemical, geophysical, petrophysical, and remote sensing data collected for one resource can often be applied to others in the same area. When supported by data standards and integrated database systems, these datasets can be reused across sectors, reducing duplication of effort and lowering the cost of assessing additional resources. This interoperability enables more efficient system-level understanding of the subsurface and supports the development of multiple resource types from a shared data foundation. Table 1-2 illustrates examples of overlapping data types used across different resource sectors.

Across all applications, the common thread is that subsurface data and assessments underpin both technical decision-making and broader economic and policy outcomes. Their value is particularly pronounced in frontier, emerging, revitalizing, and long-term monitoring contexts, where uncertainty is highest and independent, publicly available data are most critical.

FINDING 1-3: Government-produced subsurface assessments tend to focus on data generation, data compilations, and static resource assessments. These provide foundational value across a wide range of stakeholders by reducing uncertainty, enabling informed decision-making, and supporting safe and efficient resource development.

FINDING 1-4: Government resource assessments are most useful in the early stages of resource exploration, or when new concepts or technologies open opportunities for revitalizing resource development.

FINDING 1-5: Regionally consistent baseline datasets (e.g., geologic mapping and geochemical characterization, geophysical imaging, targeted drilling) are repeatedly identified as high-value inputs across essentially all subsurface resource types and stages of development.

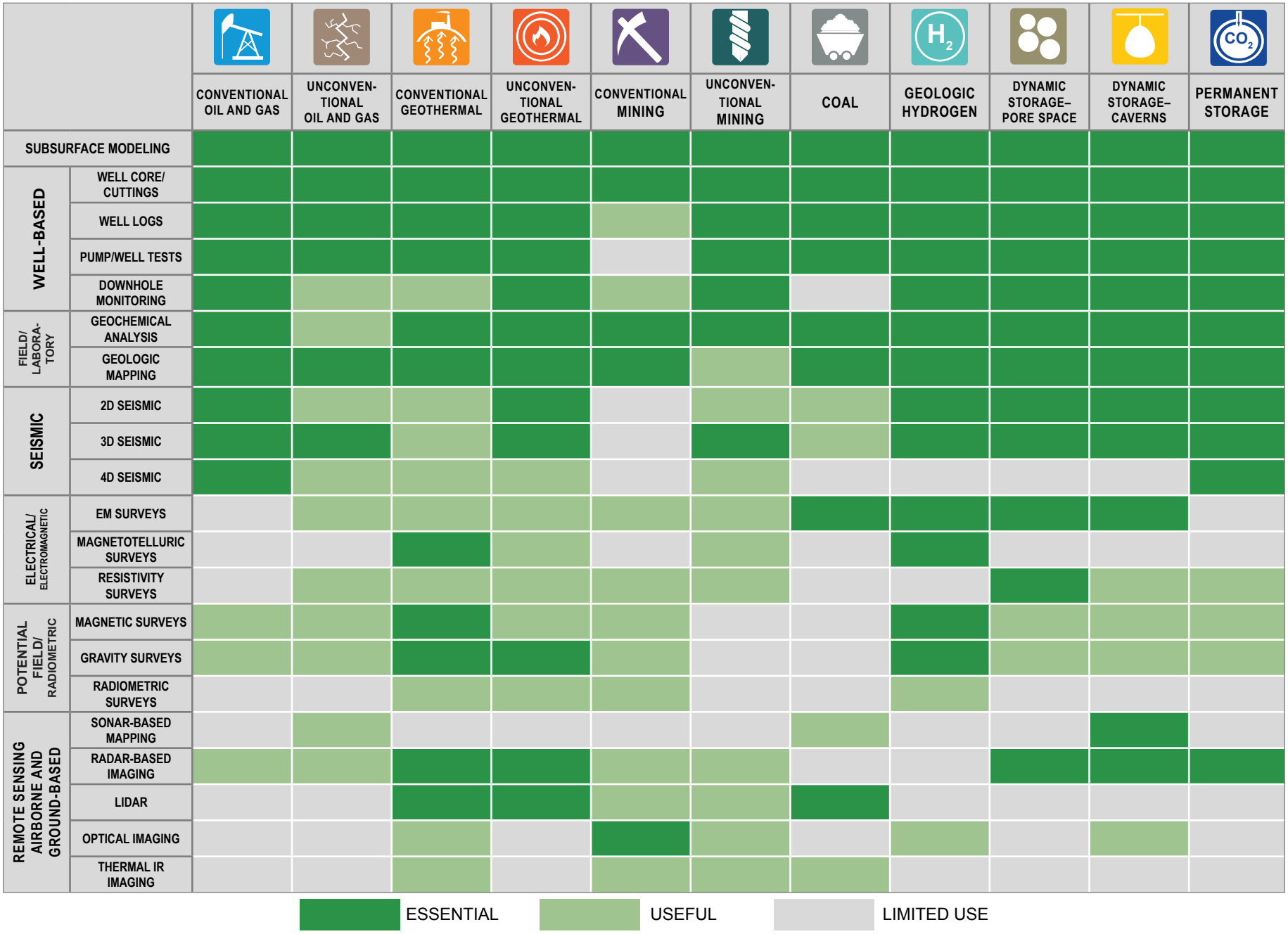


Table 1-2. *Current Importance of Subsurface Characterization Methods for the Resources Discussed in This Report*

III. SUBSURFACE ASSESSMENTS FOR EXTRACTIVE RESOURCES

The preceding discussion shows that many subsurface data types, analytical approaches, and assessment frameworks apply across resource systems. However, the way they are prioritized, integrated, and interpreted—and the decisions they support—vary by resource type, development stage, and end use. This section applies these common foundations to specific extractive resources, illustrating how subsurface assessments are used in practice.

Each section examines an extractive resource and covers: (1) key datasets and technologies for characterization; (2) assessment approaches across the resource life cycle; and (3) the role of publicly available government-produced data in supporting industry and other stakeholders. Together, these analyses highlight both shared foundations and key differences in how subsurface assessments enable exploration, development, and long-term resource management.

A. Conventional Oil and Gas

Conventional oil and gas resources are produced from subsurface reservoirs using established drilling, development, and production methods. These resources occur in porous and permeable rock formations, where hydrocarbons can flow relatively freely to the wellbore. The conventional oil and gas industry in the United States is considered mature, both onshore and across accessible offshore provinces such as the Gulf of America. Over the span of more than 165 years of exploration and production activity, a robust framework for understanding hydrocarbon systems controls has been developed and continuously refined.

Although the conventional resource base in the United States is mature, it is far from exhausted. The U.S. Geological Survey (USGS) estimates that federally managed onshore lands alone hold 29.4 billion barrels of oil, 391.6 trillion cubic feet of natural gas, and 8.4 billion barrels of natural gas liquids in undiscovered, technically recoverable resources.[17] In situ estimates of the entire domestic resource range from 2 to 4 trillion barrels of oil in place and tens of thousands of trillion cubic feet of gas in place, including conventional and unconventional accumulations as well as frontier resources such as methane hydrates.[18] In addition, the USGS maintains a natural gas compositional database that provides information on hydrocarbon and non-hydrocarbon gases including helium and carbon dioxide.[19] Naturally occurring helium and carbon dioxide, particularly helium, are considered strategic resources.

Subsurface assessment in conventional oil and gas underpins decisions across the asset life cycle, with value closely tied to evolving uncertainty. In exploration, assessments rely on regional-scale basin analysis, analog studies, seismic interpretation, and probabilistic resource estimates. As assets move through appraisal and development, growing data availability constrains models and shifts focus to development planning. In production and late-life stages, assessments support value preservation through enhanced recovery, infill drilling, and decline management. Across stages, assessment quality directly shapes decision quality. While the scale and complexity of assessments vary by operator, the underlying data, methods, and decision needs are broadly consistent.

1. Principal Subsurface Datasets

The datasets used in subsurface assessment evolve with asset maturity (Table 1-3), but two are foundational: seismic imaging and well data. Seismic imaging provides continuous, basin- to

17 Christopher J. Schenk, Tracey J. Mercier, and the 1995–2025 National and Global Oil and Gas Assessment Project Federal Lands Resource Allocation Team, "An Estimate of Undiscovered, Technically Recoverable Oil and Gas Resources Underlying Federal Lands of the Onshore United States, 2025" (U.S. Geological Survey, 2025), https://doi.org/10.3133/fs20253032.

18 National Petroleum Council, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources* (2011). T.S. Collett et al., eds., *Natural Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards* (American Association of Petroleum Geologists, 2009). John R. Dyni, *Geology and Resources of Some World Oil-Shale Deposits*, Scientific Investigations Report 2005–5294 (U.S. Geological Survey, 2006), https://doi.org/10.3133/sir20055294.

19 Sean T. Brennan, Jennifer L. Rivera, Brian Varela, Andy J. Park and Lauren A. Agyepong, "Natural Gas Compositional Analyses Dataset of Gases from United States Wells," U.S. Geological Survey data release, https://doi.org/10.5066/P9TR93E3.

reservoir-scale coverage needed to map structure and identify targets, while well data offer the only direct measurements of subsurface properties to calibrate and validate interpretations. Together, they form the backbone of conventional oil and gas assessment across the asset life cycle. Supporting datasets—gravity and magnetic, and geochemical—help reduce key uncertainties at basin, play, and reservoir scales.

FINDING 1-6: 3D seismic and well data are critical datasets for conventional oil and gas; timely public access to these data can stimulate exploration and development activity.

a. Seismic Data

Seismic data provide the primary framework for subsurface interpretation, particularly in early stages. In favorable settings, amplitude and frequency attributes can indicate porosity and fluid presence (direct hydrocarbon indicators (DHIs)), reducing exploration risk.

- 2D seismic imaging supports early-stage (frontier) screening due to broad coverage and lower cost.
- 3D seismic imaging is the standard for detailed characterization in emerging, developing, and mature basins, and underpins modern geological and geophysical interpretation workflows. However, 3D seismic data are becoming more common in frontier areas, especially offshore.
- 4D (time lapse) seismic imaging is used in mature fields to detect changes (often annually) in saturation and pressure, helping identify bypassed hydrocarbons.

b. Well Data

Well data are the only direct measurements of subsurface conditions and are essential for calibrating seismic interpretations and reservoir models. Key datasets include core, cuttings, petrophysical logs, mud logs, well tests, and production data (see Appendix B). These data progressively constrain uncertainty from appraisal through production and late-life management.

c. Gravity And Magnetic Data

Gravity and magnetic surveys provide low-cost regional insights into basin architecture, including depth to basement and the presence of igneous rocks. They are particularly useful in early-stage assessments and in complex geologic settings, where they complement seismic data to refine structural interpretations.

d. Geochemical Data

Geochemical data are used across the oil and gas life cycle to reduce key uncertainties. In early exploration and appraisal, they assess source rock presence, quality, and maturity, and help confirm a working petroleum system. As projects mature, they inform reservoir fluid properties and support production management, including allocation and flow assurance. In the retirement phase, geochemical monitoring helps verify well integrity and support safe environmentally sound abandonment.

2. Assessment Approaches

Subsurface assessment relies on models that integrate multiple data types to characterize hydrocarbon systems and predict source, migration, accumulation, and producibility. These models span scales, from basinwide frameworks that evaluate heat flow and petroleum systems to detailed, field-scale reservoir simulations that forecast pressure and production over time.

a. Basin Models

Basin modeling reconstructs the evolution of petroleum systems over geologic time, evaluating source rock maturation, hydrocarbon generation and migration, and accumulation processes. By integrating multidisciplinary data, it produces outputs such as burial histories, thermal maturity, migration pathways, and estimates of hydrocarbons in place. These results are used to identify and rank prospects and assess hydrocarbon presence, phase, and volume across basin, play, and prospect scales.

b. Reservoir Models

Reservoir models are 3D and 4D representations of the subsurface that integrate geological, petrophysical, geophysical, and engineering data. They simulate fluid distribution and flow to estimate resource size, forecast production, and optimize recovery. These models underpin field development planning and ongoing reservoir management.

c. Probabilistic Assessments

Assessment approaches evolve with project maturity. Early-stage (frontier and emerging) evaluations often use deterministic methods with fixed inputs for rapid estimates as well as probabilistic analyses. As uncertainty narrows and financial stakes rise, statistical methods are applied to capture a range of possible outcomes and associated risks. By assigning probability distributions to key variables, such as reservoir size, quality, fluid properties, and recovery factors, these approaches support more robust estimates of volumes and performance, improving risk management and investment decisions. This is particularly important when developing new projects that tend to be capital intensive and inherently have more risk and uncertainty.

3. Impact Of Publicly Available Data And Assessments

Publicly available oil and gas data and subsurface assessments have transformed how conventional oil and gas resources are screened and developed. Data that once conferred a competitive advantage—well logs, production histories, seismic datasets in some areas, and regional studies—are now widely accessible, lowering barriers to entry and accelerating prospect evaluation. Teams can more quickly prioritize opportunities, benchmark against offset performance, and make more informed capital allocation decisions with less upfront cost. As access expands, differentiation increasingly depends on how effectively data are interpreted, integrated, and applied.

Where this gets more nuanced—and where a lot of value can still be created—is around data quality and when those data were acquired. Not all datasets are equal. Much publicly available subsurface data in conventional basins were acquired using older technologies—legacy 2D seismic, early-generation 3D, and less-advanced logging tools. As a result, resolution, imaging accuracy, and depth conversion can vary significantly. In some cases, what looks like a well-defined structure with older seismic data may not hold up under modern reprocessing, or subtle reservoir features may be discovered that were previously not detectable. Operators who understand the limitations of legacy datasets—and know where modern seismic, updated petrophysics, or reinterpretation can unlock additional clarity—have a real advantage.

Public datasets also play a key role in enabling new play concepts by providing a shared technical foundation for exploration. However, these dynamics also shape risk. Widely available data can create false confidence, particularly in mature basins where datasets are extensive but uneven in quality or calibration. They can also concentrate investment in similar opportunities, increasing competition and compressing margins. In this context, value depends on the ability to critically evaluate data, challenge prevailing interpretations, and translate subsurface insight into disciplined execution.

FINDING 1-7: Publicly available oil and gas data and subsurface assessments accelerate prospect screening, improve benchmarking, and support more efficient capital allocation. However, the data value depends on careful interpretation, particularly where legacy datasets vary in quality, resolution, and processing.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• In-place volume • Access to data (often public only)	• In-place and screening estimates of recovery factor • Proximity to infrastructure • Commercialization time reduction • Access to data (often public only)	• In-place and recoverable volumes calculated with increasingly sophisticated data • Prospect economics and EUR per well • Proprietary data becomes more prominent	• Operational costs • Prospect economics • Production volumes • Assessment of bypassed pay • Cost-benefit analysis of infill and secondary recovery opportunities • Publicly available production data important	• New technology • Enhanced commercial terms • Valuation of alternate/ additional commodities or use cases
Principal Uncertainties	• Working hydrocarbon system • Commodity type (gas/ oil ratio) and saturation	• Estimated ultimate recovery • Reservoir characteristics impact on development plan	• Realized recovery factor and most effective well count, types, and distribution • Secondary recovery	• Infill drilling opportunities • Secondary recovery • Opportunities to open additional completion levels • Recompletion potential	• Tertiary recovery • Alternate/additional commodities or use cases
Principal Datasets	• 2D seismic geochemical data; gravity and magnetic data	• 2D and 3D seismic; well data (logs, cuttings); geochemical data	• 3D seismic; well data (logs, cuttings, core, DST); geochemical data	• 3D and 4D seismic well data (logs, cuttings core); production data	• 3D and 4D seismic; well data (logs, cuttings core); production data
Typical Scales of Investigation	• Very large—basin-scale assessments are common	• Often large—block-(or project-) scale (5 to >100 km^2)	• Field-(or prospect-) scale	• Field-(or prospect-) scale • Can include subfield-scale (lease or well-level) opportunities	• Field-(or prospect-) scale • Can include subfield-scale (lease or well-level) opportunities

Assessment Approaches	• Focus on hydrocarbon systems • Integrate potential field data and 2D seismic	• Refine static volumetric assessments • Develop realistic recovery factor estimations	• Probabilistic 3D model simulations common in offshore programs • Reservoir studies based on 3D seismic imaging and analysis of offset wells	• Studies based on production data • Refine probabilistic model simulations with 4D seismic in offshore programs	• Often integrating combinations of historical data from public archives with new data to refine new play concepts
Impact of Publicly Available Data	• Essential—access to public onshore and offshore data often drives new play concepts	• Essential—access to state survey log, core, DST, and production data is vital for analysis	• Proprietary data become more prominent and important • Public log, core, DST, and production data are important, especially onshore	• Proprietary production and seismic data are critical • Public log, core, DST, and production data is important, especially onshore, for infill opportunity generation	• Essential—access to public onshore and offshore data often drives new play concepts
Impact of Publicly Available Assessments	• High for commercial screening	• High for commercial screening	• In-place assessments provide context for remaining resource availability	• Important for comparison of production relative to in-place prognosis and for regulatory oversight	• New, publicly available assessments sometimes drive new opportunities
Feasibility of Generating Publicly Available Assessments	• High—already a standard practice	• Moderate—depends on access to seismic data and well information	• Moderate—depends on access to seismic data and well information	• Moderate—depends on access to seismic data and well information	• High—already a standard practice

Note: Abbreviations include estimated ultimate recovery (EUR) and drill stem testing (DST).

Table 1-3. *Key Assessment Characteristics Based on Basin or Asset Maturity for Conventional Oil and Gas*

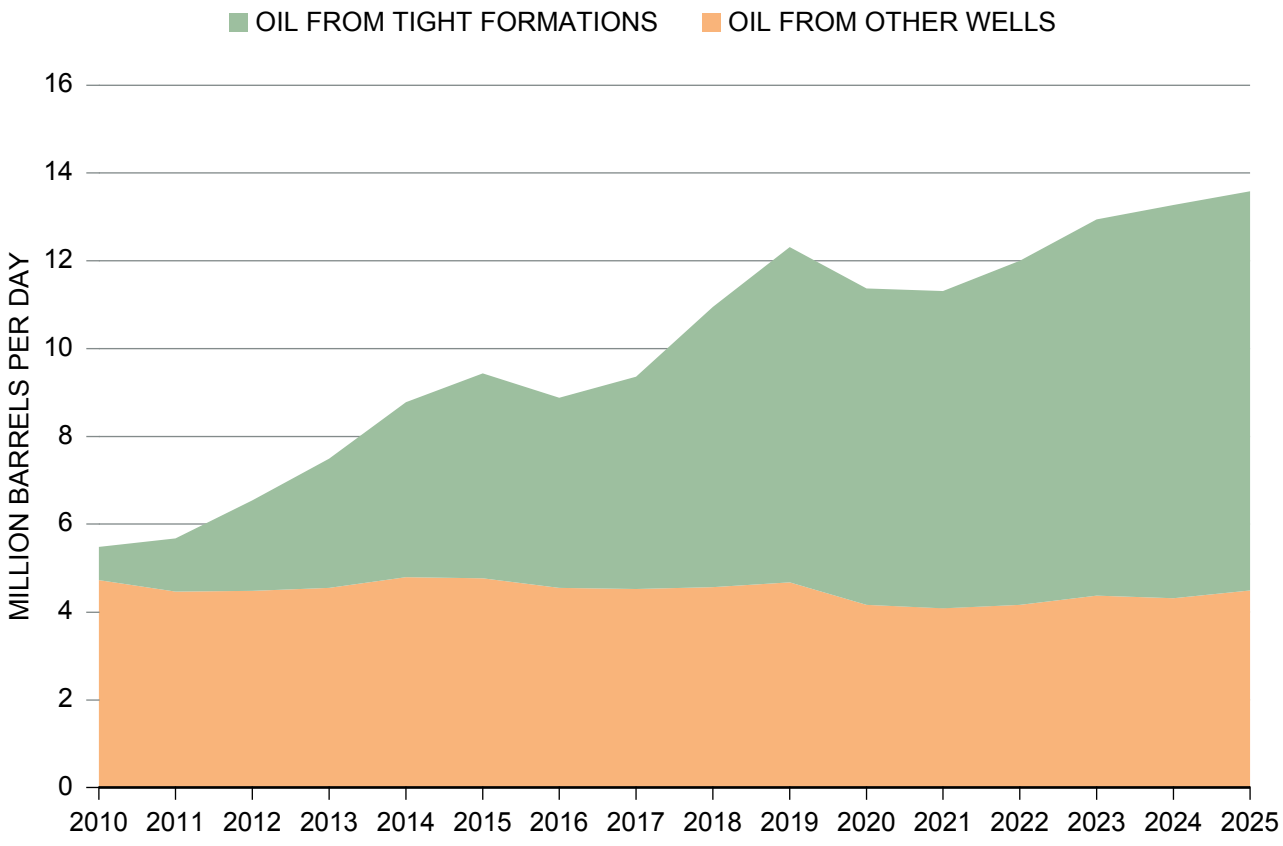
B. Unconventional Oil and Gas

The impact of unconventional resources on the nation has been dramatic. Since 2010 (Figures 1-2 and 1-3), the hydrocarbon production from the domestic oil and gas industry contributed by these tight oil and shale gas resources has dramatically increased, strengthening the United States' energy independence. Unconventional oil and gas resources require advanced technologies to produce hydrocarbons from low-permeability reservoirs, such as organic shales, tight sands, and chalks. Horizontal drilling and hydraulic fracturing have enabled commercial production from these formations, but recovery remains limited.

The challenge with unconventional oil and gas resources is that the primary recovery from unconventional reservoirs is typically low, with an estimated 70%–90% of hydrocarbons remaining in place after primary production.[20] Unlocking this stranded resource will require continued advances in technology in subsequent stages of recovery.

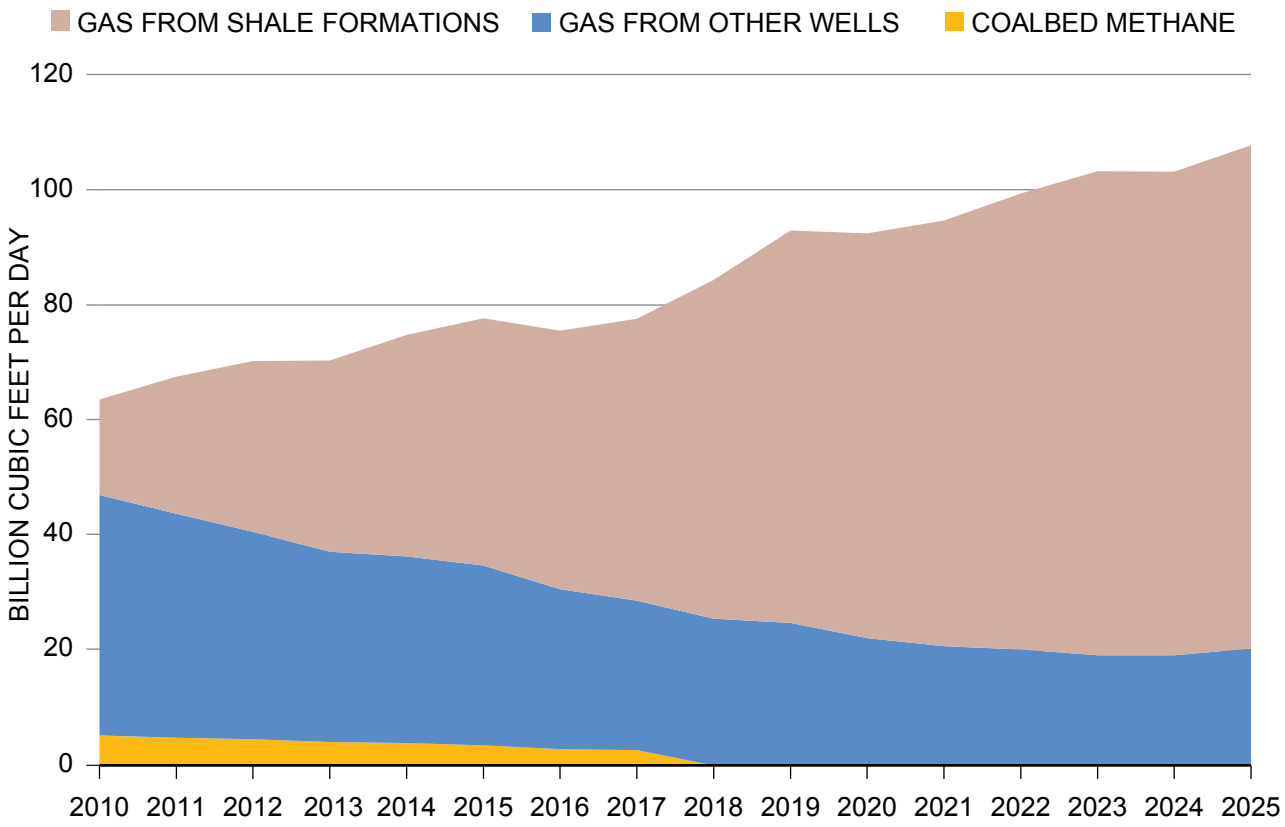
FINDING 1-8: 70%–90% of shale resources remain after primary production, representing a significant opportunity for improved recovery.

20 C. R. Clarkson, "Production Data Analysis of Unconventional Gas Wells: Review of Theory and Best Practices," *International Journal of Coal Geology* (2013), https://doi.org/10.1016/j.coal.2013.01.002.



Source: EIA. 2026.

Figure 1-2. *U.S. Oil Production Highlighting the Contribution of Tight Oil*



Source: EIA. 2026.

Figure 1-3. *U.S. Dry Natural Gas Production, Highlighting the Contribution of Shale*

Other unconventional resources—such as coalbed methane, oil shale,[21] and methane hydrates—require alternative extraction methods, including dewatering, mining, or thermal methods to extract oil and gas. While coalbed methane plays a diminishing role in the production mix from the United States, methane hydrates represent a vast potential resource. However, as with early shale development, significant technological advancements are needed before these resources can be produced economically at scale.

FINDING 1-9: Methane hydrates could substantially expand the global energy resource base, but commercial development requires major production technological breakthroughs.

21 Oil shale is rock with high organic content that can be retorted at high temperatures to generate oil.

1. Principal Subsurface Datasets

In addition to datasets used for conventional oil and gas assessments, unconventional oil and gas assessments rely on specialized geologic data, such as total organic carbon (TOC), kerogen type, and thermal maturity, to quantify the resource intensity and hydrocarbon phase. These data also underpin models of key hydraulic fracturing controls, including rock mechanical properties and in situ stress.

Data needs evolve with asset maturity (Table 1-4). In early stages (frontier), assessments rely on regional datasets—seismic, wildcat exploratory wells, and cross sections—which provide broad indications of structure and resource presence but limited resolution of high-quality zones. As development progresses, higher-resolution datasets—well logs, core samples, and seismic data—enable detailed mapping of reservoir properties

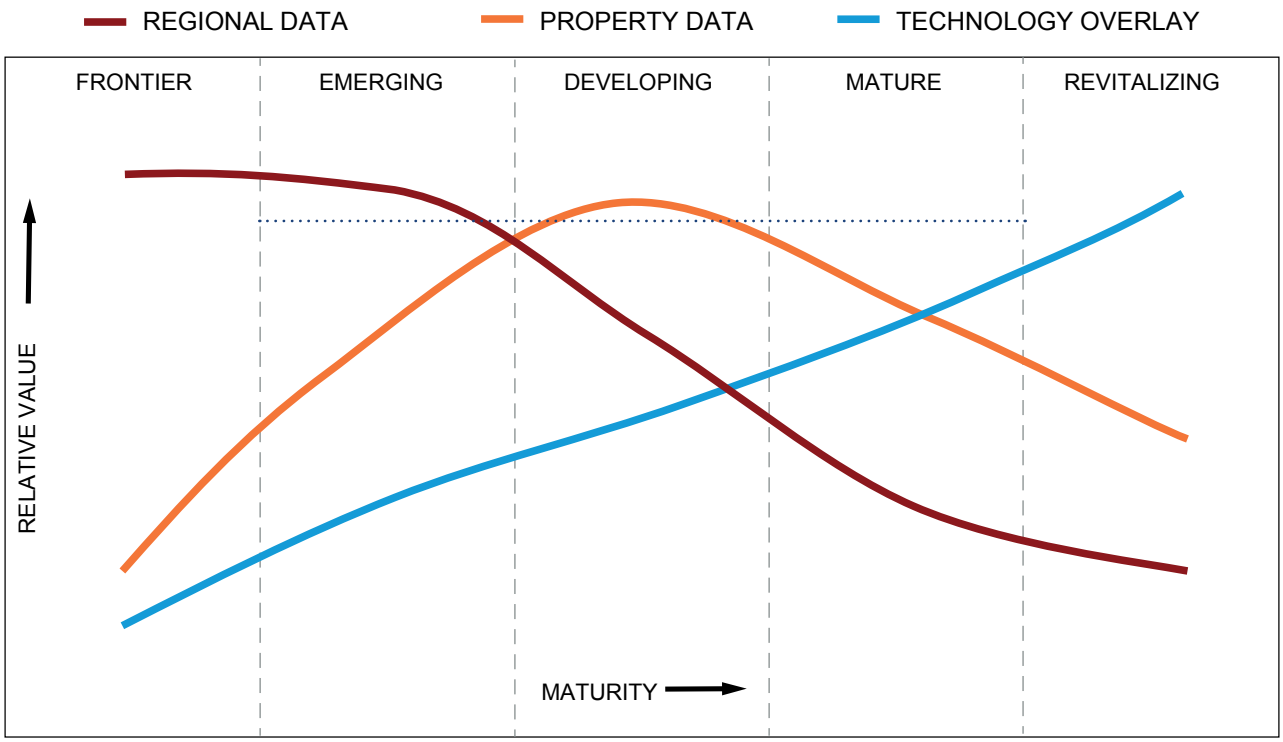


Figure 1-4. *Relative Value of Resource Data and Technology along the Resource Maturity Scale*

such as TOC, stress, and estimated ultimate recovery (EUR), supporting more precise targeting and development planning.

As plays mature, the importance of integrating these datasets with engineering decisions increases. Technological factors such as stimulation design, lateral length, and well spacing become central to optimizing recovery and overall resource performance (Figure 1-4).

Data requirements differ for other unconventional resources. Methane hydrate assessments emphasize pressure-temperature relationships alongside seismic, logging, and core data. Oil shale and coalbed methane rely heavily on core sampling to characterize organic content, yield, and gas storage properties, often drawing on methods similar to mining and coal analysis.

FINDING 1-10: Unconventional oil and gas assessment depends on specialized geologic datasets and evolves from regional, low-resolution data in early stages to high-resolution, well- and production-based datasets that enable detailed characterization and development.

2. Assessment Approaches

Assessment approaches for unconventional resources evolve with data availability and resource maturity. Evaluations of frontier-stage assets rely on simplified, often deterministic methods to estimate production ranges. As data accumulate, more rigorous, probabilistic approaches are applied, integrating production data with engineering factors such as stimulation design and recovery techniques to better define resource potential.

Approaches vary significantly by resource type. In shale oil and gas plays, assessments are largely production-driven and statistical, relying on metrics such as EUR, type curves, and completion performance to define recoverability across unconventional accumulations. Uncertainty centers on variability in well performance rather than resource presence.

Coalbed methane assessments are more physics based, relying on adsorption behavior, pressure drawdown, and two-phase flow as water is removed and gas desorbs. Recoverability depends on reservoir pressure management and permeability evolution, requiring more coupled and dynamic modeling.

Other unconventional resources rely on more process-driven frameworks. Oil shale assessments resemble mining and surface processing studies because they focus on kerogen yield and thermal conversion efficiency. Methane hydrate assessments depend on phase stability and dissociation behavior, with limited production data and greater reliance on geophysical indicators and pilot testing.

Across resource types, assessment methods shift from data-rich, empirical approaches (shale) to more theoretical and technology-dependent frameworks (hydrates), with increasing uncertainty tied to producibility rather than in-place volumes.

3. Impact Of Publicly Available Data And Assessments

Publicly available subsurface assessments and datasets are particularly valuable in the early stages of unconventional play development. Regional datasets provide a broad, low-resolution view of resource potential, helping industry prioritize prospective areas and allocate capital more efficiently.

A notable example is the U.S. Department of Energy's Eastern Gas Shales Project, launched in the mid-1970s, which generated regional mapping, resource estimates, and core, log, and test data for Devonian shales in the Appalachian Basin.[22] These datasets supported the development of the Marcellus Shale and Utica Shale in the 2000s once extraction technologies matured.

Public datasets also provide a consistent, shared technical foundation for stakeholders, improving transparency, comparability, and capital efficiency. Today, large volumes of well, production, and geologic data—combined with advances in AI/ML—enable faster analysis, but inconsistencies in subsurface interpretation (e.g., stratigraphic correlations across basins) remain a challenge. Standardized correlations and integrated public geochemical and geophysical datasets can improve accuracy and reduce assessment time.

FINDING 1-11: Publicly available regional datasets and assessments enable early-stage screening of unconventional plays, allowing firms to focus time, effort, and capital on the most prospective areas.

22 T. S. Dyman and L. A. Wilcox, "The Eastern Gas Shales Project (EGSP) Data System: A Case Study in Data Base Design, Development, and Application," *Journal of the International Association for Mathematical Geology* 15, no. 2 (1983): 363–69, https://doi.org/10.1007/BF01036076. Robert Beckwith, "The Marcellus Shale Gas Boom Evolves," *Journal of Petroleum Technology* (2013), https://jpt.spe.org/marcellus-shale-gas-boom-evolves.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• Early R&D funding • Strategic energy security interest government incentives/pilot programs	• Technological advances • Rising energy prices • Policy support for domestic supply	• Economies of scale • Infrastructure • Buildout • Integration with existing operations	• Operations optimization • Infill drilling and uphole opportunities • Stable energy prices	• Advanced enhanced oil recovery • Carbon capture utilization • Technological advancements
Principal Uncertainties	• Commodity type (gas/oil ratio) and saturation • Presence of resource • Extraction feasibility • Technical risks • Regulatory unknowns	• Reservoir characteristics • Estimated recovery • Economic viability at scale • Technology reliability	• Realized recovery factor • Optimal spacing • Production decline • Water management and sourcing	• Terminal decline rate • Recompletion potential • Uphole completion opportunities • Impacts of aging infrastructure	• Ability to sustain production economically • Contamination of legacy production
Principal Datasets	• Existing wireline data • 2D/3D seismic • Limited core data • Analog studies	• Pilot well data reservoir characterization • Advanced wireline data core analysis • Reservoir testing • Initial production tests • 2D/3D seismic	• Wireline data • 3D/4D seismic • Microseismic • Production history • Reservoir modeling • Economic modeling	• 3D/4D seismic • Extensive proprietary production databases • Decline curve analysis • Detailed reservoir simulations	• 3D/4D seismic analog studies • Detailed reservoir simulations • Application of technology • Advanced monitoring
Typical Scales of Investigation	• Regional/basin-scale reconnaissance, small-scale pilots	• Play-level appraisal • Multiwell pilots • Early field trials	• Field/development-scale • Pad drilling (shale) • Multiwell development	• Basinwide field optimization • Dense well spacing • Infill/recompletion programs	• Asset-level projects • Targeted redevelopment
Assessment Approaches	• Regional assessments • Regional seismic • Speculative volumetric estimates • Analog-based analysis • Risk-weighted evaluations • Basic lab simulations	• Early EUR modeling • Refine static volumetric assessments • Economic analysis of pilots	• Decline curve analysis • Reservoir simulation • Integrated geo-engineering models	• Decline curve analysis • AI/ML analysis of large production datasets • Fieldwide dynamic modeling	• Enhanced recovery forecasting • Revitalization modeling • Sustainability assessments

Impact of Publicly Available Data	• High—access to reliable, publicly available, regional datasets allow for the modeling of regional petroleum systems and drive new play concepts	• High—access to public wireline log, core, seismic data, completion, and production data is vital for analysis • Public resource assessments and pilot reports accelerate learning	• Moderate—public wireline log, core, completion, and production data maintain importance, but proprietary data becomes dominant • Proprietary operator data are key to competitive edge	• Low—proprietary data dominate, providing granular, field specific information • Abundant public production data support optimization	• High—access to public data provides the opportunity to learn how emerging technology is being applied, often driving new concepts
Impact of Publicly Available Assessments	• High—government-funded assessments spark interest and investment hydrocarbon estimates drive national strategies	• High—play-specific assessments guide entry • Reduced uncertainty in emerging resources affects financing	• Moderate—public log, core, completion, and production data maintain importance, but proprietary data becomes dominant	• Low—proprietary data dominate, providing granular, field specific information	• High—access to public data provides the opportunity to learn how emerging technology is being applied, often driving new concepts. Revitalization potential is often highlighted in public assessments of mature/ declining assets
Feasibility of Generating Publicly Available Assessments	• High—a foundation of data already exists across various state, federal, and private entities; including large volumes of well, completion, production, seismic, and geologic data • The speed at which these data can be integrated and analyzed will be significantly enhanced by rapidly advancing AI/ML tools	• High—a foundation of data already exists across various state, federal, and private entities; including large volumes of well, completion, production, seismic, and geologic data • The speed at which these data can be integrated and analyzed will be significantly enhanced by rapidly advancing AI/ML tools	• Moderate—detailed assessments of actively developing plays will be limited by and dependent on access to proprietary well and seismic data	• Moderate—detailed assessments will be limited by and dependent on access to proprietary well and seismic data	• Moderate—detailed assessments will be limited by and dependent on access to proprietary data

Table 1-4. *Key Assessment Characteristics Based on Basin or Asset Maturity for Unconventional Oil and Gas*

C. Conventional Utility-Scale Geothermal Energy

Geothermal electricity in the United States has grown to about 4 Gigawatts electric (GWe) since production began in 1960.[23] The USGS estimates more than 9 GWe of potential from discovered systems and more than 30 GWe from undiscovered resources.[24] Despite this, capacity additions have averaged only 50–75 MWe per year.[25]

Accelerating growth will require broader geologic, geophysical, and drilling campaigns with accompanying robust resource assessments to identify those systems without surface expression. These data have historically been invaluable to industry for estimating in-place resources and characterizing frontier and emerging geothermal resources and will become increasingly important as AI/ML tools expand exploration capabilities.

1. Principal Subsurface Datasets

Geothermal assessments evolve with resource maturity. In frontier stages, they rely mainly on temperature gradients, shallow (2 m) probes, legacy well data, heat flow measurements, geologic mapping, potential field data (gravity and magnetics), resistivity surveys (e.g., magnetotellurics), and LiDAR.

As resources advance to emerging stages, assessments incorporate 2D seismic, well testing, and initial reservoir models. In developing stages, more sophisticated reservoir modeling, flow test history matching, and temperature decline analysis are used to better characterize reservoir behavior.

Mature and revitalizing systems use similar datasets but add tools such as interferometric synthetic radar (InSAR) to monitor deformation and system dynamics. Additional datasets may be applied across stages (see Table 1-5).

2. Assessment Approaches

The conventional geothermal industry lacks a consistent assessment methodology for quantifying identified resources. This has contributed to uncertain capacity estimates and the resultant boom and bust nature of private geothermal investment. Because producing systems are relatively few and geologically diverse, most regional assessments emphasize data compilation and favorability mapping rather than estimates of technically recoverable resources (Table 1-1). The 2008 USGS assessment[26] used available well and fluid chemistry data to estimate in-place resources, but without detailed geophysical characterization and drilling, even discovered systems remain difficult to quantify. Estimating undiscovered resources is even more uncertain, relying on regional geologic analogs,[27] power density curves,[28] and probability-based approaches.

Recent studies have begun to define the geophysical fingerprints of key geothermal system types—such as volcanic[29] and basin and range extensional systems[30]—improving regional targeting through integrated geophysical analysis. However, inconsistent state permitting and data reporting, along with limited disclosure of site-specific models, continue to constrain system classification and analog training data development. Expanded, standardized datasets are essential to improve assessments and identify the potentially vast undiscovered resource base.[31]

23 Dayo Akindipe et al., *2025 U.S. Geothermal Market Report* (National Laboratory of the Rockies, 2026), https://docs.nlr.gov/docs/fy26osti/91898.pdf.

24 Colin F. Williams et al., *Assessment of Moderate- and High-Temperature Geothermal Resources of the United States*, Fact Sheet 2008–3082 (U.S. Geological Survey, 2008), https://doi.org/10.3133/fs20083082.

25 Akindipe et al., *2025 U.S. Geothermal Market Report*.

26 U.S. Geological Survey, *National Oil and Gas Resource Assessment* (accessed June 2026), https://www.usgs.gov/node/99250.

27 J.E. Faulds, M.F. Coolbaugh, and N.H. Hinz, "Inventory of Structural Settings for Nevada's Active Geothermal Systems and Late Miocene to Quaternary Epithermal Mineral Deposits," *GRC Transactions* (2021).

28 Maxwell Wilmarth, James Stimac, and G. Ganefianto, "Power Density in Geothermal Fields, 2020 Update," *Proceedings of the World Geothermal Congress 2020+1* (2021).

29 Ian Warren et al., *Innovative Subsurface Learning and Hawaiian Exploration Using Advanced Tomography (ISLAND HEAT) Phase 1 Final Report* (National Laboratory of the Rockies, 2023), https://research-hub.nlr.gov/en/publications/innovative-subsurface-learning-and-hawaiian-exploration-using-adv/.

30 Paul Schwering et al., "The Basin & Range Investigations for Developing Geothermal Energy (BRIDGE) Project," *GRC Transactions* (2022), https://gdr.openei.org/submissions/1682

31 J.E. Faulds, M.F. Coolbaugh, and N.H. Hinz, "Inventory of Structural Settings for Nevada's Active Geothermal Systems and Late Miocene to Quaternary Epithermal Mineral Deposits," *GRC Transactions* (2021).

FINDING 1-12: Improving the quality, quantity, consistency, distribution, and accessibility of geoscience data—ranging from well temperatures and geochemistry to geophysical, remote sensing, and geomechanical data—will enable more accurate and reliable capacity estimates for conventional geothermal.

3. Impact Of Publicly Available Data And Assessments

Publicly available assessments spur both private and public interest and investment in geothermal resources. They guide private investment by helping developers target exploration and reduce risk, while enabling state and federal agencies to inform policy, direct funding, and evaluate resources on public lands.

Enhancing the quality, quantity, consistency, distribution, and accessibility of publicly available geoscience data can accelerate geothermal discovery, strengthen frontier-stage assessments, and enable more effective analog comparisons across regions. Higher-resolution and better-integrated datasets also support emerging approaches, including ML, though current efforts are limited by sparse and uneven training data.[32] Expanded datasets can also reduce exploration costs and timelines, encourage leasing of federal lands, and ultimately improve geothermal competitiveness. Additionally, these data provide new insights in producing fields, supporting field expansion and application of emerging technologies for extraction.

FINDING 1-13: Expanded, higher-quality public datasets can improve resource confidence, guide policymaking, and stimulate public-private investment—addressing key barriers to expanding and accelerating the growth of the geothermal industry.

32 Stanley P. Mordensky et al., "Predicting Geothermal Favorability in the Western United States by Using Machine Learning: Addressing Challenges and Developing Solutions," *Proceedings of the 47th Stanford Geothermal Workshop* (2022), https://www.usgs.gov/publications/predicting-geothermal-favorability-western-united-states-using-machine-learning.

	Region or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• In-place characteristics • Access to data—often public only • Early R&D funding • Government incentives/ pilot programs	• In-place and screening estimates of reservoir temperature and likely extent • Proximity to infrastructure • Access to data—often public only	• Recoverable thermal content calculated with increasingly sophisticated data	• Operational costs • Prospect economics • Production decline minimization • Cost–benefit analysis of infill and repowering opportunities	• New technology • Enhanced commercial terms
Principal Uncertainties	• Active geothermal system • Equilibrated reservoir temperature • Geochemistry	• Reservoir characteristics • Flow rate and associated pressure drawdown • Geochemistry	• Reservoir characteristics • Thermal breakthrough • Temperature decline • Geochemistry	• Infill drilling opportunities • Recompletion potential	• N/A
Principal Datasets	• Legacy wells • Geochemical data • Geologic maps • Potential fields data (gravity and magnetics)	• Reservoir well data (logs, cuttings) • Geochemical data • 2D seismic imaging	• Reservoir well data (logs, cuttings) • Geochemical data • Pressure interference tests • 2D seismic imaging	• Production data • InSAR	• N/A
Typical Scales of Investigation	• Very large—regional to basin-scale	• Prospect-scale	• Prospect-scale	• Prospect-scale	• Prospect-scale
Assessment Approaches	• Data compilation • System analogs and structural controls • Tectonic—magmatic setting	• Prospect-scale geophysics • Prospect-scale temperature gradient drilling	• Prospect-scale full-size well drilling • Flow and interference tests with chemical tracers	• Flow and interference tests with chemical tracers • Surface deformation monitoring	• N/A

Impact of Publicly Available Data	• Essential—access to public data often leads to new prospect discovery	• Essential—access to public data often lowers exploration costs and leads to new prospect discovery	• Moderate	• Moderate	• N/A
Impact of Publicly Available Assessments	• High for commercial screening	• High for commercial screening	• High for knowledge transfer and analog studies	• High for knowledge transfer and analog studies	• N/A
Feasibility of Generating Publicly Available Assessments	• High—previous agency collaborations have demonstrated successful standardized regional data collection campaigns • The speed at which these data can be integrated and analyzed will be significantly	• High—previous/ongoing agency-funded projects have been invaluable and can be replicated • High—historically low funding availability has been increased	• High—previous/ ongoing agency-funded projects can be progressed to the development stage	• High—previous/ ongoing agency-funded projects can be progressed to the production stage and monitored	• High—previous/ ongoing agency-funded projects can be used as demonstration sites for new technologies

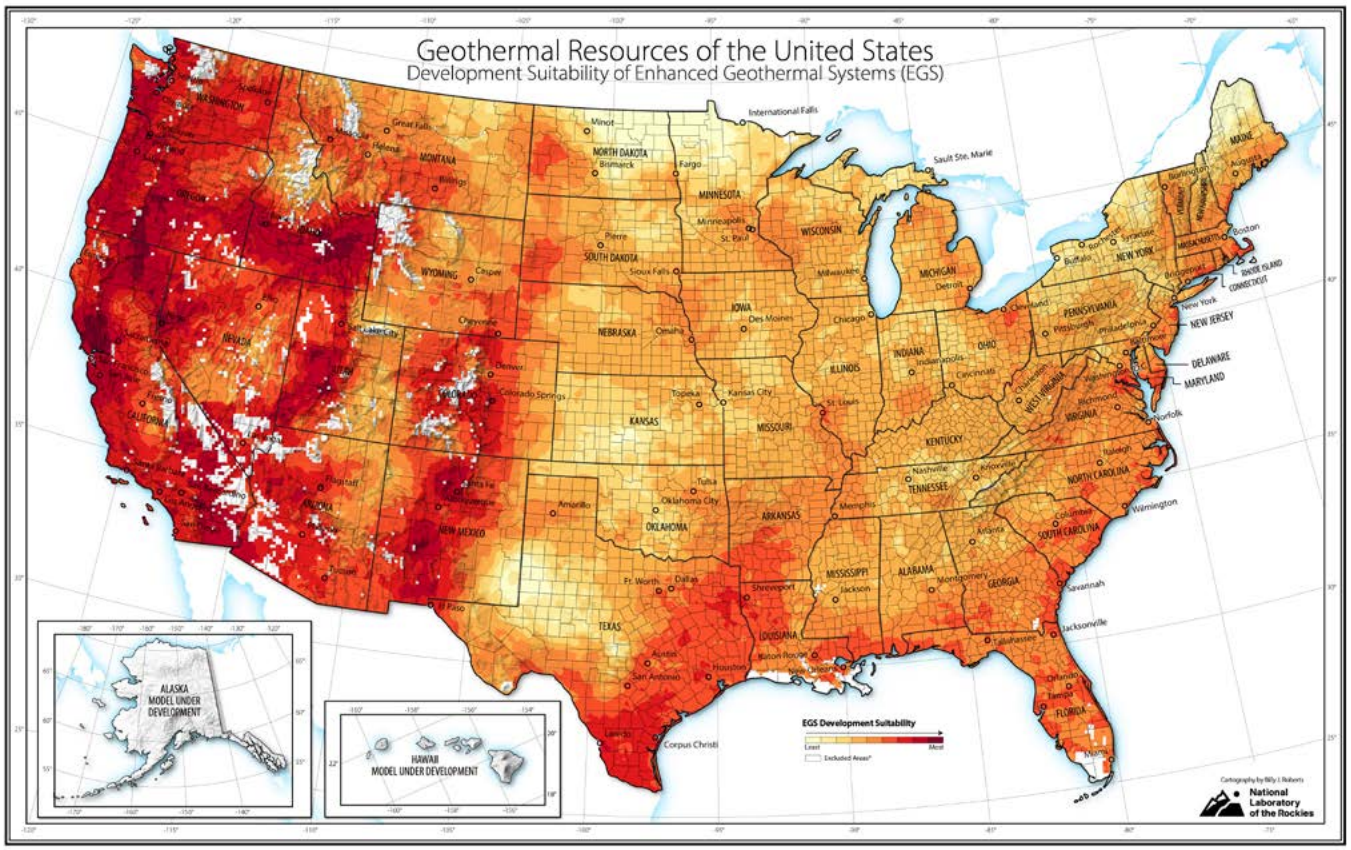
Table 1-5. *Key Assessment Characteristics Based on Basin or Asset Maturity for Conventional Utility-Scale Geothermal*

D. Unconventional Utility-Scale Geothermal Energy

Unconventional geothermal systems, such as unconventional oil and gas, require advanced subsurface engineering to access resources that are not recoverable with conventional methods. In the case of unconventional geothermal systems, the resource is heat and the engineering includes enhanced geothermal systems (EGS), closed-loop geothermal, superhot rock (>375°C), and geopressured systems. They target either heat-rich formations lacking sufficient fluid or permeability, or resources that are too deep or hot for current technologies to economically develop.

To date, only a handful of test sites have demonstrated sustained economic production, contributing only a few MWe of capacity. However, regional and national assessments by organizations such as USGS, Massachusetts Institute of Technology (MIT), Southern Methodist University, National Laboratory of the Rockies, and Stanford University indicate resource potential on the order of hundreds to thousands of GWe (Figure 1-5). This section focuses on assessments and data needs common across these technologies, as underlying rock properties and heat content are largely independent of extraction method.

FINDING 1-14: Large-scale unconventional geothermal assessments have catalyzed public and private investment by demonstrating GWe-scale potential, reducing uncertainty, and highlighting critical data gaps to guide future research and policy.



Source: Roberts. 2026. Geothermal Resources of the United States: Development Suitability of Enhanced Geothermal Systems (EGS); https://research-hub.nlr.gov/en/publications/geothermal-resources-of-the-united-states-development-suitability/.

Figure 1-5. *Geothermal Resources of the United States: Development Suitability of Enhanced Geothermal Systems (EGS)*

1. Principal Subsurface Datasets

Geothermal resource potential depends on rock properties, such as mineralogy, density, porosity, specific heat content, and thermal conductivity, that vary with depth, pressure, and temperature. Thus, assessments require integrated lithologic and thermal models that capture both lateral extent and vertical variation.

Data needs evolve with resource maturity. Frontier assessments rely on legacy well data (e.g., unequilibrated bottomhole temperature data, petrophysical and lithologic logs, drill cuttings and cores, fluid geochemistry), geothermal gradient and heat flow measurements, geologic mapping, and potential field geophysical data. Emerging assessments add 2D seismic, resistivity surveys, well testing, and microseismic monitoring (e.g., using surface and downhole seismometers, distributed acoustic sensing, or tomography). Resource assessments for assets in the developing stage incorporate downhole sensing, real-time monitoring, and remote sensing (e.g., InSAR, geodetics) to characterize system dynamics.

Across all stages, assessments depend on field and laboratory-derived rock property databases, stress/geomechanical data, and increasingly advanced modeling (e.g., probabilistic, reservoir, hydrologic). Several other datasets are often useful throughout resource maturity, as outlined in Table 1-6.

2. Assessment Approaches

Most unconventional geothermal assessments estimate heat in place by combining simplified distributed rock properties with 3D temperature models (Table 1-6). These static models are constrained by sparse and inconsistent well data, including limited equilibrated bottomhole temperature measurements and incomplete rock property data at depth.

As a result, most assessments remain national or regional in scale, with low resolution and large gaps. Higher-resolution basin- and field-scale assessments are needed to better capture geologic variability and more accurately estimate resource potential.

3. Impact Of Publicly Available Data And Assessments

Improving the quality, quantity, consistency, and accessibility of publicly available geoscience data is critical for advancing frontier-stage unconventional geothermal assessments. Standardized high-resolution datasets—such as equilibrated well temperature measurements and basin-scale thermal models—can better capture regional variability and support AI/ML applications. These data can reduce exploration risk and timelines, encourage leasing of federal lands, and improve the competitiveness of geothermal energy.

Because existing assessments are often limited in coverage and resolution, improved public data are needed to unlock the opportunities required for the expansion of geothermal development: broader geographic scope, greater confidence in resource estimates, more informed policymaking, and increased public-private investment. These datasets also support more robust estimates of subsurface heat and technical recovery across unconventional geothermal systems.

FINDING 1-15: Expanded, high-quality public datasets enable more accurate heat-in-place and technical recovery estimates by improving depth-resolved models of rock properties and temperature.

FINDING 1-16: Consistent publicly available, high-resolution regional datasets are essential for scalable modeling and AI/ML analysis of geothermal resources across both area and depth.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• Access to data—often public only • Early R&D funding • Government incentives/ pilot programs	• In-place and screening estimates of reservoir temperature and likely extent • Proximity to infrastructure • Access to data—often public only	• Economies of scale • Infrastructure buildout	• Operations optimization • Infill drilling	• Technological advancements • Lower-temperature end users • Energy storage
Principal Uncertainties	• Formation-specific temperature gradient • Depth to competent basement rock • Equilibrated bottomhole temperatures • Geochemistry • Basin-specific compaction curves	• Formation, depth, and pressure dependent: specific heat content, density, porosity, thermal conductivity, and fluid geochemistry at target reservoir temperature • Drilling hazards	• Optimal spacing • Production/ temperature decline • Water management, chemistry, and sourcing • Natural fracture network	• Terminal temperature and depth thresholds • Geochemistry • Proppant life • Impacts of aging infrastructure	• Ability to sustain production economically
Principal Datasets	• Legacy well logs • Geochemical data • Geologic maps • Core/cuttings • Field/lab rock property databases • Potential fields data (gravity and magnetics)	• Pilot well data reservoir • Characterization • Advanced wireline data • Core analysis • Reservoir testing • Initial production tests • 2D/3D seismic	• Wireline data • 2D/3D seismic • Microseismic • Production history • Reservoir modeling • Economic modeling • Downhole monitoring • Remote sensing	• Well logs • Geochemical data • Downhole monitoring • Production data • Remote sensing • Microseismic • Reservoir modeling	• Well logs • Geochemical data • Downhole monitoring • Production data • Remote sensing • Microseismic • Reservoir modeling
Typical Scales of Investigation	• Very large—nationwide to regional-to basin-scale	• Basin-to field-scale • Play-level appraisal • Multiwell pilots • Long-term flow tests	• Field/development scale	• Basinwide field optimization • Dense well spacing • Infill/recompletion programs	• Bench/depth interval-focused optimization

Assessment Approaches	• Data compilations • Regional assessments of in-place characteristics • Regional geologic modeling • Deterministic volumetric estimates	• Refined probabilistic volumetric assessments • Economic analysis of demonstration sites • Dynamic simulations • Technical recovery	• Refined probabilistic assessments • Economic analysis • Dynamic reservoir simulations • Commercial recovery • History matching	• Fieldwide dynamic modeling	• Feasibility of co-located operations
Impact of Publicly Available Data	• High—access to reliable, publicly available, regional datasets allow for the modeling and ML analysis of rock properties and temperature	• High—access to public wireline log, core, temperature, seismic, and lab data is vital for analysis and improving frontier-stage assessments • Public resource assessments and pilot reports accelerate learning	• High—public wireline log, core, completion, geochemical, geomechanical, and production data improve development outcome	• High—public geochemical and proppant research aids field optimization	• Moderate—new technology research may enhance revitalization
Impact of Publicly Available Assessments	• High—government-funded assessments increase interest, policy improvements, and investment • Geothermal resource estimates may guide national strategies	• High—prospect/demonstration-specific assessments encourage industry investment • Reduced uncertainty in emerging resources reduces financing barriers	• High—prospect/demonstration-specific assessments reduce field development risk	• High—public geochemical and geomechanical assessments aid field optimization	• Not yet understood
Feasibility of Generating Publicly Available Assessments	• High—previous agency collaborations have demonstrated successful standardized regional data collection campaigns • The speed at which these data can be integrated and analyzed will be significantly enhanced by rapidly advancing AI/ML capabilities	• High—previous/ongoing agency demonstrations have been invaluable and can be replicated • High—historically low funding availability has been increased	• High—previous/ongoing agency demonstrations can be progressed to the development stage	• High—previous/ongoing agency demonstrations can be progressed to the production stage and monitored	• High—previous/ongoing agency demonstrations can be used as demonstration sites for new technologies

Table 1-6. *Key Assessment Characteristics Based on Asset Maturity for Unconventional Utility-Scale Geothermal*

E. Conventional Mining for Essential Mineral Ore Bodies

Subsurface assessment for essential minerals differs fundamentally between high-concentration "base" metals and low-concentration "strategic" minerals, with important implications for data and methods. Base-metal systems—such as porphyry copper, banded iron formations, and Mississippi Valley-type lead-zinc deposits—are typically large, laterally continuous ore bodies with strong geophysical signatures, enabling efficient delineation using established approaches such as geologic mapping, airborne magnetics and gravity, targeted seismic surveys, and systematic drilling.

In contrast, many strategically important minerals—such as rare earth elements, gallium, and tellurium—occur at low concentrations, are spatially dispersed, or exist as trace components within larger systems. Their occurrence is often controlled by subtle geochemical and mineralogical processes that are not easily detected with conventional datasets and are frequently overlooked in early-stage assessments.

Existing geophysical datasets often lack the resolution to detect subtle mineralogical variation, while geochemical datasets and legacy drill cores commonly lack the analyses needed to quantify trace elements. Mineral systems models for many critical minerals also remain underdeveloped, limiting the ability to assess the potential to process and recover these resources.

Addressing these gaps will require more integrated and higher-resolution approaches. Advanced geophysical methods (e.g., hyperspectral imaging, magnetotellurics), next-generation geochemical tools (e.g., microanalysis, isotopic techniques, and automated mineralogy), and ML can improve detection and prediction of critical mineral systems. Reanalysis of legacy cores and samples also offers a rapid pathway to expand the knowledge base.

Improved subsurface assessments can strengthen domestic supply chains, reduce uncertainty for industry, and support more informed policy and investment decisions, thus enhancing economic resilience, national security, and environmental outcomes.

1. Principal Subsurface Datasets

Effective essential mineral assessments rely on integrating multiple datasets, each contributing differently across the exploration life cycle—from early-stage regional screening (frontier) and discovery (emerging), to detailed resource definition of inferred/indicated/measured resources (developing) and mine-planning studies of feasibility and reserve estimation (mature).[33] As resource maturity increases, data shift from broad, indirect indicators to high-resolution direct measurements that constrain geometry, grade, and recoverability (Table 1-7).

a. Geological Data

Geologic mapping, structural interpretations, and stratigraphic frameworks establish the mineral system context and identify permissive terrains in early (frontier) stages. At later stages, detailed mapping and 3D models constrain deposit geometry and guide drilling.

b. Geophysical Data

Magnetic, gravity, electromagnetic, and seismic data define structures, lithology, and alteration, especially in frontier-to emerging-stage exploration. They are most effective for high-concentration deposits with strong signals, such as base metals, while higher-resolution methods (e.g., hyperspectral, magnetotelluric, high-density seismic) are needed to detect subtle features associated with low-concentration critical minerals, especially in the emerging and developing stages.

c. Geochemical Data

Soil, sediment, and rock geochemistry are essential for early frontier- and emerging-stage targeting, especially where geophysical signatures are weak. In later (developing and mature) stages, multielement and microscale analyses are needed to understand trace element distribution and enrichment.

33 Resource Capital Funds, "Phases of Mining," *Mining & Minerals 101* (2024), https://resourcecapitalfunds.com/insights/mining-and-minerals-101/phases-mining/.

d. Remote Sensing Data

Multispectral and hyperspectral satellite or airborne data are most valuable in the frontier to emerging stages for mapping alteration footprints, lithologic variations, and surface mineralogy. In later stages, high-resolution hyperspectral data can refine alteration models and help delineate prospective zones.

e. Drilling And Borehole Data

Core, downhole geophysics, and assays provide the only direct confirmation of mineralization and are essential for late-stage (developing to mature) resource definition. For critical minerals, tighter spacing and more detailed sampling are often required to capture variability.

f. Mineralogical Data

Petrography, automated mineralogy, and microanalysis identify mineral hosts and element partitioning, especially in late-stage resource estimation. For trace-element commodities, mineralogical characterization is often a rate-limiting step, as it provides the foundation for both resource estimation and processing design.

g. Metallurgical Data

Metallurgical testing determines whether mineralization can be economically recovered. For many critical minerals, processing complexity is a primary constraint on viability.

h. Environmental And Hydrological Data

Water quality, hydrogeologic, and geochemical data inform permitting, predict environmental impacts, and affect assessment and project design. They are increasingly important in the mature and revitalizing stages of project evaluation and feasibility analysis. Early integration of environmental data can reduce project risk and improve long-term sustainability.

FINDING 1-17: Metallurgical uncertainty is often decisive. For many critical minerals, processing behavior is poorly understood, despite it determining project viability. Early integration of mineralogical and metallurgical data is essential.

2. Assessment Approaches

Subsurface assessment of essential mineral deposits integrates geological, geophysical, geochemical and metallurgical, and drilling methods across the exploration life cycle to identify potential ore bodies, delineate their size and grade, and evaluate economic potential.

- Geological Mapping and Remote Sensing: Identifies favorable lithologies, structures, and alteration zones; uses satellite imagery, hyperspectral data, and field mapping to locate potential mineralized zones.
- Geochemical Surveys and Metallurgical Analysis: Fundamental to identifying geochemistry, halos, anomalies, etc., associated with mineralization; laboratory analysis using, for example, inductively coupled plasma-mass spectrometry, inductively coupled plasma-optical emission spectrometry, and x-ray fluorescence.
- Geophysical Surveys: Airborne: magnetic, radiometric, gravity, and electromagnetic (EM) surveys to detect subsurface anomalies; ground-based: induced polarization, resistivity, and seismic methods for detailed target delineation; downhole: borehole logging (gamma-ray, resistivity, density) to characterize geology and mineralization.
- Geostatistical Modeling and 3D Resource Estimation: Develops a 3D model of the ore deposit that is divided into blocks. Geostatistical methods, such as kriging are used to estimate ore body geometry, grade, and tonnage in areas between drill holes.

Assessment approaches scale with project maturity. Early-stage (frontier) work uses regional, lower-resolution data to identify prospective areas, while later stages (developing and mature) rely on high-resolution data and drilling to delineate deposits and reduce uncertainty.

FINDING 1-18: Uncertainty shifts across the life cycle, from resource presence and geometry in early stages to continuity, metallurgy, geotechnical stability, and environmental performance in later stages. Thus, assessment methods must be tailored to maturity stage.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• Identifying permissive terrains, establishing mineral systems potential, reducing regional uncertainty	• Locating prospective targets, defining early anomalies, prioritizing areas for drilling	• Demonstrating continuity of mineralization, reducing technical risk, supporting resource estimation	• Optimizing extraction, improving efficiency, extending mine life	• Identifying overlooked zones, applying new technology to legacy data, unlocking secondary or byproduct value
Principal Uncertainties	• Regional geology, mineral systems presence, depth to basement, structural framework	• Deposit presence, geometry, grade variability, alteration footprint	• Continuity, tonnage, grade distribution, metallurgical behavior	• Operational performance, geotechnical stability, hydrological impacts	• Remaining resource potential, legacy data quality, applicability of modern methods
Principal Datasets	• Regional mapping, airborne geophysics, remote sensing, reconnaissance geochemistry	• Target-scale geophysics, soil/rock geochemistry, scout drilling, structural mapping	• Core assays, downhole logs, detailed geophysics, mineralogical and metallurgical testing	• Production drilling, geotechnical data, hydrogeologic models, environmental monitoring	• Relogged cores, reprocessed geophysics, hyperspectral mapping, targeted drilling
Typical Scales of Investigation	• Continental- to basin-scale (10s–100s of km)	• District-scale (5–50 km)	• Deposit-scale (1–10 km)	• Mine-scale (m to km)	• District- or deposit-scale with focus on previously mined or bypassed zones
Assessment Approaches	• Mineral systems analysis, regional screening, conceptual modeling	• Target delineation, anomaly ranking, early 3D geologic models	• Resource modeling, metallurgical characterization, geotechnical assessment	• Detailed mine planning, optimization modeling, environmental and hydrological forecasting	• Data integration, reinterpretation, advanced analytics, technologyenabled reassessment

Impact of Publicly Available Data	• High—often the primary source of information	• Moderate to high—guides early targeting and reduces exploration cost	• Moderate—supplements proprietary drilling and geophysics	• Low—operations rely on high-resolution proprietary datasets	• High—legacy public datasets become valuable when combined with modern tools
Impact of Publicly Available Assessments	• High—geologic surveys and national assessments shape investment decisions	• Moderate—help refine target areas and reduce risk	• Low—project-specific assessments dominate	• Low—site-specific engineering and environmental studies take precedence	• High—public assessments help identify overlooked opportunities and justify reinvestment
Feasibility of Generating Publicly Available Assessments	• High—regional datasets and conceptual models can be shared broadly	• High—nonproprietary geophysics and geochemistry can be aggregated	• Moderate—drillbased datasets become proprietary; limited public release	• Low—operational data is confidential and site-specific	• Moderate to high—legacy data can be released; new public assessments possible with modern reinterpretation

Table 1-7. *Key Assessment Characteristics Based on Basin or Asset Maturity for Conventional Mining*

3. Impact Of Publicly Available Data And Assessments

Public geoscience data—often termed "precompetitive" data—provide a shared foundation for exploration by making geological, geophysical, and geochemical information widely accessible. This transparency reduces exploration risk, lowers barrier to entry, and accelerates discovery by enabling companies to identify and pursue prospective targets more efficiently. Countries such as the United States, Canada, and Australia have demonstrated strong returns on such investments: In Australia, for example, each public dollar spent on geoscience data is estimated to generate about $1,000 in downstream exploration and mining activity.[34] Similarly, initial returns on U.S. mapping programs are highly encouraging: Industry responses in participating states have been positive, with companies citing the wealth of new data as a key factor in guiding their exploration strategies.[35]

Open data expand participation and competition. Smaller companies or prospectors can access high-quality datasets without large upfront costs, and shared information allows projects to be revisited and advanced by new operators, increasing the likelihood of resource development.

Expanding public datasets is a high-value investment with compounding benefits. In early (frontier) stages, resource maturity tends to drive industry interest; later in the life cycle (developing and mature), industry maturity can drive resource development, converting lower-confidence resources into viable projects. A promising resource can spur industry interest. For example, the delineation of a large, high-grade deposit can attract major companies, which brings funding, technology, and expertise to advance the project. Programs such as the USGS Earth Mapping Resources Initiative demonstrate how targeted public investment can catalyze private-sector exploration and development by reducing uncertainty and highlighting opportunity.

FINDING 1-19: Federal mineral assessments strongly influence private-sector behavior by reducing uncertainty, identifying promising regions, and signaling investment opportunities.

F. Unconventional Resources for Essential Minerals

Unconventional subsurface resources—such as geothermal and produced brines, mine tailings and waste rock, coal combustion residues, and deep saline formations—represent a diverse but under-characterized set of domestic sources for essential materials. These systems differ widely in geologic settings, physical forms, and operational histories: Brines require integrated thermal-hydrological-chemical modeling and dense sampling; tailings and residues behave as aboveground ore bodies governed by geotechnical and metallurgical constraints; and deep formations require advanced reservoir modeling and long-term monitoring. As a result, assessments must draw on a broader mix of datasets, more integrated modeling approaches, and greater use of legacy and publicly available data, particularly in early and late stages of asset maturity (Table 1-8).

Despite these differences, common needs include early geochemical screening, reinterpretation of existing data, and more detailed mineralogical and metallurgical characterization than is typical in conventional mining. Strengthening these assessments—through improved data, tools, and coordination—can unlock new domestic resources, convert waste streams into supply, reduce environmental liabilities, and enhance economic and national security.

FINDING 1-20: Subsurface uncertainty is higher for unconventional resources due to variable fluid chemistry, reservoir continuity, and geochemical behavior. Early-stage uncertainty is substantial. These dynamic systems require more intensive data

34 Australian Government, *Stimulating Company Activity* (Exploring for the Future Program), https://www.eftf.ga.gov.au/stimulating-company-activity.

35 Government of Saskatchewan, "Public Geoscience Investment Drives Exploration Spending," (2024), https://www.saskatchewan.ca/government/news-and-media/2024/may/13/public-geoscience-investment-drives-exploration-spending.

integration, modeling, and monitoring to reduce risk.

1. Principal Subsurface Datasets

Unconventional essential mineral resources rely on diverse, resource-specific datasets to characterize composition, scale, and recoverability. Across resource types, assessments depend on integrating geochemical, geologic, and operational data to estimate resource potential and guide extraction strategies.

a. Geothermal Brines

Key datasets include fluid geochemistry, well and reservoir data (e.g., temperature, flow rates), and geologic and geophysical surveys. These data determine elemental concentrations (e.g., lithium, manganese), constrain extractable volumes, and inform reservoir management and system design.

b. Oilfield (Produced) Brines

Water chemistry, production volumes, and reservoir characteristics are central datasets for determining resource potential. Together, these datasets define mineral concentrations, total resource scale, and production feasibility over time, while geologic context constrains accessibility and depletion rates.

c. Mine Tailings And Waste Rock

Geochemical assays, metallurgical studies, material volumes, and historical processing data are critical. These datasets reveal residual mineral content, estimate total recoverable quantities, and indicate whether reprocessing is technically and economically viable.

d. Coal Ash And Acid Mine Drainage

Chemical composition, generation rates, and flow volumes underpin assessments. These data determine whether waste streams contain economically meaningful concentrations and define the scale and longevity of potential recovery operations.

e. Deep Saline Formations

Brine chemistry, hydrogeologic properties (e.g., porosity, permeability, and extent), and pilot extraction data, where available, are essential. These datasets establish whether resources are present, estimate accessible volumes, and assess the feasibility of extraction under high uncertainty.

FINDING 1-21: Unconventional systems rely heavily on legacy oil and gas logs, geothermal records, mining archives, and power plant data, but these datasets are uneven in quality and rarely optimized for essential mineral assessment.

FINDING 1-22: Unconventional essential mineral resources depend on resource-specific datasets—particularly geochemical composition, volume/flow data, and geologic context—to determine both the presence and recoverability of minerals. Integrating these data is critical to reducing uncertainty and translating diffuse or waste stream resources into viable supply.

2. Assessment Approaches

While each resource has unique aspects, assessments generally follow a structured methodology, often in phases.

a. Frontier-Stage Screening

Early assessments compile existing data and conduct preliminary surveys to identify prospective settings (e.g., sedimentary basins with saline aquifers, or regions with large volumes of mine waste). Geologic mapping, geophysics, and remote sensing are used to locate surface expressions of mineralization or alteration that hint at the presence of essential elements.

b. Emerging-Stage Characterization

Once targets are identified, detailed sampling and modeling begin. For mine wastes, systematic sampling and geostatistical modeling define grade distribution in a tailings pile and estimates

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• Identifying resource-bearing systems (thermal gradients, brine chemistry, mineral content, storage potential; establishing conceptual viability	• Locating favorable zones; early estimates of fluid composition, temperature, mineral recovery potential, or storage injectivity	• Demonstrating technical feasibility; quantifying flow rates, chemistry, mineral recovery, or storage capacity; reducing uncertainty	• Optimizing extraction, reinjection, mineral recovery, or storage operations; improving efficiency and economics	• Unlocking additional value from legacy assets; reprocessing tailings/ CCR; extracting dissolved minerals from produced brines; repurposing deep formations
Principal Uncertainties	• Basin architecture, fluid pathways, temperature gradients, brine composition, mineral content, reservoir quality	• Continuity of resevoir properties; variability in chemistry; injectivity/ productivity; geochemical behvaior	• Long-term flow performance; scaling/precipitation risks; mineral recovery efficiency; environmental impacts	• Operational stability; induced seismicity; long-term geochemical interactions; waste-handling constraints	• Remaining resource potential; legacy data quality; environmental liabilities; applicability of new extraction or monitoring technologies
Principal Datasets	• Regional geology, heat-flow data, legacy oil and gas datasets, remote sensing, airborne geophysics	• Target-scale geophysics, geochemical sampling, well logs, early test wells, structural mapping	• Core analyses, downhole logs, pump tests, tracer tests, mineralogical and metallurgical testing, geomechanical data	• Production data, continuous monitoring (pressure, temperature, chemistry), seismicity monitoring, hydrological models	• Relogged cores, reprocessed geophysics, historical production data, hyperspectral mapping of tailings/coal combustion residues, targeted drilling or sampling
Typical Scales of Investigation	• Basin- to regional-scale (10s–100s km)	• District- or play-scale (5–50 km)	• Reservoir- or facility-scale (1–10 km)	• Wellfield-, plant-, or storage-site-scale (m to km)	• District- or site-specific-scale focused on legacy infrastructure or waste materials

Assessment Approaches	• Conceptual models of geothermal systems, brine migration, mineral solubility, or storage potential, regional screening	• Target delineation, early reservoir modeling, geochemical fingerprinting, pilot-scale sampling	• Reservoir simulation, flow and transport modeling, mineral recovery testing, geomechanical and geochemical coupling	• Operational optimization, real-time monitoring, induced seismicity management, long-term performance forecasting	• Data integration and reinterpretation, advanced analytics, reprocessing of tailings/CCR, secondary extraction or repurposing strategies
Impact of Publicly Available Data	• High—geologic surveys, heatflow maps, oil and gas well data, and hydrologic datasets are foundational	• Moderate to high—public data reduces early-stage risk and guides target selection	• Moderate—proprietary operational and well-specific data dominate	• Low—operations rely on high-resolution site-specific datasets	• High—legacy public datasets become valuable when combined with modern tools and reanalysis
Impact of Publicly Available Assessments	• High—national geothermal, brine, and storage assessments shape investment and research priorities	• Moderate—help refine target areas and reduce early uncertainty	• Low—project-specific engineering and environmental assessments dominate	• Low—site-specific operational assessments take precedence	• High—public assessments help identify overlooked opportunities in legacy oilfields, tailings, CCR, and deep saline formations
Feasibility of Generating Publicly Available Assessments	• High—regional datasets and conceptual models can be shared broadly	• High—nonproprietary geophysics, geochemistry, and legacy well data can be aggregated	• Moderate—site-specific datasets become proprietary; limited public release	• Low—operational data is confidential and facility specific	• Moderate to high—legacy data can be released; new assessments possible through reinterpretation and modern analytics

Table 1-8. *Key Assessment Characteristics Based on Basin or Asset Maturity for Unconventional Mining*

of total recoverable resource size.[36] For brines (geothermal, oilfield, or deep aquifers), fluid sampling, pump tests, and hydrogeologic modeling are used to simulate brine movement and grade over time, which is crucial for brine resources that can change as they are produced (a key difference from static hardrock ore bodies).

c. Developing-Stage Process Evaluation

Assessments focus on mineral extraction feasibility through laboratory testing of extraction methods. For a given resource, experts might compare hydrometallurgy (chemical leaching), physical separation techniques (e.g., froth flotation for solids, membrane filtration or sorbent extraction for liquids), and fluid extraction to determine recovery efficiency and technical viability.

d. Mature-Stage Feasibility Analysis

Final assessments integrate resource, processing, and economic models. This includes scaling extraction processes (flow sheets, energy/material balances), estimating costs and revenues, and evaluating project viability under different market scenarios. The end result is often a feasibility study or technical report that consolidates all findings: estimated resource size/grade, recoverable portion, proposed extraction method with expected yields, economic model (net present value, return on investment), and risk factors. These reports follow standard formats similar to mining or oil and gas projects but include additional considerations unique to these resources (e.g., for brines: the pumping strategy and aquifer recharge must be described, analogous to a mine plan).

3. Impact Of Publicly Available Data And Assessments

Improving publicly available data for unconventional essential mineral resources has a transformative impact by reducing project evaluation time, lowering costs, and expanding participation. Public datasets can enable broader, faster, and more transparent assessments across the resource life cycle. Specifically, publicly available data can do the following:

- Enable Data-Driven Exploration and Screening: Open datasets support AI/ML and advanced analytics, allowing multiple stakeholders (e.g., national labs, universities, and startups) to independently identify high-potential targets and accelerate early-stage (frontier) exploration.
- Lower Barriers to Entry: Accessible, high-quality data attract smaller companies, new investors, and public-private partnerships that would otherwise lack the resources to conduct initial assessments.
- Improve Risk Assessment and Transparency: Public data enhance stakeholder confidence, support informed decision-making, and can streamline permitting and regulatory processes.

Public data provide the greatest value at the frontier and revitalizing stages. In frontier settings, regional datasets—geologic surveys, heat-flow mapping, oil and gas well records, remote sensing, and historical mining data—often represent the only available information and are critical for initial screening and investment decisions. In revitalizing stages, these same datasets—augmented by modern reprocessing and analytics—enable reevaluation of legacy assets, including depleted geothermal fields, mature oilfields, historical mine districts, and aging coal combustion residue repositories. This pattern underscores a central theme: Public geoscience data are disproportionately valuable at the beginning and end of the resource-development life cycle.

In contrast, developing and mature stages rely primarily on proprietary, site-specific data (e.g., core analyses, downhole logs, pump tests, tracer tests, geomechanical measurements, and continuous operational monitoring) to quantify performance and recovery. As a result, the role of publicly available data diminishes as projects advance into the operational phase. This dynamic is consistent across geothermal brines, produced brines, deep saline formations, and reprocessing of tailings or coal combustion residues.

36 C. Özgen Karacan, Oktay Erten, and Josep Antoni Martín-Fernández, "Assessment of Resource Potential from Mine Tailings Using Geostatistical Modeling for Compositions: A Methodology and Application to Katherine Mine Site, Arizona, USA," *Journal of Geochemical Exploration 245* (2023): https://doi.org/10.1016/j.gexplo.2022.107142.

FINDING 1-23: Public geoscience data deliver the greatest value in frontier and revitalizing stages, where the data enable initial discovery and reevaluation of legacy resources; their influence decline as assessments shift to proprietary, site-specific data for developing and mature assets.

G. Coal Extraction

Coal has historically been one of the most important energy resources in the United States. From the late 18th century through the 20th century, coal fueled industrial expansion, powered electricity generation, and served as a cornerstone of national energy security. Coal remains a strategically significant U.S. energy and industrial resource, with ongoing relevance for regional economies, export markets, and emerging applications such as carbon-based materials and critical minerals. As energy demand evolves and new uses for coal-derived products expand, accurate subsurface assessment is increasingly important to quantify both traditional reserves and unconventional resource potential.

Coal extraction has traditionally relied on surface and underground mining, where assessments focus on seam thickness, depth, quality, and continuity. Emerging approaches—including in situ gasification and potential leaching of critical minerals such as rare earth elements—introduce new assessment challenges requiring characterization of deeper seams, geochemical behavior, and fluid flow processes. These developments expand the scope of coal resource assessment beyond conventional mining to include both energy and nonenergy resource potential.

1. Principal Subsurface Datasets

Principal subsurface datasets for coal assessments include core samples and geophysical well logs, which define coal seam thickness, depth, quality, and continuity. Surface mapping and regional geologic data constrain spatial extent and key mining parameters such as strip ratio. Laboratory analyses of coal samples provide heating value, ash content, and elemental composition (e.g., sulfur, sodium) informing both resource quality and end use.

Extensively developed basins—such as the Appalachian, Illinois, and Powder River basins—also provide large volumes of geological, geophysical, and production data, supporting relatively well-constrained resource assessments.

2. Assessment Approaches

Coal assessments integrate stratigraphic drilling, geologic data, and modeling to characterize seam thickness, extent, and lateral continuity of coal resources. Economic, legal, and societal constraints—such as depth, seam thickness, coal quality, and land-use restrictions—are applied to distinguish total resources from recoverable reserves.[37]

Assessments are conducted across multiple scales (Table 1-9). The National Coal Resource Assessment was a multiyear effort by the USGS to better assess both coal quantity and quality across five regions that account for most (>90%) domestic coal production.[38] Subsequent regional efforts focused more on calculating recoverable coal resources relative to total coal resource in place.[39] Basin- and mine-scale assessments provide higher-resolution data for operational decisions, permitting, and environmental compliance. Recent efforts have focused less on discovery and more on refining recoverable reserves based on geological constraints and mining technology limitations.[40]

37 Brian N. Shaffer, *Assessing U.S. Coal Resources and Reserves* (U.S. Geological Survey, 2017), https://www.usgs.gov/centers/central-energy-resources-science-center/science/us-coal-resources-and-reserves-assessment.

38 Mark A. Kirschbaum, "Geologic Assessment of Coal in the Colorado Plateau," in *The National Coal Resource Assessment Overview* (U.S. Geological Survey, 2009), https://pubs.usgs.gov/pp/1625f/downloads/ChapterA.pdf.

39 U.S. Geological Survey, "Assessments Evolved: USGS Coal Research in the 21st Century" (2017), https://www.usgs.gov/news/featured-story/assessments-evolved-usgs-coal-research-21st-century.

40 U.S. Geological Survey, "Assessments Evolved: USGS Coal Research in the 21st Century" (2017), https://www.usgs.gov/news/featured-story/assessments-evolved-usgs-coal-research-21st-century.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Mature**	**Revitalizing**
Value Drivers	• N/A	• In-place tonnage • Coal quality/composition • Access to data	• Improved resource recovery • Value-added opportunity (e.g., Rare Earth Elements extraction)	• Costs reduction • Application of new technologies to improve/ enable access to uneconomic resources (e.g., in situ recovery) • Maximize resource utilization prior to reclamation	• N/A
Principal Uncertainties	• N/A	• Composition • Seam thickness/variability • Overburden variability	• Potential for improved resource recovery • Impacts to mine operations/ potential for increased efficiency	• Cost • Characterization of unmineable coal seams	• N/A
Principal Datasets	• N/A	• Geologic mapping • Core sampling/drill cuttings • Geochemical analysis • Modeling	• Geologic mapping • Core sampling/drill cuttings • Geochemical analysis • Modeling	• Geologic mapping • Geochemical analysis	• N/A
Typical Scales of Investigation	• N/A	• Regional-scale • Project-area-scale	• Mine-scale	• Mine-scale	• N/A
Assessment Approaches	• N/A	• Establish resource availability • Determine resource recovery	• Reserve/resource modeling	• Reserve/resource modeling • Technology assessment	• N/A

Impact of Publicly Available Data	• N/A	• High—currently limited availability	• Low—proprietary information associated with active mining	• Low—proprietary information associated with active mining	• N/A
Impact of Publicly Available Assessments	• N/A	• Moderate	• Low—proprietary information associated with active mining	• Low—proprietary information associated with active mining	• N/A
Feasibility of Generating Publicly Available Assessments	• N/A	• Moderate—contingent on access to data typically associated with active mining operations	• Low—data typically associated with active mining operations	• Low—data typically associated with active mining operations	• N/A

Note: Frontier and revitalizing assets do not exist for coal given the maturity of the resource.

Table 1-9. *Key Assessment Characteristics Based on Asset Maturity for Coal*

Despite extensive historical mining data, uncertainty remains in structurally complex and deeply buried seams. Emerging applications—such as in situ gasification, enhanced coalbed methane recovery, and carbon sequestration—introduce additional technical and economic uncertainty.

FINDING 1-24: Coal assessments combine drilling and modeling to define resource extent and apply economic and regulatory filters to estimate recoverable reserves. While resources are generally well constrained, improved characterization and geochemical data, particularly of deep seams, could support emerging technologies and new uses.

3. Impact Of Publicly Available Data And Assessments

Enhanced publicly available data can significantly improve decision-making. Many existing datasets are outdated or inconsistently digitized, limiting accuracy and usability. Updating and standardizing these datasets would improve resource estimates, particularly for coal quality and composition, and support evaluation of emerging applications such as in situ mining and critical mineral recovery.[41]

Federal and state agencies have long recognized the importance of coal assessments in supporting land-use planning, leasing decisions, environmental regulation, and long-term energy forecasting. Modernized assessments could update estimates of remaining reserves and enable reevaluation of coal resources previously deemed uneconomic under current technologies and market conditions.

For industry, improved assessments support both new development and optimization of existing mine operations, such as mine life extension, reclamation planning, and possible transition to alternative uses. Advances in technology and changes in market dynamics may increase the viability of deeper, thinner, or structurally complex seams, as well as new applications such as underground coal gasification and carbon sequestration.

FINDING 1-25: Public coal assessments support land-use planning, leasing, regulatory decisions, and long-term energy forecasting, while reducing investment risk and informing both existing mine operations and emerging uses of coal resources.

H. Geologic Hydrogen

Geologic hydrogen is an emerging subsurface energy resource with early commercial production demonstrated in Mali, West Africa,[42] and active exploration globally, including in the United States.[43] Interest is driven by the potential to unlock a naturally occurring, low-carbon primary energy resource in geologic settings that are largely underexplored or were previously overlooked. The USGS recently conducted a high-level prospectivity assessment of the Lower 48 states to identify regions with the potential for geologic hydrogen (Figure 1-6).[44] In addition, helium may be found in association with geologic hydrogen in certain geologic settings (areas with ancient radiogenic crust).[45]

Geologic studies are also ongoing to identify areas where hydrogen could be produced in situ by stimulating iron-rich rocks in the subsurface.[46] Recent field-testing in Oman is encouraging and

41 National Research Council, "Chapter 3: Coal Resource, Reserve, and Quality Assessments," in *Coal: Research and Development to Support National Energy Policy* (National Academies Press, 2007), https://www.nationalacademies.org/read/11977/chapter/5.

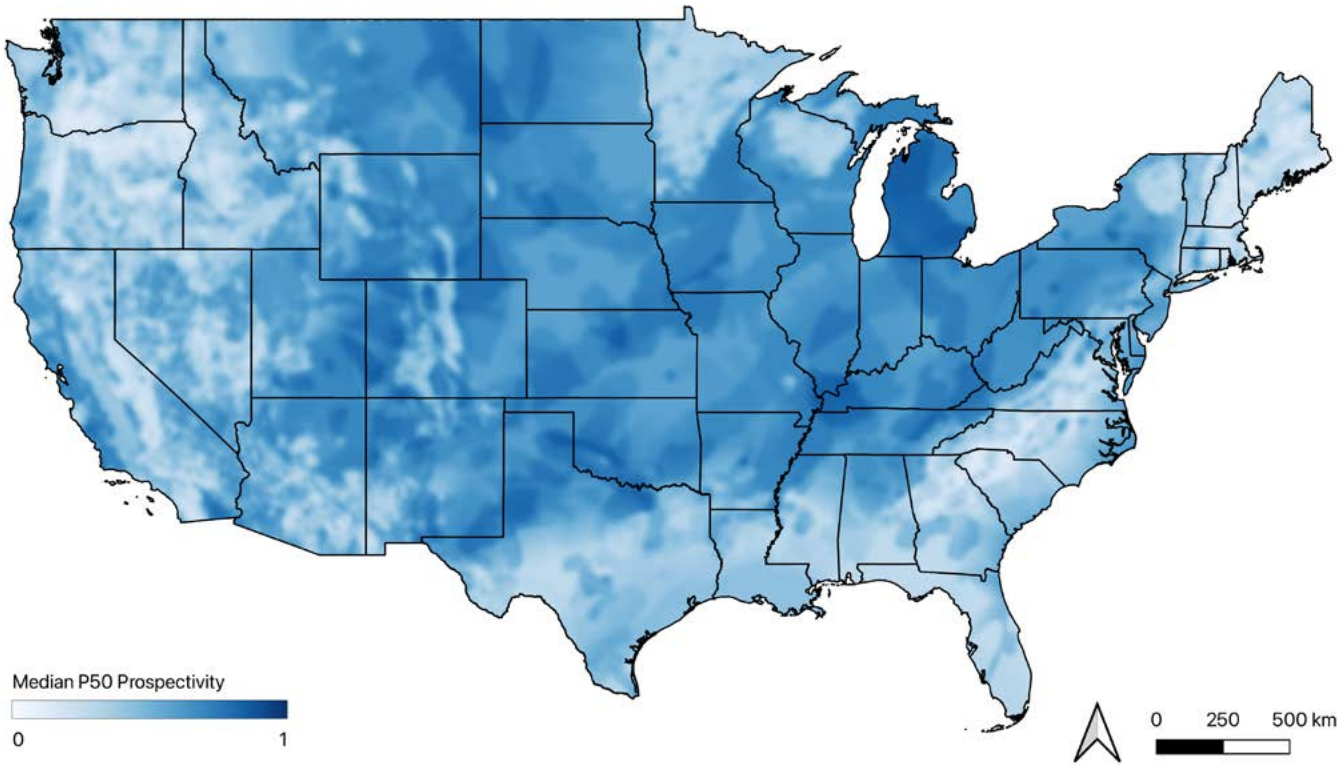
42 Ousmane Maiga et al., "Characterization of the Spontaneously Recharging Natural Hydrogen Reservoirs of Bourakébougou in Mali," *Scientific Reports* (2023), https://doi.org/10.1038/s41598-023-38977-y.

43 In the United States, only a handful of exploration wells for geologic hydrogen have been drilled; they are in Kansas, Nebraska, and Minnesota. No economic discoveries have been announced to date.

44 S.E. Gelman, J.S. Hearon, and G.S. Ellis, *Prospectivity Mapping for Geologic Hydrogen* (U.S. Geological Survey, 2025), https://doi.org/10.3133/pp1900.

45 Carolina Olivares et al., "A new exploration tool in the search for native hydrogen and helium," *The Impacts of Igneous Systems on Sedimentary Basin and their Energy Resources;* B. Kilhams et al., Geological Society of London, https://doi.org/10.1144/SP547-2023-49.

46 Alexis S. Templeton et al., "Low-Temperature Hydrogen Production and Consumption in Partially Hydrated Peridotites in Oman: Implications for Stimulated Geological Hydrogen Production," *Frontiers in Geochemistry* (2024), https://doi.org/10.3389/fgeoc.2024.1366268.



Source: Data from USGS. 2025. https://www.usgs.gov/media/images/geologic-hydrogen-prospectivity-map.

Figure 1-6. *Prospectivity of Hydrogen in the Conterminous United States*

similar settings in the United States could be prospective for stimulated production. However, technology for stimulating hydrogen remains at low readiness and requires further validation.

FINDING 1-26: Geologic and geo-stimulated hydrogen represent potential energy resources that could contribute significantly to the United States' energy portfolio, but realizing this potential depends on improved subsurface characterization and technology de-risking.

1. Principal Datasets

Principal datasets for geologic hydrogen include geologic mapping, rock and core analyses, drilling cuttings, gas and fluid geochemistry, soil surveys, well logs, and geophysical data (aeromagnetic, gravity, and, where available, seismic). Examples include archived geologic samples and analyses of these samples in public repositories, satellite-based gravity data, aeromagnetic surveys such as those acquired through the USGS Earth Mapping Resources Initiative (Earth MRI) program, geologic maps, and publicly available

well data. Together, these datasets are essential for identifying prospective hydrogen sources, migration pathways, and potential accumulation zones in largely underexplored settings.

At this frontier stage, access to high-quality, publicly available data and interpretations is especially important (Table 1-10). Integrated subsurface datasets can accelerate early screening, reduce exploration risk, and support new entrants with limited resources.

FINDING 1-27: Public datasets—including geologic maps, well data, geophysical surveys, and archived geologic samples—are essential for identifying prospective regions and guiding early-stage exploration.

FINDING 1-28: Greater understanding of the hydrogen systems in prospective areas, including source rock distribution, generation, migration, trapping, and preservation of hydrogen is fundamental to reduce uncertainty.

2. Assessment Approaches

Assessment of geologic hydrogen begins with identifying source rocks capable of generating hydrogen, such as iron-rich igneous rocks that chemically react with water through serpentinization, or ancient radiogenic crustal rocks that produce hydrogen via radiolysis of water. The next step is evaluating migration pathways and potential traps where hydrogen could accumulate in extractable concentrations. For geo-stimulated hydrogen, assessments focus on the depth, distribution, and reactivity of iron-bearing rocks that could be enhanced to increase hydrogen generation.

Although comprehensive, publicly available resource estimates have not yet been made for the U.S., future resource estimates would need to consider both naturally occurring and potentially stimulated hydrogen, using stochastic methods to capture a range of outcomes, similar to frontier oil and gas assessments. Key uncertainties include the distribution of source rocks, the presence and effectiveness of traps and migration pathways, and hydrogen losses during migration and storage due to leakage or chemical and biological processes. The decay of radiogenic minerals in crustal rocks is also known to be a major source of helium, and in certain geologic settings, hydrogen and helium resources may be associated with each other.

FINDING 1-29: Geologic hydrogen assessments face high uncertainty in source distribution, migration, trapping, and loss processes, requiring integrated subsurface data and probabilistic methods similar to frontier oil and gas exploration.

FINDING 1-30: Stimulated hydrogen is attractive in that the subsurface uncertainty is reduced to the distribution and depth of hydrogen source rocks where in situ development could be engineered; however, laboratory experimentation, pilot tests, and modeling are required to prove technologies to commercially develop stimulated hydrogen resources.

3. Impact Of Publicly Available Data And Assessments

Publicly available data are paramount for geologic hydrogen and geo-stimulated hydrogen ventures, which remain at the frontier stage with no proven resources in the United States. Exploration is largely led by smaller companies with limited financial and technical resources, making access to high-quality public data critical for early screening and risk reduction.

Subsurface assessments from the USGS and state geological surveys provide a foundational resource for identifying prospective regions and guiding early exploration. Initial efforts—such as studies in Kansas and Texas—demonstrate the value of these programs, but broader coverage and higher-resolution data are needed to support industry decision-making.

Expanding and refining public datasets will require sustained state and federal investment in data acquisition, analysis, and interpretation. Such efforts can accelerate exploration, lower barriers to entry, and support the development of a new domestic energy resource.

FINDING 1-31: Geologic hydrogen exploration in the United States is currently led by resource-constrained companies; public assessments conducted by the USGS and state geological surveys are critical to reduce risk and support investment.

IV. SUBSURFACE ASSESSMENT FOR DYNAMIC AND PERMANENT STORAGE

Underground storage of energy resources and waste products occurs across a spectrum of geologic settings defined by both storage medium and purpose. Storage may take place in natural pore space such as depleted oil and gas reservoirs and saline aquifers, or in engineered voids, most commonly salt caverns. Most current subsurface natural gas storage capacity resides in depleted hydrocarbon reservoirs, followed by salt caverns and saline aquifers (Figures 1-7 and 1-8), but assessment work has shown that the vast majority of potential subsurface pore space is located in saline aquifers.[47] In all cases, effective storage requires establishment of a confining zone or other mechanism to ensure containment.

These settings support two primary classes of storage: dynamic and permanent. Dynamic storage systems used for oil, natural gas, compressed air, hydrogen, and thermal energy involve repeated injection and withdrawal cycles. They prioritize deliverability, operational flexibility, and proximity to infrastructure. Dynamic storage occurs in both porous media and engineered caverns, with gas and liquid hydrocarbons storage representing the most mature application. Emerging uses include compressed air energy storage and subsurface thermal energy storage, such as reservoir thermal energy storage, which stores and recovers heat in suitable permeable formations. These systems enable the storage and later recovery of heat, offering a flexible complement to intermittent energy resources.[48]

In contrast, permanent storage—most notably for carbon dioxide (CO_2), as well as acid gas and produced water—focuses on long-term containment with no retrieval. These systems place greater emphasis on secure trapping mechanisms, seal integrity, and long-term monitoring. The differing objectives of dynamic and permanent storage lead to distinct assessment approaches, design requirements, and risk profiles across storage types.

A. Dynamic Storage in Porous Media

Dynamic storage in porous media primarily uses depleted reservoirs and, in some regions, saline aquifers. These formations provide large working volumes, predictable deliverability, and direct integration with existing pipeline infrastructure, making them the most mature and widely used form of underground gas storage for natural gas or hydrogen.[49] Effective deployment depends on accurate characterization of reservoir properties—such as porosity, permeability, pressure behavior, and connectivity—which control storage capacity, injectivity, and withdrawal performance over repeated cycles.

1. Principal Subsurface Datasets

Identification of new storage reservoirs in porous media is driven by system requirements, including working gas capacity, peak-day deliverability, and proximity to pipeline infrastructure. Subsurface screening therefore focuses on candidate reservoirs that are most likely to meet these operational criteria.

47 National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition* (2015), https://www.netl.doe.gov/node/5841. U.S. Geological Survey, *National Assessment of Geologic Carbon Dioxide Storage Resources—Results* (2013), https://pubs.usgs.gov/circ/1386/.

48 Jeffrey D. Pepin et al., "Reservoir Thermal Energy Storage Pre-Assessment for the United States," *Geothermics* (2025), https://doi.org/10.1016/j.geothermics.2025.103256.

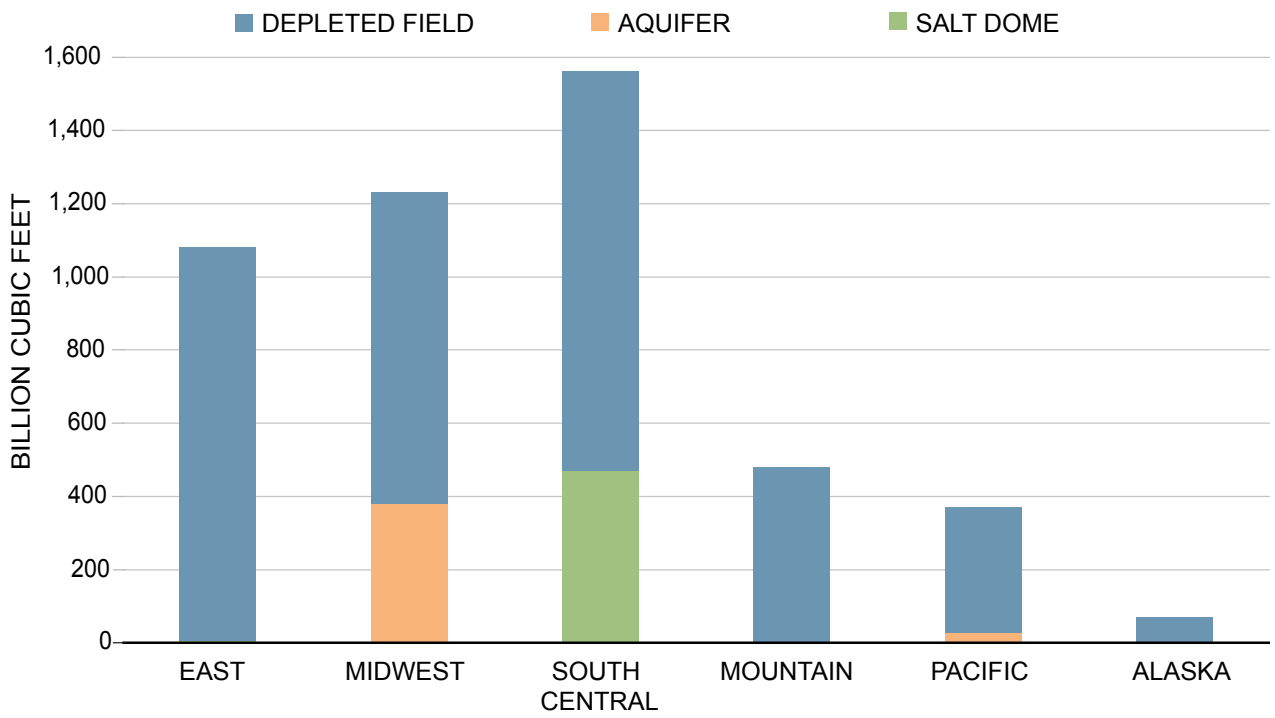
49 U.S. Energy Information Administration, *The Basics of Underground Natural Gas Storage* (2015), https://www.eia.gov/naturalgas/storage/basics/.

H_2	Basin or Asset Maturity				
	Frontier	**Emerging***	**Developing***	**Mature***	**Revitalizing***
Value Drivers	• In-place volume • Access to data, often public only	• In-place and screening estimates of recovery factor • Proximity to infrastructure • Commercialization time reduction • Access to data, often public only	• In-place and recoverable volumes calculated with increasingly sophisticated data • Prospect economic and EUR per well • Proprietary data becomes more prominent	• Operational costs • Prospect economics • Production volumes • Assessment of bypassed pay • Cost–benefit analysis of infill and secondary recovery opportunities • Publicly available production data important	• New technology • Enhanced commercial terms • Valuation of alternate/ additional commodities or use cases
Principal Uncertainties	• Working hydrogen system • Distribution of iron-bearing source rocks or granitic terrains	• Estimated ultimate recovery • Reservoir characteristics impact on development plan	• Realized recovery factor and most effective well count, types, and distribution • Secondary recovery	• Infill drilling opportunities • Secondary recovery • Opportunities to open additional completion levels; recompletion potential	• Tertiary recovery • Alternate/additional commodities or use cases
Principal Datasets	• Geological maps, 2D seismic data, geochemical data, potential fields data (gravity and magnetics), remote sensing	• 2D and 3D seismic data • Well data (logs, cuttings) • Geochemical data • Production (flow) test	• 3D seismic data • Well data (logs, cuttings, core) • Production (flow) test • Geochemical data	• 3D and 4D seismic data • Well data (logs, cuttings core) • Production data	• 3D and 4D seismic data • Well data (logs, cuttings core) • Production data
Typical Scales of Investigation	Regional-scale—distribution of igneous source rocks	• Often large-block-(or project-) scale (2–>40 square miles)	• Field-(or prospect-) scale	• Field-(or prospect-) scale • Can include sub-field-scale (lease- or well-level) opportunities	• Field-(or prospect-) scale • Can include sub-field-scale (lease- or well-level) opportunities

Assessment Approaches	• Focus on hydrogen systems • Integrate potential fields data and 2D seismic data	• Refine static volumetric assessments • Develop realistic recovery factor estimations	• Probabilistic 3D model simulations common in offshore programs • Reservoir studies based on 3D seismic and analysis of offset wells	• Studies based on production data • Refine probabilistic model simulations with 4D seismic in offshore programs	• Often integrating combinations of historical data from public archives with new data to refine new play concepts
Impact of Publicly Available Data	• Essential—access to public onshore data to inform play prospective resource areas	• Essential—access to state survey log, core, DST, and production data is vital for analysis	• Proprietary data becomes more prominent and important • Public log, core, DST, and production data are important, especially onshore	• Proprietary production and seismic data are critical. • Public log, core, DST, and production data are important, especially onshore, for infill opportunity generation	• Essential—access to public onshore and offshore data often drives new play concepts
Impact of Publicly Available Assessments	• High for play screening	• High for commercial screening	• In-place assessments provide context for remaining resource availability	• Important for comparison of production relative to in-place prognosis and for regulatory oversight	• New, publicly available assessments sometimes drive new opportunities
Feasibility of Generating Publicly Available Assessments	• High—already a standard practice	• Moderate—depends on access to seismic data and well information	• Moderate—depends on access to seismic data and well information	• Moderate—depends on access to seismic data and well information	• High—already a standard practice

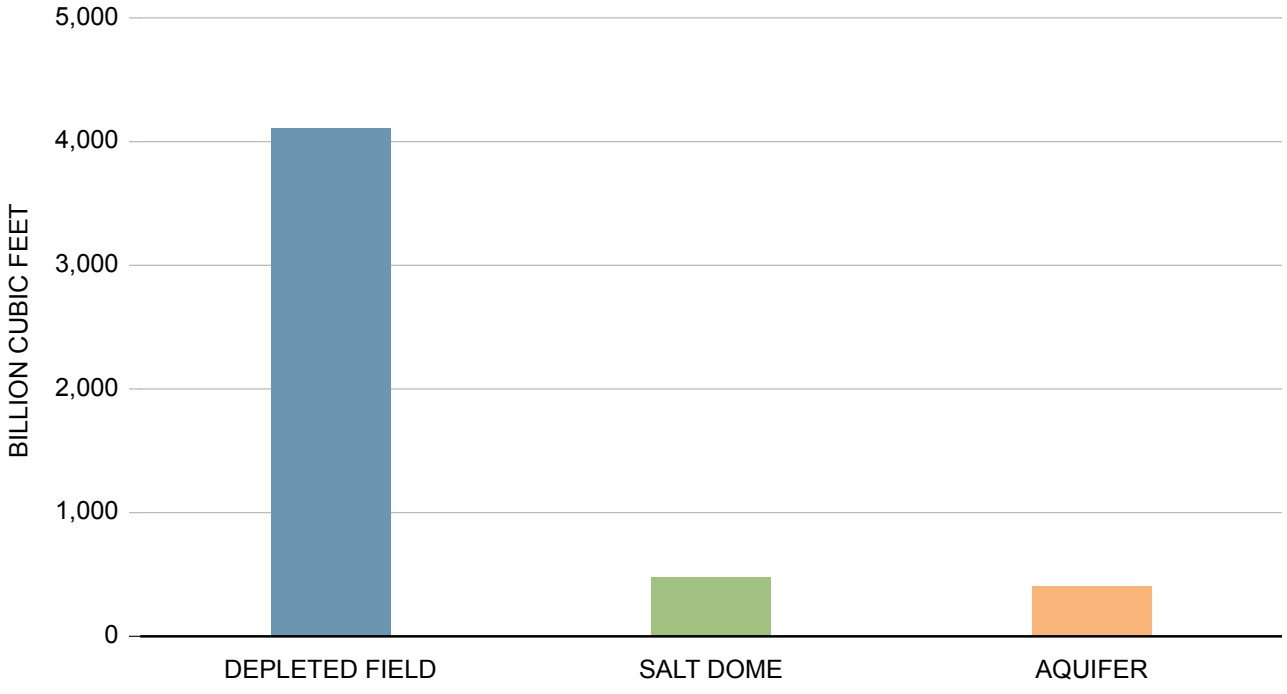
Note: *Because geologic hydrogen is currently only being produced in Mali, Africa, and not currently being produced in the United States, the Basin Maturity fields are projected to be similar to conventional oil and gas.

Table 1-10. *Key Assessment Characteristics Based on Basin or Asset Maturity for Geologic Hydrogen*



Source: EIA. 2026.

Figure 1-7. *U.S. Working Natural Gas Storage by Region and Type as of December 2024*



Source: EIA. 2026.

Figure 1-8. *U.S. Working Natural Gas Storage Capacity by Type as of December 2024*

Assessments rely heavily on regional geological and operational databases, which compile decades of industry data from hundreds of existing storage reservoirs pertinent to potential storage reservoirs. Information from these online databases can then be used to define initial areas of interest—including specific fields, trends, or broader basins—and to support early-stage screening.

Core datasets include production history, estimates of hydrocarbons initially in place, reservoir pressure and drive mechanisms, well performance and stimulation history, well density, depth, reservoir type, and available well logs and core data (Table 1-11). Together, these data constrain storage capacity, injectivity, and withdrawal performance.

FINDING 1-32: The most important datasets for dynamic storage in porous media are field production, and geologic and well data, which define reservoir capacity and performance.

FINDING 1-33: Publicly available datasets provide essential system-level and geologic context for early-stage screening, enabling identification and evaluation of candidate storage reservoirs.

2. Assessment Approaches

These datasets support a screening process that narrows potential sites to reservoirs suitable for gas storage. Key criteria include sufficient storage capacity, effective lateral connectivity, reliable vertical and lateral containment, manageable areal extent, and minimal operational constraints from existing wells.

Uncertainty evolves over the operational life cycle of the prospect storage asset. In early stages, uncertainties center on reservoir continuity, caprock integrity, and pressure support. In developing stages, uncertainties shift to permeability changes, well performance variability, and aquifer movement. In mature systems, uncertainties focus on well integrity, long-term compaction or subsidence potential, and the performance of repurposed wells.

3. Impact Of Publicly Available Data And Assessments

Significant foundational data (e.g., production history, formation tops, and well logs) already exist in state and federal databases, reflecting decades of hydrocarbon development. These datasets are especially valuable in developing and mature stages, where they enable rapid screening of candidate reservoirs and support repurposing of depleted fields for storage.

However, inconsistent formats, variable data quality, and limited integration constrain their usability. Harmonization, standardization, and expansion of these datasets would improve screening efficiency, reduce project risk, and support more consistent evaluation across regions. Achieving this will require coordinated efforts among federal and state agencies to develop common data standards and practices.

FINDING 1-34: Extensive legacy data from industry in federal and state geological databases provide a strong foundation for dynamic storage in porous media, but harmonization and standardization are needed to unlock their full value for screening, repurposing, and development, offering significant value to both public and private stakeholders.

	Basin or Asset Maturity				
	Frontier	Emerging	Developing	Mature	Revitalizing
Value Drivers	• N/A	• N/A	• Recognized shortfall in regional storage capacity; alignment with organizations' business strategy; favorable preliminary economics; proximity to existing pipeline infrastructure	• Maximum storage quantity; unsubscribed capacity for arbitrage opportunities; peak deliverability sustainability	• N/A
Principal Uncertainties	• N/A	• N/A	• Mapped storage reservoir for vertical and lateral containment; caprock integrity; presence of geologic features, e.g., faults that could compromise reservoir containment; storage volume capacity; rate/deliverability potential; condition of existing production wells, location and condition of abandoned wells	• Effective or undrained storage capacity; risk of loss of reservoir containment via geologic features like spill-points and faults; impounded storage gas; condition of existing injection/ withdrawal wells; mapped storage horizon beyond protective acreage; storage of mineral rights; well data density	• N/A
Principal Datasets	• N/A	• N/A	• Field historical information: discovery date; discovery pressures (surface and bottomhole); reservoir temperature; depth of producing formation; other hydrocarbon-bearing formations above or below the formation of interest; operator's estimate or other estimates of initial hydrocarbon in place; total production to date; native fluid analyses (chemical analyses of gas, oil, water, PVT analyses if applicable) • Field production history (all phases): gas, oil, water as applicable on a periodic basis (daily/ weekly/monthly on as detailed a level as can be obtained) • Field reservoir pressure history: bottomhole pressures and/or wellhead pressures on a periodic basis (as above) • Gathering system diagrams; charts or maps; charts/diagrams/maps of production/processing equipment and well locations	• Cement bond logs; casing inspection logs; annulus pressure tests; gas sample collection; semiannual shut-in pressure tests; well deliverability and pressure transient testing	• N/A

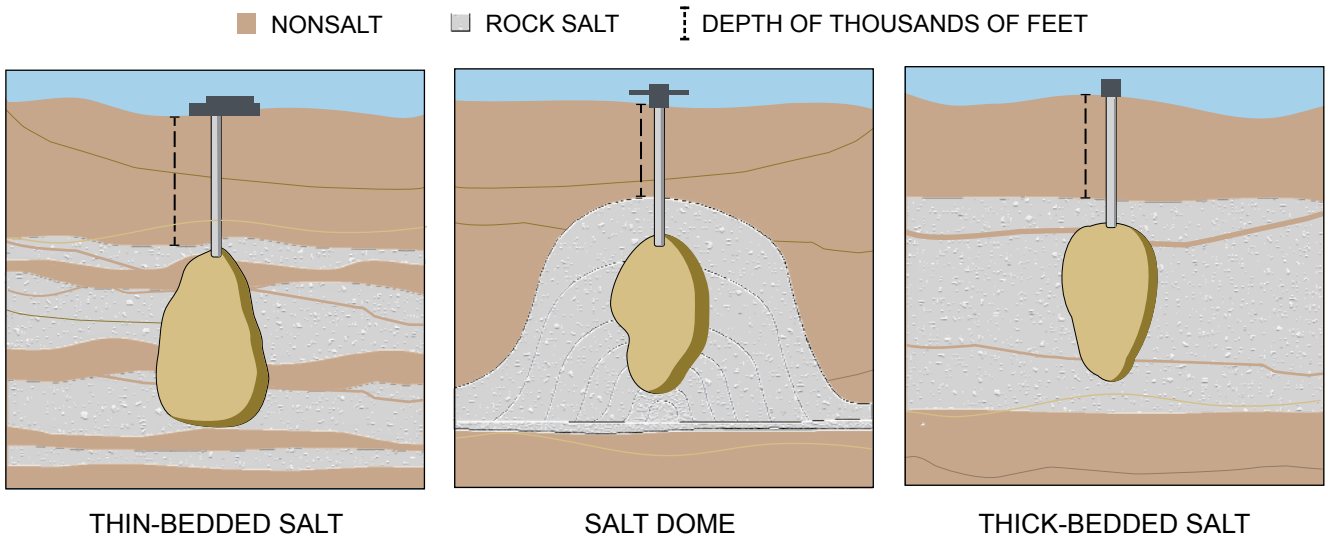
Typical Scales of Investigation	• N/A	• N/A	• Multimeter-to full-field-level	• Well-to full-field-level	• N/A
Assessment Approaches	• N/A	• N/A	• Volumetric methods; material balance; production decline analysis; full field-scale reservoir simulation	• Material balance; geologic boundary risk assessments; well casing and annulus risk assessments	• N/A
Impact of Publicly Available Data	• N/A	• N/A	• High—public data reduces early-stage risk, guides target selection and identifies fatal flaws that could cull an opportunity	• Minimal	• N/A
Impact of Publicly Available Assessments	• N/A	• N/A	• Moderate—help refine target areas and reduce early uncertainty but requires independent verification	• Minimal	• N/A
Feasibility of Generating Publicly Available Assessments	• N/A	• N/A	• High—nonproprietary geophysics, logging, core analysis, geochemistry, and well-testing data can be aggregated and used to reduce uncertainty	• High—nonproprietary well logging for casing condition and biannual inventory reports for well and storage field integrity are documented with state and federal regulatory authorities	• N/A

Table 1-11. *Key Assessment Characteristics Based on Basin or Asset Maturity for Dynamic Storage in Porous Media*

B. Dynamic Storage in Engineered Salt Caverns

Salt caverns are engineered voids created by solution mining in thick, laterally continuous salt formations, including bedded salts and domes (Figure 1-9). They provide safe, reliable underground storage due to salt's unique properties—low permeability, self-healing behavior, and creep deformation that allow caverns to maintain integrity under repeated pressure cycling.

Subsurface assessments focus on identifying salt formations of sufficient thickness and quality, and on evaluating geomechanical behavior to ensure cavern stability and well integrity. Key considerations include salt impurity content, creep rates, structural (roof, web, and floor) stability, and cavern evolution over time, all of which influence capital cost, well design, and operating flow rates. Caverns are typically used for high-deliverability storage of natural gas, hydrogen, and other energy carriers.



Note: Not drawn to scale.

Figure 1-9. Bedded Salt Deposit and Bedded Salt Cavern

1. Principal Subsurface Datasets

Principal datasets for salt cavern storage focus on defining salt geometry, composition, and geomechanical behavior (Table 1-12). Core inputs include legacy well and cavern records, seismic and other geophysical data to map salt boundaries, drilling and core data, laboratory geomechanical testing, sonar surveys of cavern geometry, and pressure and temperature monitoring. These datasets are integrated through geological, geomechanical, and thermal-hydraulic models to assess cavern stability, predict creep and shape evolution, and define operating limits and monitoring requirements.

Global and regional salt maps, such as those from the Solution Mining Research Institute, support early-stage screening by identifying salt occurrence and general formation characteristics (e.g., geologic age, range of depths). However, these datasets are often low resolution. Expanding them to include location-specific depths, thicknesses, impurity contents, and geomechanical properties would significantly improve site selection and reduce development risk, adding

substantial value to the solution mining and underground storage industries.

2. Assessment Approaches

Subsurface assessment for salt cavern storage is data-driven and evolves across the project life cycle, focusing on salt geometry, composition, and geomechanical stability.

a. Developing Stage

Early prospecting uses regional geology to identify areas with suitable domal or bedded salt, and define site boundaries, cavern spacing, and initial integrity considerations. As projects advance, assessments shift toward detailed characterization, including geomechanical analysis, cavern-specific modeling, operating limits, and long-term integrity planning. Test drilling or research of available geological records can allow engineers to evaluate salt quality, including purity and presence of insoluble minerals that may affect cavern performance.

b. Mature Stage

Operational assessments focus on monitoring and maintaining well and cavern integrity, constraining salt creep, cavern stability, and long-term convergence under repeated pressure and temperature cycling. Dynamic operations characterized by frequent pressure and temperature cycling impose unique demands on cavern geometry, thermal response, creep rates, and minimum/maximum allowable pressures. Robust assessments ensure that caverns operate within safe envelopes, avoid tensile fracturing, maintain stable roof and pillar configurations, and sustain long-term deliverability.

FINDING 1-35: Subsurface assessments transform raw geologic salt resources into engineered, high-performance storage assets that meet modern market, safety, and regulatory expectations.

3. Impact Of Publicly Available Data And Assessments

Enhanced publicly available data could significantly improve salt cavern storage development by reducing uncertainty and accelerating site screening. Improved access to well logs, seismic data, cavern records, and regulatory filings would reduce duplicative effort, improve early-stage decision-making, and enable more efficient identification of suitable salt formations. Standardized datasets—such as reference geomechanical properties, baselines of salt impurity distributions, and cavern performance histories—would narrow uncertainty ranges for new developers and provide benchmarks for design, safety, and operational integrity.

Public data provide the greatest value in early stages, while regional screening and site selection depend on limited information. As projects move into developing and mature stages, proprietary, site-specific data dominate detailed design and operations, but public datasets remain important for benchmarking and risk context.

Expanded and standardized databases could also support emerging applications, such as compressed air energy storage,[50] and improve alignment between subsurface resources and energy infrastructure needs across onshore and offshore settings.

Developing enhanced, publicly available assessments is feasible through data aggregation and anonymization supported by public-private partnerships, academic consortia, and regulatory coordination.

FINDING 1-36: Consolidated and standardized public datasets on salt formations and cavern performance can reduce early-stage uncertainty, improve site selection, and support safer, more efficient design and operation of salt cavern storage systems.

50 J. Richard Bowersox, John B. Hickman, and K.A. Skeese, Assessing Compressed Air Energy Storage (CAES) Potential in Kentucky to Augment Energy Production from Renewable Resources (2022), presented at the Joint 56th Annual North-Central/71st Annual Southeastern Section Meeting, https://bit.ly/3SA6A4I.

	Basin or Asset Maturity				
	Frontier	Emerging	Developing	Mature	Revitalizing
Value Drivers	• N/A	• N/A	• Recognized shortfall in regional storage capacity; alignment with organization's business strategy; favorable preliminary economics; proximity to existing pipeline infrastructure; presence of suitable salt formations (domal or bedded) of adequate thickness and quality	• Maximum storage quantity; unsubscribed capacity for arbitrage opportunities; peak deliverability sustainability; cavern cycling efficiency	• N/A
Principal Uncertainties	• N/A	• N/A	• Salt formation thickness, purity, and lateral continuity; presence of insolubles that may affect cavern performance; geomechanical properties of salt (creep rates, strength); proximity to other caverns or mining activities; caprock and salt boundary integrity; achievable cavern geometry and volume; location and condition of existing wells	• Long-term cavern convergence and stability; roof, web, and floor integrity; well casing and cement condition under cyclic loading; cavern shape evolution over time; salt creep impacts on storage capacity and deliverability; cap rock interface deformation impacting well casing integrity	• N/A
Principal Datasets	• N/A	• N/A	• Regional salt formation maps and geological records; drilling reports and core analyses from nearby wells; salt quality data (purity, insoluble content); geomechanical testing results (creep, strength); sonar surveys of existing caverns in the area; well completion and cementing records; Solution Mining Resource Institute GIS salt formation layers	• Periodic sonar surveys documenting cavern geometry and volume changes; well mechanical integrity test (MIT) records; pressure monitoring data (injection/withdrawal cycles); subsidence monitoring data; regulatory filings with state and federal authorities	• N/A
Typical Scales of Investigation	• N/A	• N/A	• Multimeter-to full-cavern/field-level	• Individual-cavern-to full-field-level	• N/A

Assessment Approaches	• N/A	• N/A	• Geomechanical modeling; salt quality and purity analysis; leach design simulation; volumetric capacity estimation; cavern spacing and interaction analysis	• Sonar-based cavern shape monitoring; geomechanical stability assessments; well integrity evaluations; pressure transient analysis; convergence and creep modeling	• N/A
Impact of Publicly Available Data	• N/A	• N/A	• High—public data on salt formation locations, depths, and thicknesses reduces early-stage risk and guides site selection	• Moderate—would assist in understanding salt geomechanics and cavern behaviors	• N/A
Impact of Publicly Available Assessments	• N/A	• N/A	• Moderate—help refine target areas and inform preliminary cavern design but require site-specific verification	• Moderate— would assist in identifying behavior trends for existing caverns	• N/A
Feasibility of Generating Publicly Available Assessments	• N/A	• N/A	• High—nonproprietary geological surveys, drilling reports, and publicly available salt formation maps can be aggregated and expanded to reduce uncertainty	• High—regulatory filings, including mechanical integrity tests and periodic sonar surveys are documented with state and federal authorities	• N/A

Table 1-12. *Key Assessment Characteristics Based on Basin or Asset Maturity for Dynamic Storage in Salt Caverns*

C. Permanent Storage in Porous Media

Permanent storage in porous media involves the long-term containment of fluid byproducts from energy production and industrial processes—most notably carbon dioxide, as well as acid gas and produced water—in deep geologic formations. These storage activities are regulated by the U.S. Environmental Protection Agency Class II or Class VI Underground Injection Control frameworks,[51] depending on the origin and nature of the fluid being stored, and the nature of the host reservoir.

Most storage potential is found in saline aquifers, which are estimated to account for 97% of possible U.S. storage resources.[52] Additional options include producing or pressure-depleted oil and gas reservoirs, which offer well-characterized geology and, in many cases, the potential for enhanced hydrocarbon recovery. These reservoirs are particularly attractive because they can both store carbon dioxide and enhance hydrocarbon recovery, potentially increasing ultimate production. Storage assessments for these reservoirs[53] are generally more mature than estimates of storage resources in other formations.

As suitable reservoirs and/or regional seals do not occur everywhere in the United States, for some regions it may be necessary or convenient to consider a variety of emerging play types. For carbon dioxide storage, these play types include unmineable coal seams, organic shales (with potential for enhanced hydrocarbon production), and basalt formations, or conventional reservoir rocks associated with composite confining systems.[54]

The life cycle of permanent storage in porous media differs from extractive resources. While early stages (frontier, emerging, and developing) are similar as other resources and focus on site identification and characterization, later phases shift to operating/injecting (instead of mature) and post-closure site care instead of revitalizing. The latter—which can easily span a period of 10 to 200 years after injection ceases, depending on the applicable regulations and the permit conditions—emphasizes long-term monitoring to ensure containment and reservoir integrity.

Effective permanent storage in porous media depends on accurate characterization of reservoir capacity, injectivity, and long-term containment, which are defined by a combination of geologic, geophysical, and operational datasets.

1. Principal Subsurface Datasets

Principal datasets for permanent storage in porous media are similar to those used in oil and gas assessments and focus on defining capacity, injectivity, and containment. Core inputs include subsurface maps; well data (e.g., logs, cores, cuttings, and fluid samples); 2D and 3D seismic data; fluid and rock geochemical analyses; and geologic models (Figure 1-13). These datasets are used to characterize reservoir properties (e.g., porosity, thickness) and seal integrity.

Legacy oil and gas data are particularly valuable. Extensive well logs archived by state regulators provide high-resolution information on reservoir and seal properties, enabling basin-scale screening, and in data-rich areas, construction of detailed 3D models. Additional datasets—such as seismicity records, fault and basement maps, groundwater data, pressure regimes, and carbon dioxide infrastructure—further constrain storage potential and site suitability and aid in managing some of the unique risks of permanent storage, such as induced seismicity.

FINDING 1-37: Key datasets for permanent storage of fluids in porous media include well data, seismic and geologic maps, geochemistry and infrastructure information, which together define reservoir capacity, injectivity, and long-term containment.

FINDING 1-38: Legacy oil and gas well data held by states are a critical national asset.

51 U.S. Environmental Protection Agency, *Underground Injection Control Well Classes*, https://www.epa.gov/uic/underground-injection-control-well-classes.

52 National Energy Technology Laboratory, *Carbon Storage ATLAS,* (2015) https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf.

53 Maryana Emad Helmi et al., "Unlocking the Potential of CO_2 Storage in Saline Aquifers: Challenges, Knowledge Gaps, and Future Directions for Large-Scale Storage," *Geoenergy Science and Engineering* (2025), https://doi.org/10.1016/j.ges.2025.100366.

54 Alexander P. Bump et al., "Composite Confining Systems: Rethinking Geologic Seals for Permanent CO_2 Sequestration," *International Journal of Greenhouse Gas Control* 126 (2023), https://doi.org/10.1016/j.ijggc.2023.103908.

that if leveraged fully, would enable higher-resolution and more accurate characterization of many basins, with improved confidence in resource assessments.

2. Assessment Approaches

Assessment approaches for permanent storage in porous media are similar to those used in conventional oil and gas exploration but adapted to storage-specific objectives and reservoir types.[55,56] They evolve across the project life cycle, with uncertainty shifting from resource presence to long-term containment and performance.

a. Frontier Phase

Assessments focus on identifying suitable pore space and confirming the presence of effective confining zones to isolate injected fluids from underground sources of drinking water.

b. Emerging Phase

Efforts refine estimates of storage capacity and evaluate confinement integrity through additional data collection (e.g., appraisal wells) and modeling of reservoir behavior under injection conditions.

c. Developing Phase

Assessments address reservoir and seal heterogeneity, quantify injectivity and storage efficiency, and use simulation to define plume behavior and the area of review. Geochemical interactions between injectate, brine, and rock are also evaluated.

d. Operating Phase

Monitoring and modeling focus on maintaining injectivity, managing pressure, and tracking plume migration, storage complex integrity, and fault stability.

e. Post-Closure Phase

Assessments ensure long-term containment by evaluating plume migration and confirming that injected fluids remain securely stored.

55 Sean T. Brennan et al., *A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage* (U.S. Geological Survey, 2010), http://pubs.usgs.gov/of/2010/1127/.

56 National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition* (2015), https://www.netl.doe.gov/node/5841.

3. Impact Of Publicly Available Data And Assessments

Publicly available data are critical for assessing permanent fluid storage, as these data support site characterization, suitability determination, area-of-review analysis, and overall project feasibility. Their primary impact is improved site selection, leading to more successful site-specific characterization outcomes. Currently, about one-third of wells drilled during site appraisal reveal that storage is either not technically feasible within regulatory constraints or not economically viable.

Enhanced publicly available assessments can significantly improve understanding of site suitability for permanent storage, optimize injection and monitoring/reporting/verification strategies, and better quantify risks related to protection of underground sources of drinking water and induced seismicity. Incorporating the most recent data increases assessment value and improves site selection, which should lead to a higher rate of projects reaching commercial viability.

Feasibility will be dictated by (1) the nature, scope, scale, and frequency of desired assessments; (2) data availability and accessibility; and (3) capacity (financial, personnel, and time) of agencies leading assessment, including the ability to work across agencies and groups. Legacy subsurface data from oil and gas exploration are particularly valuable, but key uncertainties will require additional data collection relating to groundwater, geochemistry, geomechanics, and seismicity. The effectiveness of nationwide assessments will depend on integrating large volumes of existing data—especially well logs in state databases—using modern digital tools to enable efficient analysis.

FINDING 1-39: We estimate that one-third of wells evaluated for permanent storage in frontier and emerging settings are found to be technically or economically unviable. Publicly available resource assessments and standardized, aggregated datasets can reduce this risk by improving transparency, supporting benchmarking, and enabling more efficient early-stage opportunity screening.

	Basin or Asset Maturity				
	Frontier	**Emerging**	**Developing**	**Operating /Injecting**	**Post-Closure Site Care**
Value Drivers	• Pore/pressure space • Sealing formation • Distance to emitter • Depth subsurface • Access to data—often public only	• Effective available pore/ pressure space • Confirmed sealing formation • Better understanding of potential geohazards	• Storable quantities (capacity) • Safe operating pressure with respect to seal • Strategy to avoid/mitigate any eventual geohazards	• Ability to safely meet targets for committed rate and total quantity • Change in reservoir pressure vs. stored quantities	• Verifiable stability of plume • Possibility to terminate or reduce monitoring effort after a period of demonst-rated stability
Principal Uncertainties	• Likelihood of a viable storage complex	• Estimated ultimate storable (EUS) quantities • Storage efficiency • Injectivity establishment • Confining zone seal capacity/mechanical integrity	• EUS • Area of review (AOR) • Injection and confining zone heterogeneity • Storage efficiency • Physicochemical interactions	• EUS • AOR conformance • Injectivity maintenance • Well and confining zone integrity • Tectonic stability • Physicochemical interactions	• AOR conformance • Well and confining zone integrity • Physicochemical interactions
Principal Datasets	• Geologic maps • 2D seismic, magnetic and gravity surveys • Groundwater maps • Legacy well logs	• Multiclient or commissioned 2D or 3D seismic data • Appraisal well logs, tests, rock/fluid samples	• Injection and monitoring well logs, tests, rock/fluid samples	• Historical injection data Continuous monitoring data incl. pressure, microseismic, fiber DTS • Episodic monitoring data: fluid samples, tests, saturation logs, sparse seismic or 4D seismic data	• Continuous monitoring data incl. pressure, microseismic, fiber DTS • Episodic monitoring data: fluid samples, tests, saturation logs, sparse seismic or 4D seismic data

Typical Scales of Investigation	• Regional- or basin-scale	• Basin-, field-, or block-scale	• Field- or block-scale	• Defined by the AOR	• Defined by the AOR
Assessment Approaches	• Focus on the probability of the storage complex (vs. just reservoir) • Integration of maps and seismic with logs or known formation properties (e.g., porosity)	• Basin-scale modeling • Field-scale modeling • Higher reliance on 3D seismic and on legacy well logs • Incorporation of USDOE/RCSP pilot project well data for greater detail on storage-specific uncertainties and geohazards • Appraisal well drilling and evaluation (initially at least, this is carried out by and proprietary to the operator)	• Carried out by the operator • Field-scale modeling, including 3D seismic, legacy well logs, and project appraisal well(s) data, including logs, rock and fluid samples, routine and special core analysis, and well tests • Dynamic simulation is typically carried out to aid in the detailed assessment of possible geohazards	• Carried out by the operator • Dynamic simulation history matching with pressure and mass balance, various monitoring measurements of plume profile and extent	• Carried out by the operator • Acquisition, interpretation and follow up of the monitoring program
Impact of Publicly Available Data	• 2D seismic lines are expected to be more available/practical to use at basin-scale and would enable regional modeling of formation depths, thicknesses, and structure • Publicly available legacy (oil and gas) logs can enable quantitative basinwide porosity models and estimated sealing formation (salt, shale) distribution	• Publicly available 3D seismic would allow better modeling of storage complex size, structure, and potential geohazards at field-scale • Publicly available legacy (oil and gas) logs can enable quantitative basinwide porosity models and estimated sealing formation (salt, shale) distribution	• Can be helpful when the operator has only drilled and evaluated a limited number of wells	• Minimal impact • Data relied upon at this phase is acquired specifically from the operator's field and wells by the operator during appraisal, development, and operations. (It may be disclosed to the state and EPA and thus will be useful to future projects in the basin)	• No impact

Impact of Publicly Available Assessments	• Help prospective storage project operators to understand the location of possible storage resources relative to the source of emission • Better understand the chance of success (COS) • Reduce wasted effort leasing or evaluating nonviable acreage	• Publicly available assessments at a basin-scale would greatly aid operators to select sites within a given basin having a high COS	• Reduced	• Minimal	• N/A
Feasibility of Generating Publicly Available Assessments	• It is highly feasible to generate assessments on a regional/national-scale that deliver added value versus what is currently available.	• At the emerging phase assessments ideally need to go down to a finer scale • In many basins, this is highly feasible given the enormous volume of legacy well logs held in state databases	• At this phase, a useful public assessment would be in the form of a published pilot project from the same formation and basin documenting the key learnings and project performance vis-à-vis the key uncertainties of these projects	• N/A	• N/A

Table 1-13. *Key Assessment Characteristics Based on Basin or Asset Maturity for Permanent Storage*

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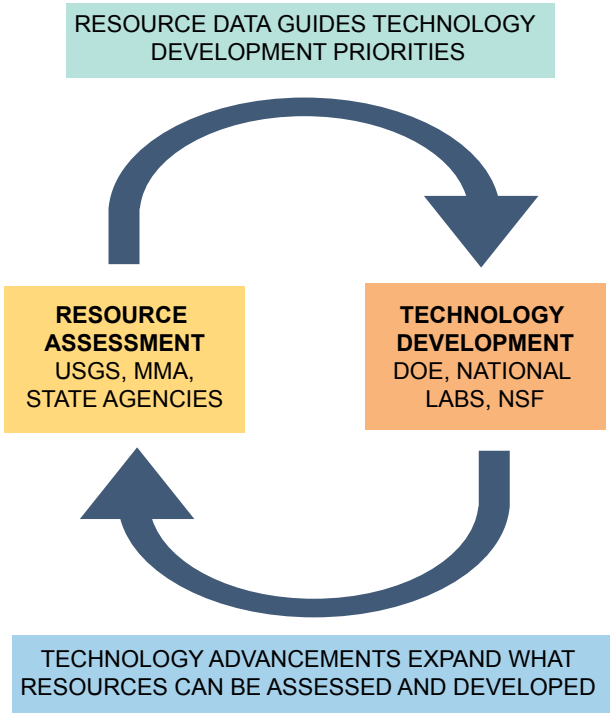
CHAPTER 2 |
SYNTHESIS OF PUBLICLY AVAILABLE SUBSURFACE DATA AND ASSESSMENTS

I. INTRODUCTION

In this chapter, NPC provides an inventory and synthesis of existing federal and state initiatives related to resource characterization and assessment, and technology research, development, and deployment across the United States (Figure 2-1). It reviews the roles, methodologies, and data contributions of key agencies and programs at both levels of government, spanning multiple resource types. In doing so, NPC highlights the substantial capabilities that already exist within state surveys and federal agencies to characterize the nation's resource base, including data collection, geology-based assessments, production and reserves reporting, and technology development and demonstrations. At the same time, NPC highlights an opportunity to complement and enhance the critical ongoing work and service by identifying important gaps in scope, integration, and timeliness, and provide recommendations that would improve decision-relevant understanding of subsurface resource potential. This synthesis identifies both the foundation and limitations of existing public-sector assessment frameworks, setting the stage for resource-specific recommendations in this chapter and cross-sectoral recommendations in Chapter 3.



Note: Both resource assessment and technological development use key datasets provided by a variety of institutions. These include NOAA, NASA, state and federal resource regulatory agencies, and industry.

Figure 2-1. *Primary Missions of Core Agencies in Resource Assessment and Technology Research, Development, and Deployment*

II. KEY OVERARCHING BASELINE GEOLOGIC AND GEOPHYSICAL DATASETS

A. Current Landscape of Government Initiatives

Overarching baseline datasets, collected by federal and state organizations, are foundational to understanding a wide range of resource categories. While some of these datasets are discussed in greater detail in later, resource-specific sections, this section highlights programs and activities that broadly enhance cross-cutting understanding by providing baseline data and geologic context at state and national scales.

The U.S. Geological Survey (USGS) serves as the primary federal geoscience data collection agency and the lead agency for federating many geoscience data types. Core efforts in topographic and geologic mapping, such as the 3D Elevation Program (3DEP)[57] and the National Cooperative Geologic Mapping Program (NCGMP)[58]—provide critical context for subsurface interpretation. Other programs, including Earth Mapping Resources Initiative (Earth MRI), have expanded geophysical and geochemical coverage across the United States through airborne magnetic and radiometric surveys, gravity data acquisition, and other complementary datasets that support integrated subsurface characterization.

State geological surveys are key partners in these data collection efforts, contributing to federal initiatives such as the NCGMP and Earth MRI. However, the ability of state geological surveys to participate in these efforts and initiatives is contingent on federal funding. Many state surveys also lead their own state-level data collection and assessment efforts,[59] further enriching the national data landscape. The results of a state survey taken for this study (Table 2-1) show that data collection and assessments are limited to specific resources in specific areas, and initiatives to assess emerging resources—such as geologic hydrogen and unconventional geothermal—have not materialized at scale.

FINDING 2-1: Resource assessment and data collection programs involving federal and state partnerships have successfully produced cost-effective, standardized collaborative results. One significant gap in these programs is inadequate federal support for assessments of emerging resources. To date, ongoing state partnerships for assessing poorly understood resources such as geological hydrogen and unconventional geothermal have not been developed.

FINDING 2-2: The requirement for matching funds by the state geological surveys has had both positive and negative effects. Matching funds have leveraged federal funds allowing for more productivity, but also have limited opportunities for many state geological surveys to participate in meaningful ways.

Additional federal agencies play important roles in collecting baseline information. The NASA Earth Sciences Division gathers geophysical data through airborne and satellite platforms, including instruments such as the Airborne Visible/Infrared Imaging Spectrometer. Offshore, the Marine Minerals Administration (MMA)[60] and the National Oceanic and Atmospheric Administration (NOAA) collect essential geophysical and bathymetric data through ship-based surveys and through the National Centers for Environmental

57 The USGS 3DEP baseline data is nearly complete for the United States. This program is used for many purposes, including mapping geological structure, stratigraphy, and geomorphology. It is particularly useful in vegetation-covered areas. These data are used in mineral, oil and gas, geothermal, and geologic hydrogen evaluation.

58 The NCGMP was established by the National Geologic Mapping Act of 1992 and reauthorized in 2021 by the Infrastructure Investment and Jobs Act through 2031. The NCGMP was designed to enable general geologic mapping across all 50 states. Funding for the program recently increased to $44.6 million in 2023. This program includes: FEDMAP, a federal mapping initiative; STATEMAP, a state mapping initiative that requires a one-to-one funding match from participating states; and EDMAP, a geologic mapping training program for students that also requires a one-to-one match.

59 Association of American State Geologists, *State Geological Surveys Capabilities Dashboard*, https://www.stategeologists.org/dashboard.

60 The MMA was formerly the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

	State Has Resource	State Unsure If It Has Resource	Published Assessment in Last 10 Years*	Assessment in Progress**
Conventional Oil and Gas	66%	0%	42%	0%
Unconventional Oil and Gas	55%	3%	44%	0%
Conventional Geothermal	55%	10%	56%	13%
Unconventional Geothermal	45%	14%	14%	14%
Conventional Sources of Essential Minerals	97%	3%	48%	16%
Unconventional Sources of Essential Minerals	76%	7%	48%	24%
Coal	72%	0%	29%	0%
Geologic Hydrogen	24%	45%	0%	38%
Subsurface Pore Space of Storage	76%	7%	41%	9%
Subsurface Caverns for Dynamic Storage	48%	7%	13%	0%

Notes: 29 states answered the survey: AK, AR, AZ, DE, FL, IA, IN, KS, KY, MA, ME, MN, MO, MS, MT, ND, NH, NM, NV, OH, OK, OR, PA, TX, UT, VA, VT, WA, and WY.

*States that answered "yes" to having the resource and reported having published an assessment.

**States that answered "yes" and have work in progress or answered "unsure" but have work in progress.

Table 2-1. *Results from NPC Survey of Association of American State Geologists*

Information. Finally, the National Science Foundation (NSF) and the Department of Energy (DOE) support a broader ecosystem of subsurface data collection through research and development funding and awards across the United States.

B. Gaps and Challenges

Despite these extensive federal and state efforts, significant gaps remain in the availability, resolution, and coverage of baseline geologic and geophysical data, limiting their effectiveness for comprehensive resource assessment.

Government-supported surficial mapping programs, such as the USGS's NCGMP that funds mapping by state geological surveys, play a critical role in establishing baseline geologic understanding and identifying areas of potential resource interest. These efforts provide essential context and have substantially advanced knowledge of the nation's surface and near-surface geology. While the NCGMP has provided sustained support for geologic mapping, overall coverage remains limited, with only about 20% of the United States mapped at the regional scale and less than 6% at finer resolutions.[61] This gap persists despite evidence that the cumulative economic benefits of U.S. geologic mapping and its derivative products are at least seven to ten times greater than the cost of production.[62] Similarly, the USGS's Earth MRI program has funded additional regional hyperspectral mapping in the Southwest, yet overall U.S. hyperspectral datasets collected by USGS and NASA across the United States require additional funding to provide complete national coverage. Near-global hyperspectral coverage may become available with the successful launch, currently planned for 2028, of a new thermal infrared satellite being developed in a collaboration between NASA and the Italian Space Agency.[63]

While surficial mapping programs provide essential context, they are inherently limited in their ability to characterize subsurface geology. As a result, key questions regarding resource volume, quality, recoverability, and storage integrity can remain unresolved. Public geophysical data acquired by the USGS, NASA, NOAA, and NSF, including data acquired through Earth MRI since 2019, provides essential datasets for enabling construction of 3D geologic maps and models used in a wide range of resource assessments. Data acquired in the past six years has more than tripled national coverage, and, as of October 2024, approximately 23% of the onshore United States is covered by geophysical data (Figure 2-2). However, throughout much of the country, significantly more data are required to create updated, high-resolution, and continuous geophysical datasets.

FINDING 2-3: Surface mapping programs provide essential geologic context, but resolving questions of subsurface resource volume, quality, recoverability, or storage integrity requires dedicated subsurface characterization.

FINDING 2-4: While recent initiatives under NCGMP, Earth MRI, and related programs have significantly advanced the collection of baseline geologic and geophysical data, more surveys are required to reduce extensive gaps in areal coverage. These gaps include regionally consistent and regularly spaced geophysical surveys (gravity, magnetic, resistivity, hyperspectral, passive seismic, seismic reflection, geodetics, etc.), which will enhance opportunities to apply machine learning and artificial intelligence.

USGS, MMA, and NOAA collect offshore geophysical and bathymetric data. As of 2024, only 54% of the United States' coastal seafloor, marine seafloor, and Laurentian Great Lakes lakebed has been mapped.[64] Less is known about the marine

61 American Geosciences Institute, *Economic Analysis of the Costs and Benefits of Geological Mapping in the United States of America from 1994 to 2019* (2025), https://www.americangeosciences.org/static/pdf/GeoMapAnalysis.pdf.

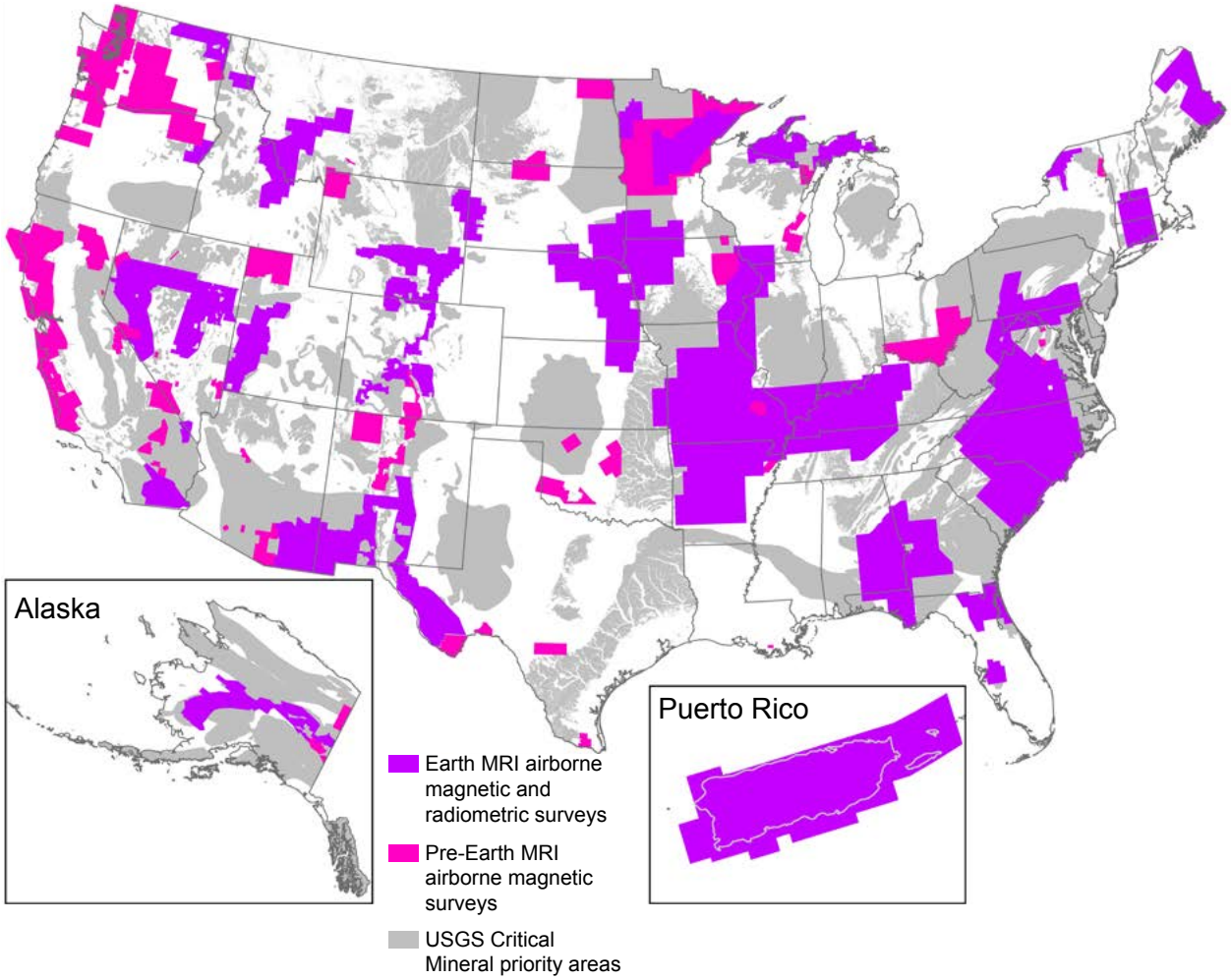
62 American Geosciences Institute, *Economic Analysis of the Costs and Benefits of Geological Mapping in the United States of America from 1994 to 2019* (2025), https://www.americangeosciences.org/static/pdf/GeoMapAnalysis.pdf.

63 NASA, *Surface Biology and Geology Mission*, https://science.gsfc.nasa.gov/solarsystem/projects/621/; USGS, *Surface Biology and Geology Mission*, https://www.usgs.gov/media/images/surface-biology-and-geology-sbg-mission-illustration.

64 Congressional Research Service, *Frequently Asked Questions: Mapping of U.S. Ocean and Coastal Waters*, CRS Report R47623 (2023), https://www.congress.gov/crs-product/R47623#_Toc204787490.

sediments and associated resources in marine sediments below the seafloor and lakebed. Despite the increased commercial interest in seafloor and marine sediments for mineral and other energy-related (e.g., methane hydrates) resources, the recent retirement by NSF of the JOIDES Resolution, a drilling research vessel and the flagship of the U.S.-led International Ocean Discovery Program, has resulted in a hiatus of U.S.-led ocean drilling. Such drilling programs provide important data on the formation and distribution of deep-sea energy and mineral resources.

FINDING 2-5: Gaps in seafloor mapping and subsurface sediment characterization limit the United States' ability to assess offshore mineral and energy resources, a challenge compounded by the loss of the JOIDES Resolution and the resulting hiatus in U.S.-led ocean drilling.



Source: USGS. 2026. https://www.usgs.gov/special-topics/earth-mri/science/earth-mri-progress.

Figure 2-2. *Geophysical, Geological Mapping, Geochemistry, LiDAR, Hyperspectral, Mine Waste Acquisitions from Earth MRI, 2019–2024*

III. CONVENTIONAL AND UNCONVENTIONAL OIL AND GAS RESOURCES

A. Current Landscape of Government Initiatives

The U.S. federal and state governments play a central role in assessing and regulating both conventional and unconventional oil and gas resources. At the federal level, the USGS Energy Resources Program within the Department of the Interior (DOI), is authorized to conduct geology-based assessments of undiscovered, technically recoverable oil and gas resources in priority basins onshore and offshore state waters.[65] While MMA is the lead agency for resource assessments in federal waters, the USGS also conducts assessments in some, but not all, federal offshore basins, separately or in collaboration with MMA.

USGS assessments use probabilistic, play-based methodologies and peer-reviewed approaches (e.g., through the American Association of Petroleum Geologists). Recent updates include the Permian Basin (2025)[66] and the Haynesville Shale plays (2024).[67] These assessments cover both conventional accumulations and unconventional resources, such as shale gas and tight oil, using standardized methodologies applied at the scale of petroleum systems and assessment units. In addition to assessments, the USGS conducts applied research into petroleum systems, including source generation and organic geochemistry, mineralogy, depositional environments and stratigraphy, basin history, tectonics, and field mapping. This research is particularly important in frontier basins.

USGS maintains the only national-scale database of produced-watergeochemistry (Figure 2-3).[68] Within that database are well identifiers and locations as well as associated geologic, physical, and chemical properties, including critical mineral composition and organic characterization data for U.S. oil and gas wells. The USGS has developed a probabilistic methodology for quantifying the volume of water and proppant injection and water production associated with the development of continuous (unconventional) petroleum plays. This methodology directly links to their more recent assessments of undiscovered resources in specific areas, including the Williston Basin and the Gulf Coast. This work provides critical information for future water use planning and waste management in these areas and others as they are assessed.

In addition to conventional and unconventional oil and gas (shale, coalbed methane, and tight reservoirs) assessments, the USGS published an assessment in 2008 of the technically recoverable methane hydrate resource for the North Slope of Alaska and published an update in 2019.[69] The USGS continues to partner with DOE and the Japan Organization for Metals and Energy Security on the Alaska North Slope (Prudhoe Bay) for gas hydrate production testing.[70]

MMA conducts assessments of undiscovered technical and economic recoverable resources on the Outer Continental Shelf (OCS) under the Outer Continental Shelf Lands Act, complementing USGS assessments. These national assessments are completed every five years (most recently in 2026)[71] and support the National OCS Oil and Gas Leasing Program. MMA also maintains an inventory of discovered resources on the OCS, where applicable, including produced volumes,

65 Authorized under the Organic Act of 1879, Energy Act of 2000, and the Energy Policy Act of 2005.

66 USGS, *Permian Basin Oil and Gas Assessments*, https://www.usgs.gov/centers/central-energy-resources-science-center/science/permian-basin-oil-and-gas-assessments.

67 USGS, *Gulf Coast Geologic Energy Assessments* (Energy Resources Program), https://www.usgs.gov/programs/energy-resources-program/science/gulf-coast-geologic-energy-assessments.

68 USGS, *National Produced Waters Geochemical Database, Version 3.0* (2023), https://www.usgs.gov/tools/us-geological-survey-national-produced-waters-geochemical-database-ver-30-december-2023.

69 USGS, *Assessment of Gas Hydrate Resources in the North Slope of Alaska (2018)*, https://www.usgs.gov/centers/central-energy-resources-science-center/science/assessment-gas-hydrate-resources-north-0.

70 USGS, personal communication, April 9, 2026.

71 Bureau of Ocean Energy Management (BOEM), *Assessment of Undiscovered Resources on the United States Outer Continental Shelf, 2026*, https://www.boem.gov/oil-gas-energy/resource-evaluation/undiscovered-resources.

reserves, and contingent resource.[72] In 2012, the MMA (then operating as BOEM) also completed in-place assessments of methane hydrates in the federal OCS,[73] but is currently minimally active in gas hydrates studies.[74]

The DOE plays a complementary role in oil and gas assessments to the DOI's geology-based undiscovered and contingent resource estimates. The U.S. Energy Information Administration (EIA), under DOE, provides annual estimates of proved reserves (e.g., 46.0 billion barrels of oil and 17 trillion m^3 [603.6 trillion ft^3] of gas at year-end 2024),[75] along with production data, short- and long-term energy outlooks, and drilling productivity metrics. The Office of Oil and Gas within the DOE Hydrocarbons and Geothermal Energy Office (HGEO) supports research, development, and demonstration focused on increasing recovery factors in unconventional reservoirs, lowering break-even costs, and beneficial reuse of produced water.[76] HGEO also maintains large-scale data platforms such as the Energy Data eXchange (EDX) and the Global Oil and Gas Infrastructure database.[77] The newly established National Energy Technology Laboratory (NETL) Oil &

72 BOEM, *Discovered Resources* (Outer Continental Shelf Resource Evaluation Program), https://www.boem.gov/oil-gas-energy/resource-evaluation/discovered-resources.

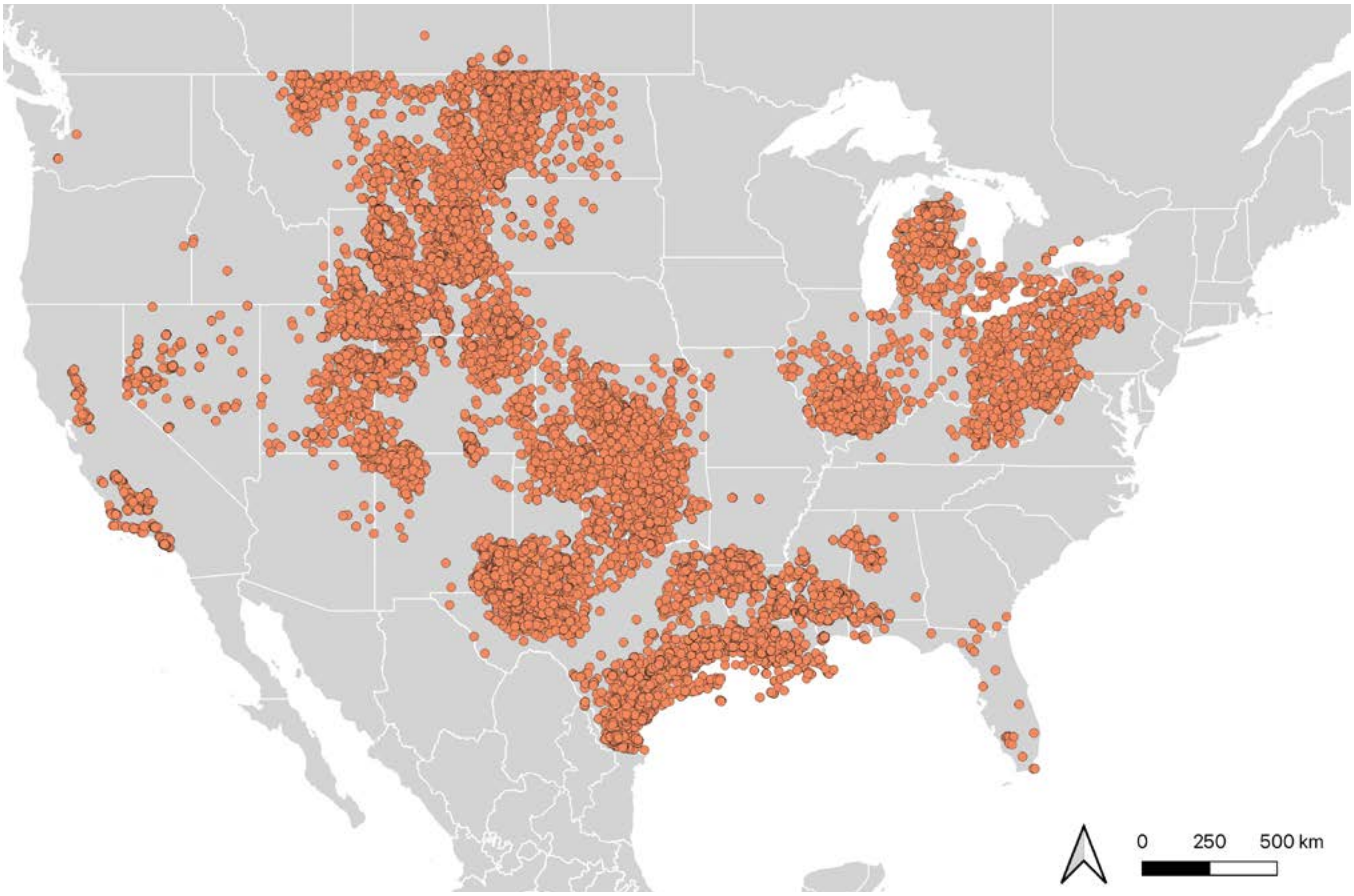
73 BOEM, *Assessment of In-Place Gas Hydrate Resources of the Lower 48 United States Outer Continental Shelf* (BOEM Fact Sheet RED-2012-01, 2012), www.boem.gov/sites/default/files/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Resource_Evaluation/Gas_Hydrates/BOEM-FactSheetRED_2012-01.pdf.

74 BOEM, personal communication, April 7–8, 2026.

75 EIA, *U.S. Crude Oil and Natural Gas Proved Reserves, Year-End 2024* (annual report series), April 27, 2026, https://www.eia.gov/naturalgas/crudeoilreserves/index.php.

76 DOE, *Office of Oil and Gas* (Hydrocarbons and Geothermal Energy Office), https://www.energy.gov/hgeo/office-oil-and-gas.

77 National Energy Technology Laboratory (NETL), *New Global Oil and Gas Infrastructure Database Is One More Way NETL Brings Knowledge to Power*, 2018, https://netl.doe.gov/node/5551.



Source: USGS. "USGS U.S. Produced Waters Database." 2024. https://www.usgs.gov/media/images/usgs-us-produced-waters-database.

Figure 2-3. *Map of Produced Water Locations*

Gas Center of Excellence is poised to advance research on enhanced unconventional recovery techniques and produced-water treatment and use, among other priorities.[78] DOE, with NETL as the lead agency, also plays a role in methane hydrates research (including on the Alaska North Slope in Prudhoe Bay) under the Methane Hydrate Research and Development Program.[79]

RECOMMENDATION 2-1: The NPC recommends DOE continue funding and support for the long-term methane hydrate production test site at Prudhoe Bay. The site's unique infrastructure, well-characterized subsurface data, proven hydrate resources, and instrumented wells provide an unparalleled platform to advance commercial production methods and establish methane hydrates as a significant global resource.

Federal regulatory and revenue-management agencies—including the Bureau of Land Management (BLM), the MMA, Office of Natural Resources Revenue, and the U.S. Forest Service (USFS)—collect data relevant to oil and gas resource assessments. They also, in turn, use assessment data to manage onshore federal mineral estate,[80] plus portions of the OCS under federal leasing, permitting, safety, environmental, and revenue oversight.

At the state level, geological surveys and oil and gas regulatory commissions provide more granular, basin-specific data, well records, and resource characterization tied to development and regulatory oversight. In major producing regions, such as Texas and New Mexico, regulators and geological surveys are developing pilot programs, datasets, and regulatory frameworks to enable produced water reuse, while grappling with disposal constraints and induced seismicity risks.[81, 82] State agencies also are primary data sources for the USGS National Produced Water Geochemical Database.

Together, these federal and state efforts produce a robust, publicly accessible foundation of geologic knowledge, resource estimates, and production data across both conventional and unconventional oil and gas systems.

B. Gaps and Challenges

1. Oil and Gas Assessment Methodology

Despite the breadth of federal and state activity, important gaps remain in the scope of government assessments and how they are integrated. Public-sector resource assessment activities remain somewhat fragmented across agencies and jurisdictions due to differences in agency authorities and responsibilities, data access, budget and workforce capacity, and reporting structures.

A key distinction is that assessments across federal agencies are not always designed to answer the same questions. USGS assessments focus on undiscovered, technically recoverable resources (UTRR) and generally do not account for economic viability, infrastructure constraints, or above-ground risks. USGS basin assessments are conducted on irregular intervals, often spanning 5 to 15 years. In comparison, MMA assessments of conventional oil and gas focus on both UTRR and undiscovered economically recoverable resources (UERR). However, MMA assessments of UTRR and UERR do not include methane hydrates, gas in geopressurized brines, or oil and natural gas that could be present in insufficient quantities or quality (low-permeability "tight" reservoirs) to be produced by conventional recovery techniques.

In practice, government assessments provide a strong geologic data foundation for understanding the resource base, but do not deliver an

78 NETL *Oil & Gas Center of Excellence, Key Facilities & Research*, https://www.netl.doe.gov/centers-of-excellence/oil-gas.

79 Established by the Methane Hydrate Research and Development Act of 2000: U.S. Congress, *Methane Hydrate Research and Development Act of 2000*, H.R. 1753 (106th Congress, 2000), https://www.congress.gov/bill/106th-congress/house-bill/1753.

80 U.S. Department of the Interior, *Division of Mineral Resources*, https://www.doi.gov/solicitor/division-mineral-resources.

81 Texas Produced Water Consortium, *Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward*, 2022, https://www.depts.ttu.edu/research/tx-water-consortium/downloads/22-TXPWC-Report-Texas-Legislature.pdf.

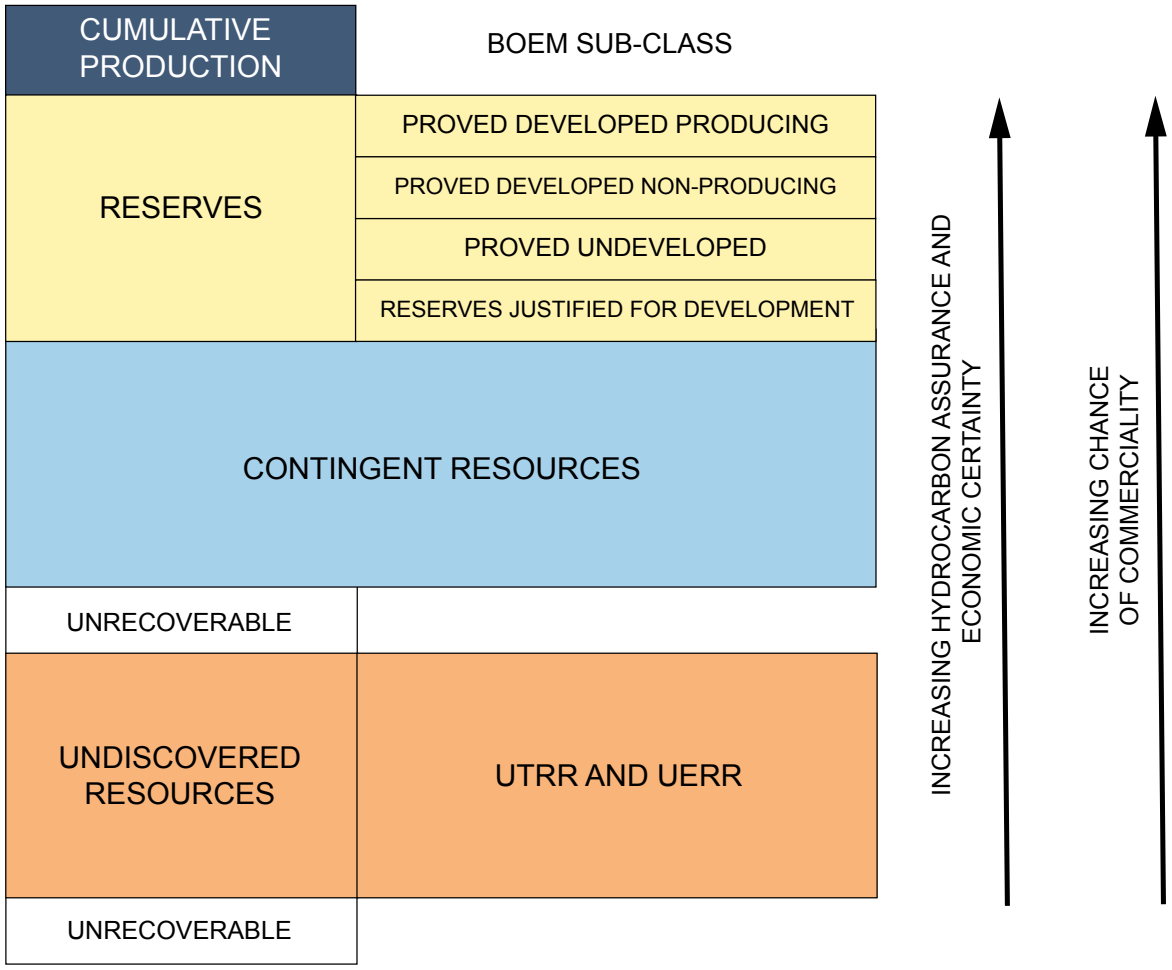
82 Valerie Volcovici, "In Arid New Mexico, Rural Towns Eye Treated Oil Wastewater as a Solution to Drought," *Reuters*, September 11, 2024, https://www.reuters.com/business/environment/arid-new-mexico-rural-towns-eye-treated-oil-wastewater-solution-drought-2024-09-11.

integrated, dynamic view of commercially and operationally realizable supply. To do so at a national level would require significant effort.

The building blocks for such an integrated assessment system would include interagency agreements to use common methodologies for assessing UTRR and UERR, contingent resources, and reserves for both onshore and offshore. In addition, public onshore assessments by the USGS would need to also assess UERR. Contingent resources would need to be assessed for both onshore and offshore and EIA reserves would need to be incorporated into both onshore and offshore assessments.

These structural limitations are compounded by methodological challenges that are particularly acute for unconventional resources. Estimated ultimate recovery assumptions are highly sensitive to factors such as well spacing, completion design, and parent-child well interactions—parameters that are evolving more rapidly than federal assessment cycles can capture.

These gaps highlight a core challenge: While the United States maintains world-leading capabilities in geologic assessment and data collection, it lacks a coordinated, frequently updated, and methodologically consistent framework from undiscovered resource to proven reserves (Figure 2-4) across agencies for translating inputs into a comprehensive, decision-relevant view of oil and gas resource potential.



Note: Not to scale.
Source: BOEM. "2026 National Assessment of Undiscovered Oil and Gas Resources of the U.S. Outer Continental Shelf."

Figure 2-4. *MMA (formerly BOEM) Resource Classification Framework*

FINDING 2-6: The United States has world-leading geologic assessment and data capabilities but lacks a coordinated, frequently updated, and methodologically consistent framework across agencies to translate them into a comprehensive, decision-relevant view of oil and gas resource potential from undiscovered resource to proven reserves.

RECOMMENDATION 2-2: The NPC recommends DOE support unconventional oil and gas reservoir pilot projects to advance recovery technology and to inform USGS's technical recoverable assessments.

RECOMMENDATION 2-3: The NPC recommends USGS, the Marine Minerals Administration, and DOE work toward coordinating existing methodologies into a comprehensive and methodologically consistent oil and gas assessment system that links undiscovered technically and economically recoverable resources, contingent resources, and reserves for both the onshore and offshore.

2. Produced Water Assessments

Similarly, significant gaps and challenges remain in advancing produced water from a managed waste stream to a widely deployable resource. While reuse within oil and gas operations—such as hydraulic fracturing and waterflooding—is increasingly common, broader applications in agriculture, industry, or environmental uses face substantial technical, regulatory, and data-related barriers.[83]

A central challenge is that the composition of produced water varies widely across basins and even within individual fields as a function of geologic, operational, and temporal factors. The composition differences often span orders of magnitude in key constituents and create significant challenges for treatment, risk assessment, and reuse suitability.[84] Broader reuse beyond oilfield applications will require detailed, site-specific geochemical data[85] that are not currently compiled or standardized at a national scale.

FINDING 2-7: Across all major hydrocarbon-producing states, produced water data systems are robust for volumes and operations but systematically lack standardized geochemical data and integrated reuse frameworks, limiting their utility for resource assessment and beneficial reuse.

RECOMMENDATION 2-4: The NPC recommends that USGS continue improving the assessment of produced water as a resource for beneficial reuse by quantifying formation-specific volumes and constituents.

3. Data Standardization And Interoperability

Data standardization and interoperability remain persistent challenges across the U.S. oil and gas data systems, limiting the ability to integrate, compare, and fully leverage available information. Datasets are fragmented across more than half a dozen federal agencies and more than 30 state regulators and geological surveys, each operating under different mandates, data models, and release practices. Additional challenges include inconsistent and noninteroperable metadata between federal and state systems, spatial inaccuracies in legacy datasets, and uneven data accessibility, with some jurisdictions offering modern application programming interfaces (APIs) while others rely on static reports or PDFs.

In addition, inconsistencies across jurisdictions—including how resources and reserves are defined, and variations in formation nomenclature, well status classifications, and measurement

83 NPC, forthcoming report on the beneficial reuse of produced water (December 2026).

84 Ayusha Ariana et al., "Pathways for Potential Exposure to Onshore Oil and Gas Wastewater: What We Need to Know to Protect Human Health," *Geohealth* (2025), https://pmc.ncbi.nlm.nih.gov/articles/PMC11966568.

85 Wenbin Jiang et al., "Characterization of Produced Water and Surrounding Surface Water in the Permian Basin, the United States," *Journal of Hazardous Materials* (2022), https://www.sciencedirect.com/science/article/abs/pii/S0304389422001972.

units—complicate efforts to compare and integrate datasets across state and federal systems. State systems lack consistency in key elements such as well identifiers, formation nomenclature, reporting units, and reporting frequency, which complicates cross-jurisdictional analysis. There is no single national database that integrates well, production, and geologic data across states, and significant volumes of subsurface information, including seismic data, well logs, and performance datasets remain proprietary and inaccessible to public-sector assessors. These challenges are further compounded by the heterogeneity of the data itself. Existing datasets span multiple generations and formats—from raw and unprocessed data to quality-controlled, processed, and fully interpreted products. This raises fundamental questions about how to reconcile, validate, and integrate disparate sources into coherent assessments.

Emerging issues, including the need to incorporate coproduced resources into resource assessments, to integrate carbon capture and storage (CCS) assessments, and to better collect induced seismicity and environmental monitoring data further strain existing frameworks. AI introduces both opportunity and risk: While it offers new pathways to harmonize and analyze large, heterogeneous datasets, it also heightens concerns about the loss of expertise needed to interpret results.

FINDING 2-8: Establishing a national data exchange standard (common schema and APIs), shared identifier conventions, and routine federal-state reconciliation would enable consistent integration and use of subsurface data for national-scale analysis.

IV. CONVENTIONAL AND UNCONVENTIONAL GEOTHERMAL

A. Current Landscape of Government Initiatives

The current landscape of geothermal resource assessment in the United States reflects a growing recognition of geothermal energy's potential across a range of technologies, including conventional hydrothermal systems, enhanced geothermal systems (EGS), closed-loop systems, and emerging supercritical (superhot) rock geothermal. Governmental efforts are primarily led by the USGS, DOE, and various states, with increasing coordination across programs and agencies. Geothermal assessment, exploratory drilling, and demonstration have historically received vastly lower levels of federal funding relative to other energy resources, but recently there has been a paradigm shift in federal support for its advancement and deployment.

The USGS has several authorizations directing it to complete geothermal research and assessment, which are all coordinated by the USGS Geology, Energy, and Minerals Mission Area's Energy Resources Program (ERP).[86] Specific topic areas receive contributions from additional programs, including Earth MRI and multiple science centers such as the Geology, Minerals, Energy, and Geophysics Science Center and the Central Energy Resources Science Center. Geothermal funding in ERP was increased from ~$2.5 million in FY25 to $7.5 million in FY26 and the USGS was directed by the House Appropriation Committee to spend no less than $7.5 million in FY27 on state-by-state geothermal assessments.[87,88] These state-by-state assessments were directed to quantify the resource that could be used for EGS, deep closed-loop systems, and supercritical geothermal systems, which could vastly expand the scale of geothermal energy production. This program signals a renewed federal focus on systematically quantifying geothermal resources nationwide.

One of the most comprehensive geothermal resource assessments was published by USGS in 2008,[89] but was limited to the western United

86 Including the Geothermal Steam Act of 1970, Geothermal Energy Research, Development, and Demonstration Act of 1974, Energy Policy Act of 1992, Energy Policy Act of 2005, Energy Independence and Security Act of 2007, and Energy Act of 2020.

87 House of Representatives, *Department of the Interior, Environment, and Related Agencies Appropriations Bill, 2027* (2026), https://docs.house.gov/meetings/AP/AP00/20260603/119362/HMKP-119-AP00-20260603-SD002.pdf.

88 USGS, *Budget Justifications and Performance Information, Fiscal Year 2027* (U.S. Department of the Interior, 2026), https://www.doi.gov/sites/default/files/documents/2026-04/fy2027greenbookusgs.pdf.

89 As required by the Energy Policy Act of 2005.

States.[90] The Energy Act of 2020 mandated that the USGS update its 2008 geothermal resource assessment, expand the scope of resource types evaluated, and extend geographic coverage to include Alaska, Hawaii, and Puerto Rico.[91] Several new projects led by ERP have begun since this legislation, including the Geothermal Resource Investigations Project, which seeks to better understand geothermal resources through characterization, monitoring, and conducting resource assessments. In 2025, the USGS released two assessments for the Great Basin, a conventional geothermal favorability assessment[92] and an EGS assessment that estimated EGS resources could potentially provide up to 10% of current total U.S. power production capacity.[93]

The DOE complements USGS assessment work through research, development, and demonstration programs, particularly for advancing frontier technologies, including EGS and superhot/supercritical geothermal systems. These include activities within the HGEO, Advanced Research Projects Agency-Energy (ARPA-E), and national laboratories. In 2016, the National Laboratory of the Rockies (NLR, formerly NREL) used the most recent Southern Methodist University temperate-at-depth maps to calculate a deep EGS resource potential estimate of 5,157 GWe.[94] DOE has several ongoing field-scale demonstrations, including the Frontier Observatory for Research in Geothermal Energy (FORGE) and a $20 million superhot EGS project at Newberry Volcano.[95] Other awards are supporting drilling demonstrations and regional partnerships for data collection.[96] In February 2026, DOE announced a $171.5 million funding opportunity to support next-generation geothermal field-scale testing, including EGS field validation, closed-loop, and superhot/supercritical field tests.[97] All Office of Geothermal-funded projects must upload their data to DOE's Geothermal Data Repository, which superseded the National Geothermal Data System.

Several recent interagency collaborations have occurred between USGS and DOE such as Geoscience Data Acquisition for Western Nevada (GeoDAWN), which in 2022 acquired high-resolution airborne magnetic and radiometric data over northern and western Nevada and eastern California.[98] This was followed by GeoFlight in 2023, which acquired high-resolution airborne magnetic and radiometric data over the Salton Trough in Southern California.[99]

Internationally, countries such as Iceland, New Zealand, and Japan continue to lead in geothermal innovation, particularly in high-temperature and magmatic systems. Programs such as Derisking Exploration for Geothermal Plays in Magmatic Environments highlight global efforts across U.S. national laboratories and organizations in Iceland, Norway, Germany, Switzerland, and France to de-risk geothermal exploration in challenging magmatic environments.[100]

FINDING 2-9: Chronic underinvestment in geothermal has constrained resource

90 Colin F. Williams et al., *Assessment of Moderate- and High-Temperature Geothermal Resources of the United States*, USGS Fact Sheet 2008–3082 (2008), https://www.usgs.gov/node/99250.

91 Erick R. Burns, Colin F. Williams, and Jacob DeAngelo, *Enhanced Geothermal Systems Electric-Resource Assessment for the Great Basin, Southwestern United States*, USGS Fact Sheet 2025–3027 (2025), https://doi.org/10.3133/fs20253027.

92 Stanley P. Mordensky et al., "Favorability Mapping for Hydrothermal Power Resource Assessments of the Great Basin, USA," *Geothermics* (2025), https://www.sciencedirect.com/science/article/pii/S0375650525002019?via%3Dihub.

93 Erick R. Burns, Colin F. Williams, and Jacob DeAngelo, *Enhanced Geothermal Systems Electric-Resource Assessment for the Great Basin, Southwestern United States*, U.S. Geological Survey Fact Sheet 2025–3027 (2025), https://doi.org/10.3133/fs20253027.

94 Chad Augustine, National Renewable Energy Laboratory (NREL), *Update to Enhanced Geothermal System Resource Potential Estimate* (2016), https://docs.nlr.gov/docs/fy17osti/66428.pdf.

95 DOE, "Heating Things Up: GTO's Superhot Rock Research Breaking New Ground," *Geothermal Technologies Office*, January 14, 2025, https://www.energy.gov/hgeo/geothermal/articles/heating-things-gtos-superhot-rock-research-breaking-new-ground.

96 DOE, *Regional Partnerships in Geothermal Data* (Geothermal Technologies Office), https://www.energy.gov/hgeo/geothermal/regional-partnerships-geothermal-data.

97 DOE, *Energy Department Announces $171.5 Million to Expand U.S. Geothermal Energy*, February 25, 2026, https://www.energy.gov/articles/energy-department-announces-1715-million-expand-us-geothermal-energy.

98 USGS, *GeoDAWN Airborne Magnetic and Radiometric Surveys for the Northwestern Great Basin, Nevada and California* (2024), https://www.usgs.gov/data/geodawn-airborne-magnetic-and-radiometric-surveys-northwestern-great-basin-nevada-and.

99 USGS, *GeoFlight Airborne Magnetic and Radiometric Surveys of the Salton Trough, Southern California* (2025), https://www.usgs.gov/data/geoflight-airborne-magnetic-and-radiometric-surveys-salton-trough-southern-california.

100 Amanda Kolker et al., *DEEPEN: DErisking Exploration for Geothermal Plays in Magmatic ENvironments: Cooperative Research and Development (Final Report)* (2025), OSTI, https://www.osti.gov/biblio/2565646.

assessment, technology development, and deployment and recent funding requests signal the need for a sustained increase in federal support.

B. Gaps and Challenges

Although several national and regional assessments have been conducted, they have mostly relied on the same sets of input data, which are sparse, inconsistent across scale and resolution, and have limited coincident coverage. In 2021, NLR indicated that broad areas of the Western United States estimated to have geothermal potential lack sufficient geologic and geophysical coverage necessary for even regional resource exploration.[101] Reliable geothermal assessment depends on robust geologic context, including consistent mapping and geophysical data across regions. However, key foundational datasets—such as unified, full coverage depth-to-basement maps[102] and improved national-scale 3D geologic models—remain incomplete or unavailable. In addition, the availability and accessibility of high-quality thermal measurements remain limited, including shallow (e.g., 2 m) measurements, regional temperature gradients, equilibrated bottom-hole temperature (BHT) measurements and continuous temperature-with-depth logs in existing wells, and temperature gradients in basement rocks underlying sedimentary basins to determine formation-specific geothermal gradients and guide basin-specific BHT corrections. The lack of high-quality thermal measurements and high-pressure/high-temperature rock property measurements significantly constrain assessment accuracy. While some of this information may not yet exist for all areas with consistent resolution, other valuable subsurface data relevant to geothermal resources—particularly from those planned for abandonment—are at risk of being lost without coordinated preservation efforts.

Recent USGS Earth MRI efforts, such as GeoDAWN, serve as valuable examples of how public funding can add significantly to necessary foundational resource assessment data. Additional ongoing efforts, such as the North Dakota Geological Survey temperature logging campaign,[103] demonstrate scalable approaches that could significantly improve thermal characterization if implemented nationwide.

FINDING 2-10: Many recent geothermal resource assessments have continued to rely on previously compiled datasets with inconsistent resolution and coverage, rather than incorporating substantial new data. A major update to underlying datasets will be required to advance the geothermal industry.

FINDING 2-11: Reliable geothermal resource evaluation requires comprehensive geologic context, such as depth-to-basement maps and national-scale 3D geologic models, which are currently lacking.

FINDING 2-12: Reliable regional geothermal resource assessments require detailed lithologic and thermal models that span not only a broad areal extent but also depth interval.

FINDING 2-13: Geothermal-relevant subsurface data are at risk of loss without coordinated preservation and data stewardship efforts.

101 Greg Rhodes et al., *Analysis of Selected Publicly Available Geothermal Exploration Data Gaps* (National Renewable Energy Laboratory), https://publications.mygeoenergynow.org/grc/1034448.pdf.

102 USGS, *3D Geologic Framework for Use with the U.S. Geological Survey National Crustal Model for Seismic Hazard Studies* (Version 2.0 September 2025), https://www.usgs.gov/data/3d-geologic-framework-use-us-geological-survey-national-crustal-model-seismic-hazard-studies.

103 Travis Stolldorf, "Using Static Temperatures to More Accurately Predict Geothermal Gradients in the Williston Basin," *Geo News* (North Dakota Geological Survey *Geo News*, Winter 2020), https://www.dmr.nd.gov/ndgs/documents/newsletter/2020Winter/Using_Static_Temperatures_to_More_Accurately_Predict_Geothermal_Gradients_in_the_Williston_Basin.pdf.

RECOMMENDATION 2-5: The NPC recommends DOI and DOE increase the acquisition of thermal, hydraulic, mechanical, and chemical data through drilling of new research wells and from wells of opportunity (e.g., oil and gas wells planned for abandonment, orphaned wells under state/federal oversight) and support laboratory and demonstration-scale testing under high-pressure/high-temperature conditions across diverse geologic settings.

RECOMMENDATION 2-6: The NPC recommends DOI and DOE consider assuming ownership of, or creating a program that enables access to, a limited number of distributed deep wells for core and fluid collection, instrumentation, monitoring, potential deepening, and additional demonstrations of unconventional geothermal technologies.

Superhot geothermal holds significant potential[104] as it can yield as much as an order of magnitude greater electric power per well (>30 MWe).[105] However, no superhot well to date has been sustainable, and actual production requires wells to be sustainable over many years. Only one site in the United States, the Geysers geothermal field in California, has recorded superhot temperatures, which are typically beyond the operating envelope of most instruments and equipment. The field will not advance without new efforts in materials science and engineering for tubulars, drill bits, valves, cement, accommodation for thermal expansion of casing, and extreme sensors. The temperature conditions in superhot geothermal settings are akin to extreme planetary environments. Indeed, bottom-hole conditions in the Iceland Deep Drilling Project (2.1 km), Krafla Caldera, Iceland, resemble the surface of Venus. Also, experiments are needed on very high-temperature "cloud" and thermal fracturing, to build on what has been accomplished in Japan.[106]

The United States currently lacks a government-supported testbed framework comparable to those in countries such as New Zealand, Japan, and Iceland. It also does not have a project at the scale of the original EGS initiative, the Hot Dry Rock Project at Los Alamos, or the Salton Sea Scientific Drilling Program, which was the first large-scale drilling project of the U.S. Continental Scientific Drilling Program.[107] A public-private partnership would address this gap, especially if it were designed with a high degree of transparency. One possible model would include mechanisms such as time-limited data embargoes for participating entities, similar to the approach used by the NSF-supported International Scientific Continental Drilling Program.

FINDING 2-14: Basic research, development, and deployment is needed to further advance the unconventional geothermal industry. This could occur through the development of public-private partnerships.

RECOMMENDATION 2-7: The NPC recommends DOE and NSF advance material science research and demonstrations to develop drilling capabilities and processing equipment in superhot conditions.

V. CONVENTIONAL AND UNCONVENTIONAL ESSENTIAL MINERALS

A. Current Landscape of Government Initiatives

The current landscape of federal and state resource assessments for conventional mining of essential minerals reflects a long-standing but

104 Jenna Hill, *A Technology Road Map for Next-Generation Geothermal,* (2025), Clean Air Task Force, https://www.catf.us/wp-content/uploads/2025/09/CATF_SHRTechRoapMapReport_Digital_09.18.25.pdf.

105 Trenton T. Cladouhos and Owen A. Callahan, "Heat Extraction from SuperHot Rock—Technology Development," *Proceedings, 49th Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-227 (2024), https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Cladouhos.pdf.

106 Noriaki Watanabe et al., "Cloud-Fracture Networks as a Means of Accessing Superhot Geothermal Energy," *International Journal of the Japanese Symposium on Rock Mechanics* 16, no. 1 (2020), https://www.jstage.jst.go.jp/article/ijjsrm/16/1/16_1/_pdf/-char/en.

107 John H. Sass, "Salton Sea Scientific Drilling Program," *Earthquakes & Volcanoes* 20, no. 4 (1988): 156–160, https://pubs.usgs.gov/publication/70168823.

unevenly coordinated set of programs focused on geologic mapping, mineral occurrence documentation, and deposit-scale characterization. Federal leadership for mineral assessments is centered within the USGS,[108] whose Minerals Resources Program (MRP) provides the nation's primary public-sector capabilities for identifying and mapping mineral resources.[109] MRP programs, including Earth MRI, integrate geologic mapping, airborne geophysics, geochemistry, and mineral systems analysis to characterize the distribution and potential of essential minerals across the United States. USGS also maintains the Mineral Resources Data System, the U.S. Mineral Deposit Database, and the National Minerals Information Center, which collectively provide national-scale information on mineral occurrences, deposit types, production histories, and material flows. These datasets support federal assessments mandated under the Energy Act of 2020, including periodic updates to the U.S. critical minerals list[110] and national evaluations of supply risk, import reliance, and domestic resource potential.

USGS initiatives related to unconventional mineral resource assessment are rapidly evolving. Earth MRI, in particular, represents a major expansion of USGS's investment in high-resolution geoscience data applicable to both conventional and unconventional systems. USGS also maintains national-scale datasets such as the National Produced Waters Geochemical Database and has identified 46 of the 60 currently designated critical minerals in produced-water samples, highlighting its potential as an unconventional resource stream.[111] Concentrations and diversity of these elements vary by basin, with comparatively fewer critical minerals observed in produced waters from the Appalachian Basin, Bakken, and Permian shale plays.[112] Ongoing USGS and DOE/NETL research indicates that while most occurrences are at low concentrations, certain basins and formations show localized enrichment of elements such as lithium, rare earth elements, and bromine—suggesting potential opportunities for selective recovery where geochemistry, volumes, and treatment technologies align.[113] USGS has also recently published assessments of critical minerals in mine waste repositories and coal ash basins. Through Earth MRI, the Produced Waters Database, and new brine-chemistry and mine-waste mapping initiatives, USGS is filling critical data gaps that guide private-sector exploration.

In addition to mineral resources on land, MRP also provides research and resource assessment support to MMA and NOAA in their responsibilities to explore the seabed and regulate marine mineral production in national (MMA) and international (NOAA) waters. These three agencies led development of the U.S. Offshore Critical Minerals Mapping Plan,[114] and are collaborating on expeditions to implement the plan and advance understanding of the potential to develop critical marine mineral production. To help inform these efforts, the National Academies have begun a study that will recommend a research strategy.[115]

DOE complements USGS assessment efforts through research, development, and demonstration programs that advance extraction, processing, and materials-refining technologies relevant to conventional critical-mineral mining. DOE's Advanced Materials and Manufacturing Technologies Office and the Critical Materials Institute support improvements in mineral processing, separation science, and metallurgical recovery for hard-rock and other conventional feedstocks.

108 Authorized to do research on minerals by the Organic Act of March 3, 1879, Energy Act of 2020, Infrastructure Investment and Jobs Act 2021, as well as Executive Orders 13817 and 14241.

109 The annual appropriated funding level for MRP as varied between ~$69–$75 million (FY2022–FY2026). Of this total, ~$11 million is allocated for Earth MRI. Earth MRI data collection and mapping have been accelerated through $320 million in supplemental funding under the IIJA, provided at a level of $64 million per year from FY2022 through FY2026.

110 Authorized by EO 13817 and the Energy Act of 2020.

111 DOE, *Produced Water from Oil and Gas Development and Critical Minerals* (Fact Sheet, June 2024), https://bit.ly/4i5EdWx.

112 DOE, *Produced Water from Oil and Gas Development and Critical Minerals* (Fact Sheet, June 2024), https://bit.ly/4i5EdWx.

113 USGS, *USGS U.S. Produced Waters Database* (image, September 24, 2024), https://www.usgs.gov/media/images/usgs-us-produced-waters-database.

114 Requested by EO 14285: Unleashing America's Offshore Critical Minerals and Resources, https://www.presidency.ucsb.edu/documents/executive-order-14285-unleashing-americas-offshore-critical-minerals-and-resources.

115 National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Seabed Critical Mineral Resources* (Project DELS-OSB-24-04), https://www.nationalacademies.org/projects/DELS-OSB-24-04.

NETL contributes expertise in geologic characterization, advanced imaging, and materials analysis, while maintaining large-scale data platforms such as the EDX. Together, these programs strengthen national capabilities in ore characterization, beneficiation, and extractive metallurgy—key components of assessing and developing conventional critical-mineral resources.

Additionally, the DOE plays a central role in advancing the recovery of essential minerals from unconventional resources through research, development, and demonstration programs focused on fluid chemistry, selective extraction, and materials separation. These investments span geothermal brines, oilfield produced waters, mine tailings, coal-combustion residuals, and deep saline formations, reflecting a broad federal commitment to diversifying domestic mineral supply.

DOE's funding has enabled rapid progress across multiple unconventional resource pathways. Recent awards include $10.9 million for direct lithium extraction technologies in geothermal systems, $25 million through ARPA-E's RECOVER program for wastewater-mining innovations, and more than $8 million for university-led extraction research targeting produced waters. At the demonstration scale, DOE has committed $225 million to a lithium-extraction plant in the Smackover Formation and provided a $1.4 billion loan guarantee for the nation's first commercial geothermal lithium facility at the Salton Sea. Similar investments are advancing rare-earth recovery from coal ash and acid mine drainage, with Bipartisan Infrastructure Law-funded front-end engineering studies laying the groundwork for the first U.S. demonstration plant. Together, these programs strengthen national capabilities in characterizing, extracting, and processing essential minerals from brines, tailings, coal combustion residuals (CCR), and other unconventional sources—key components of evaluating and developing these emerging resource pathways.

Complementing these research and assessment activities are a suite of other federal research and regulatory activities. The Office of Surface Mining Reclamation and Enforcement maintains extensive datasets on coal mines and associated waste streams. BLM and the USFS oversee mineral access and environmental compliance on federal lands, maintaining extensive permitting, land status, and operational datasets. The Environmental Protection Agency (EPA) maintains regulatory and environmental monitoring data for CCR units and underground injection wells.

At the state level, geological surveys and mining agencies provide the foundational deposit-scale geoscience information that underpins conventional essential mineral exploration and development. These agencies maintain detailed geologic mapping, mineral occurrence databases, historical mine records, and mine waste inventories, along with permitting and land status information essential for project planning. Many states operate long-running mineral resource mapping programs, conduct airborne geophysical surveys, and curate drill core libraries and geochemical datasets that complement federal efforts. Although the scope and maturity of these state systems vary widely, together they supply the high-resolution geological, structural, and geochemical data required to characterize ore systems, refine exploration targets, and support national-scale synthesis by federal agencies.

State geological surveys and environmental, water, and oil and gas agencies also provide many of the foundational datasets required to assess unconventional sources of essential minerals. These agencies maintain produced-water chemistry records, oil and gas well logs, injection well data, geothermal field information, and inventories of mine tailings, waste rock, and coal combustion residuals. They also collect site-specific environmental and hydrological data—such as water quality measurements, discharge volumes, and waste management records—that are essential for evaluating resource potential, environmental liabilities, and processing constraints. Many states operate long-running produced-water sampling programs, maintain detailed oil and gas field databases, or curate mine waste and legacy site inventories that complement federal datasets. Although the scope and maturity of these systems vary widely, together, they provide the high-resolution operational, geochemical, and environmental information needed to

characterize unconventional resource potential and support national-scale synthesis by federal agencies.

Together, these federal and state initiatives form a substantial foundation for understanding the nation's conventional mineral resource base. However, they remain distributed across multiple agencies, vary in update frequency, and are not integrated into a unified national assessment of economically viable mineral supply.

B. Gaps and Challenges

1. Assessment Methodology

Despite strong geologic capabilities, the United States lacks a coordinated, consistently updated national framework for assessing conventional mineral resources. Federal assessments for conventional minerals focus primarily on geologic potential—mapping mineral systems, identifying permissive tracts, and documenting known deposits—rather than providing a dynamic view of economically recoverable supply. Existing efforts for unconventional minerals are distributed across programs designed for geothermal energy, oil and gas operations, mine reclamation, or waste management—not mineral resource assessment. As a result, methodologies differ widely in scope, resolution, and intended use.

These methodological challenges further complicate assessment efforts. Many conventional minerals occur as byproducts or in complex, polymetallic systems, making them difficult to quantify using traditional deposit-scale approaches. Resource estimates are often insensitive to assumptions about ore grades, mineralogy, processing behavior, and market conditions, which vary across deposit types and are not consistently captured in public datasets. In addition, many U.S. mineral belts lack modern geophysical coverage, high-resolution geochemistry, or updated geologic mapping, which limit the ability to delineate permissive tracts or identify new exploration targets.

Unconventional systems present unique technical challenges. Fluid-dominated resources such as geothermal and produced brines require integrated thermal-hydrological-geochemical modeling to understand fluid pathways, mineral solubility, and long-term system behavior. Solid waste systems such as tailings and CCR require detailed mineralogical and metallurgical characterization to evaluate recoverability, heterogeneity, and environmental constraints. Deep saline formations require reservoir modeling and geochemical analysis to assess injectivity, brine composition, and potential for co-production. Despite this progress, the funding landscape remains uneven across resource types and stages of development. Geothermal and deep-saline brines are advancing toward commercial deployment, while oilfield brines, coal ash, and mine tailings remain largely at the pilot stage due to technical, economic, and regulatory barriers. Feedstock variability, low metal concentrations, high processing costs, and complex permitting requirements continue to limit private investment, making federal support essential for de-risking early projects and demonstrating economic viability at scale.

Overall, the current funding environment reflects a significant federal commitment to essential mineral recovery but also underscores the need for sustained, coordinated investment. Assessment cycles are also irregular and often tied to episodic funding, resulting in uneven geographic coverage and long intervals between updates. While Earth MRI has accelerated data acquisition in priority regions, many areas with potential for essential minerals have not been systematically evaluated in decades. Many datasets—particularly those related to fluid chemistry, mine waste inventories, and CCR composition—are incomplete, outdated, or inconsistent across jurisdictions. Proprietary constraints further limit access to high-resolution subsurface data, especially for produced brines and deep saline formations. The funding landscape for unconventional minerals remains uneven across resource types and stages of development, underscoring the need for sustained, coordinated investment to bridge the gap between promising pilot projects and reliable domestic production. Continued alignment of DOE's technology programs with USGS's resource-characterization efforts will be critical to maturing these emerging supply chains and reducing U.S. dependence on foreign sources of essential minerals.

FINDING 2-15: The United States maintains strong geologic assessment capabilities for essential minerals but lacks a unified, regularly updated national framework that integrates geologic, geochemical, hydrological, and metallurgical considerations into a decision-relevant view of domestic supply potential.

RECOMMENDATION 2-8: The NPC recommends policymakers, USGS, DOE, state geological surveys, and industry partners establish a coordinated national minerals program by 2029 that restores the integrated capabilities once housed in the former U.S. Bureau of Mines—linking geologic assessment, extractive metallurgy, mineral processing research, and pilot-scale demonstration.

This program should do the following:

- Expand the Earth Mapping Resource Initiative to produce national scale prospectivity maps using integrated geologic, geophysical, geochemical, and mineral systems modeling.
- Launch a national mineralogy and metallurgy program that requires all federally funded essential minerals projects to include early stage mineralogical characterization and bench-scale metallurgical testing.
- Establish at least three multisite mineralogical and metallurgical testbeds to benchmark extraction performance across conventional and unconventional feedstocks.

RECOMMENDATION 2-9: The NPC recommends USGS, in coordination with DOE and state geological surveys, implement by 2028 a unified national framework for minerals assessment and processing. This framework should publish resource-specific assessment playbooks that define sampling protocols and minimum dataset requirements—including geologic, geophysical, geochemical, drilling, mineralogical, metallurgical, geotechnical, and environmental data—for each resource maturity stage.

2. Data Standardization And Interoperability

Data standardization challenges are pervasive across the essential mineral resource domain. Federal and state datasets differ in nomenclature, spatial resolution, data models, and reporting practices, complicating efforts to integrate information across jurisdictions. Mineral occurrence databases contain records spanning multiple decades and levels of detail, with inconsistent metadata, variable coordinate accuracy, and heterogeneous classification systems. Many legacy datasets remain undigitized or lack modern geospatial attributes, which limits their utility for national synthesis.

Data standardization challenges are particularly acute for unconventional resources, which span multiple regulatory and operational domains. Fluid chemistry datasets vary in sampling protocols, analytical methods, and reporting formats, complicating comparisons across basins. Mine waste and CCR datasets differ in classification systems, spatial resolution, and metadata completeness. Subsurface datasets for deep saline formations and geothermal systems are distributed across energy, environmental, and land-management agencies with limited interoperability.

Subsurface datasets—such as drill core logs, assay results, geophysical surveys, produced-water chemistry, geothermal reservoir properties, mine-waste mineralogy, and CCR composition—are often proprietary or held by private companies, restricting public-sector assessors' ability to characterize deposit geometry, grade distribution, and mineralogical complexity. Even where data exist, differences in sampling protocols, analytical methods, and reporting standards hinder comparability across regions and deposit types. Identifier mismatches across federal and state systems (e.g., well IDs, facility IDs, and mine IDs) further hinder integration. Many legacy datasets lack geospatial accuracy or standardized

mineralogical descriptors, which limits their utility for modern assessments. Meanwhile, emerging analytical tools such as hyperspectral imaging, ML, and automated mineralogy require standardized, high-quality datasets that are not yet widely available.

FINDING 2-16: A national, interoperable data architecture—spanning geologic, geophysical, geochemical, and mineralogical datasets—is essential for modern mineral resource assessments but remains underdeveloped and inconsistently implemented across federal and state systems.

3. Interagency Collaboration

Institutional constraints compound these technical challenges. Federal and state agencies face declining funding, workforce shortages, and limited capacity to modernize data systems or reconcile datasets across programs. The dissolution of the U.S. Bureau of Mines (USBM) in 1996 eliminated the nation's only federal entity with a unified mandate for mineral exploration, extractive metallurgy, mine engineering, and mineral processing research. When USBM was disbanded, its functions were divided across multiple agencies—USGS assumed responsibility for mineral resources and data collection; National Institute for Occupational Safety and Health inherited mine safety research; and DOE absorbed portions of materials science and processing research and development. However, no single agency retained USBM's integrated capability to link geologic characterization, mineral processing, extractive metallurgy, and mine engineering innovation under one coordinated mission. As a result, today's federal landscape is fragmented: USGS focuses on geology and assessments, DOE on materials processing and technology development, and BLM and state agencies on permitting and site-specific oversight. This division leaves persistent gaps in mineral processing research, pilot-scale demonstration, and the translation of resource assessments into deployable domestic production.

The Critical Materials Collaborative, established by DOE to enhance intra-agency, inter-agency, and cross-sector coordination of critical materials activities from prospecting to manufacturing, shows good progress toward increased efficiency and communication. This has enabled formal collaboration across DOE offices and NSF, as well as informal relationships with other federal agencies.

The National Science and Technology Council is the cabinet-level council of advisers to the president on science and technology and serves as the principal means by which the executive branch coordinates science and technology policy across the federal research and development enterprise. The Critical Minerals Subcommittee[116] within Office of Science and Technology Policy is responsible for coordinating federal science and technology efforts for critical mineral supply chain resiliency. However, its funding is not specified and instead supported through member agency budgets. Additionally, the subcommittee has met only a few times during the Trump administration.

FINDING 2-17: Further progress in building out the interagency and intersector partnerships for the critical minerals collaborative would be useful to further improve efficiency and communication.

VI. COAL

A. Current Landscape of Government Initiatives

Coal resources and reserves in the United States are among the most comprehensively documented of any domestic energy resource. Both thermal and metallurgical coal deposits have been mapped extensively, with estimates suggesting that available U.S. reserves could last up to 400 years under current assumptions. However, this long-term resource availability contrasts with the projected economic lifespan of existing coal-fired power plants, many of which have been closed due to environmental and economic pressure associated with increased competition from

116 Codified in 2021 in the IIJA.

natural gas.[117] Coal is projected to drop to 3% or 9% (depending on the EIA AEO2026 case) of U.S. electricity energy generation by 2035, from 17% in 2025.[118]

As a result, emphasis has shifted away from primary resource identification of mineable coal assets toward in situ development and technological innovation. The DOE has prioritized funding for plant modernization, alternative uses of coal, carbon management, and recovery of critical minerals from coal and mine waste. For example, in September 2025, DOE announced $625 million in funding to reinvigorate and expand the coal industry, including support for recommissioning and retrofitting plants, improving rural energy affordability, advancing wastewater management systems, and enabling dual fuel and natural gas cofiring capabilities.[119] A subsequent February 2026 announcement allocated $175 million toward coal plant modernization.[120]

In parallel, a robust ecosystem of federal data products continues to support coal resource understanding. The USGS plays a central role in coal resource assessment, particularly on federal lands. This responsibility continues today, as demonstrated by the work toward the release of an updated coal resources and reserves overlapping federal lands map.[121] Earlier foundational efforts included the National Coal Resources Data System (NCRDS), active from approximately 1975, which is a cooperative program between USGS and state geological surveys.[122] While the NCRDS is still active, it has not made any recent awards to state surveys. Similarly, the National Coal Quality Inventory,[123] conducted roughly between 1999 and 2005 in partnership with DOE, USGS, and the Electric Power Research Institute, provided detailed coal quality data through another federal-state collaboration.[124]

The EIA maintains the Coal Reserves Database[125] and publishes the "Annual Coal Report,"[126] along with frequent updates on production, consumption, and pricing. DOE's Coal Data Collection[127] platform provides both domestic and international datasets. Meanwhile, legacy systems such as USGS NCRDS remain important repositories, housing stratigraphic (USTRAT), geochemical (USCHEM/COALQUAL), and historical resource estimate (USCOAL) data.[128]

FINDING 2-18: Coal is a mature resource relative to other energy/mineral resource assessments.

B. Gaps and Challenges

Coal resource assessment in the United States faces relatively few traditional gaps. Compared to other energy and mineral resources, coal is considered a mature resource with well-established methodologies, datasets, and institutional knowledge. There are few gaps in resource assessments.

117 EIA, "Most of the planned coal capacity retirements are in the Midwest of Mid-Atlantic regions," *Today in Energy*, July 14, 2025, https://www.eia.gov/todayinenergy/detail.php?id=65744.

118 EIA, *Annual Energy Outlook 2026*, Table 8, "Electricity Supply, Disposition, Prices, and Emissions," https://bit.ly/45Tg2TW.

119 DOE, *Energy Department Announces $625 Million Investment to Reinvigorate and Expand America's Coal Communities*, September 29, 2025, https://www.energy.gov/articles/energy-department-announces-625-million-investment-reinvigorate-and-expand-americas-coal.

120 DOE, *Energy Department Announces $175 Million to Modernize Coal Plants, Keeping Affordable Reliable Power Online for Americans*, February 11, 2026, https://www.energy.gov/articles/energy-department-announces-175-million-modernize-coal-plants-keeping-affordable-reliable.

121 As directed by EO 14261, https://www.presidency.ucsb.edu/documents/executive-order-14261-reinvigorating-americas-beautiful-clean-coal-industry-and-amending.

122 USGS, *National Coal Resources Data System*, Geology, Energy & Minerals Science Center, May 31, 2022, https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/national-coal-resources-data-system.

123 USGS, *National Coal Quality Inventory (NaCQI) and U.S. Geological Survey Coal Quality Databases*, Fact Sheet FS-120-99 (1999), https://pubs.usgs.gov/fs/1999/0120/report.pdf.

124 USGS, *National Coal Quality Inventory (NaCQI), Final Technical Report* (June 14, 2006), https://www.osti.gov/servlets/purl/891305-eYDNO0/.

125 EIA, *U.S. Coal Reserves: With Data for 2024* (November 19, 2025), https://www.eia.gov/coal/reserves/.

126 EIA, *Annual Coal Report* (November 19, 2025), https://www.eia.gov/coal/annual/.

127 EIA, *Coal Data Collection* (Data.gov dataset), https://catalog.data.gov/dataset/coal-data-collection.

128 USGS, *National Coal Resources Data System (DCRDS)*, Geology, Energy & Minerals Science Center (May 31, 2022), https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/national-coal-resources-data-system.

As a result, the need for new large-scale resource identification efforts is limited.

However, this maturity also introduces challenges. Much of the foundational data infrastructure—such as NCRDS and earlier cooperative programs—has seen reduced activity or funding in recent years. While these systems remain valuable, sustaining and updating them to reflect modern analytical techniques and emerging priorities (e.g., critical mineral recovery from coal and waste streams) may require renewed attention.

FINDING 2-19: Mature, comprehensive historical databases of coal resources would benefit from updates to reflect modern analytical techniques and emerging priorities, including critical mineral recovery from coal and waste streams.

RECOMMENDATION 2-10: The NPC recommends USGS, in coordination with DOE for technology development, work with states to revise and/or develop new assessments to better characterize the quality and composition of undeveloped coal resources. Such assessments will provide greater opportunity to determine the suitability of utilizing remaining coal resources for emerging market opportunities.

VII. GEOLOGICAL (NATURAL) HYDROGEN

A. Current Landscape of Government Initiatives

Systematic assessment of geological hydrogen resources is in the earliest stages. The first production from wells began in Mali in the Bourakebougou Field in 2012 where to date, 24 wells have been drilled.[129] About 200 exploration wells across the world have been, or are in the process of being, drilled.[130] While no commercial discoveries have been announced, significant shows of hydrogen have been announced in dedicated wells in the United States, Canada, and Australia.[131] Ongoing exploration activities are also occurring in South America, Europe, and Africa.

Within the U.S. government, geologic assessment work has primarily been done by the USGS, and applied research has primarily been completed through limited funding from DOE ARPA-E and NASA.

In January 2025, the USGS published the first peer-reviewed, open-source assessment methodology for performing probabilistic qualitative assessments for geologic hydrogen and a high-level prospectivity national mapping effort across the continental United States.[132] USGS is working to complete a similar assessment of Alaska by the end of 2026. As noted in the USGS report, geologic hydrogen can be generated from iron-rich igneous rocks that chemically react with water through serpentinization, or from ancient radiogenic crustal rocks that produce hydrogen via radiolysis of water. The decay of radiogenic minerals in crustal rocks is also known to be a major source of helium, and in certain geologic provinces, hydrogen and helium resources may be associated with each other.[133] This association may warrant combined resource assessment in the future.

ARPA-E has complemented these assessments with research and early-stage technology development, including $20 million to 16 projects across

129 Qian-ning Tian et al., "Origin, Discovery, Exploration and Development Status and Prospect of Global Natural Hydrogen Under the Background of 'Carbon Neutrality,'" *China Geology 5*, no. 4 (2022): 722–733, https://doi.org/10.31035/cg2022046.shu.

130 Craig Bettenhausen, "Trillions of Tons of Hydrogen May Be Waiting Under Our Feet: A New Energy Industry Is Emerging Around Hydrogen Made by Rocks Instead of Renewables," *Chemical & Engineering News* (March 14, 2025), https://cen.acs.org/energy/hydrogen-power/Trillions-tons-hydrogen-waiting-under/103/i7.

131 Craig Bettenhausen, "Trillions of Tons of Hydrogen May Be Waiting Under Our Feet: A New Energy Industry Is Emerging Around Hydrogen Made by Rocks Instead of Renewables," *Chemical & Engineering News* (March 14, 2025), https://cen.acs.org/energy/hydrogen-power/Trillions-tons-hydrogen-waiting-under/103/i7.

132 USGS, "Prospectivity Mapping for Geologic Hydrogen," January 16, 2025, https://www.usgs.gov/publications/prospectivity-mapping-geologic-hydrogen.

133 HyTerra website referencing hydrogen and helium concentrations from well sampling and testing in Kansas and Nebraska.

eight states to advance technologies for stimulating and recovering subsurface hydrogen.[134] This funding has been directed to support work at DOE national labs, industry partners, and universities. The primary focus of this research has been to better characterize hydrogen source rocks and potential methods to stimulate hydrogen production. This work has been occurring at DOE national labs as well as with U.S. universities and industry partners.[135]

NASA has also funded some limited research on geological hydrogen generation, microbial activity and geological hydrogen, remote sensing for hydrogen, and hydrogen seeps on Earth in order to better understand hydrogen generation and processes on other planets.[136] There is currently no federal authorization that specifically references geological or natural hydrogen research or assessment.

FINDING 2-20: While geological hydrogen is not yet a proven resource, early assessment by the USGS coupled with recent research and industry exploration efforts suggests it could be an important global resource.

B. Gaps and Challenges

Similar to oil and gas assessments, geological hydrogen potential will require an assessment of both conventional (hydrogen produced from an accumulation that is trapped in a reservoir after it migrated from its source rock) and unconventional (hydrogen produced directly from the source rock through stimulation) sources. Currently, the prospectivity mapping for conventional geologic hydrogen is qualitative and assigns relative prospectivity values and not quantitative values for in-place resources.[137] The USGS has also not begun assessing stimulated (unconventional) hydrogen prospectivity. The USGS total budget for geologic hydrogen assessment is approximately $1 million per year and personnel are limited to a few employees. The geologic hydrogen program is an internal program within the USGS that lacks congressional authorization and publicly stated goals beyond the completion of the Alaska Assessment in late 2026. Additional support for the geological hydrogen program could come from Earth MRI, which supports both mineral and energy resources and has mechanisms for partnerships with state geologic surveys, universities, and industry.[138] It will be difficult to complete comparable assessments of Hawaii and offshore, let alone advance more quantitative assessments, without congressional direction and funding.

FINDING 2-21: Although a high-level, qualitative prospectivity assessment of the continental United States has been completed, the USGS has not yet completed prospectivity assessments for Hawaii or U.S. offshore geological hydrogen resources.

FINDING 2-22: Existing assessments for the contiguous United States remain largely qualitative and could be improved with further research and rigorous quantitative methods.

The emerging geologic hydrogen sector also faces challenges common to other subsurface resources in that it lacks robust mechanisms to encourage collaboration between states and industry. As a preliminary step to addressing this

134 Advanced Research Projects Agency–Energy (ARPA-E), "U.S. Department of Energy Announces $20 Million to Explore the Potential of Geologic Hydrogen," September 7, 2023, https://arpa-e.energy.gov/news-and-events/news-and-insights/us-department-energy-announces-20-million-explore-potential-geologic-hydrogen.

135 ARPA-E, "U.S. Department of Energy Announces $20 Million to 16 Projects Spearheading Exploration of Geologic Hydrogen," February 8, 2024, https://arpa-e.energy.gov/news-and-events/news-and-insights/us-department-energy-announces-20-million-16-projects-spearheading-exploration-geologic-hydrogen.

136 NASA, *AVIRIS—Airborne Visible/Infrared Imaging Spectrometer*, Jet Propulsion Laboratory, https://aviris.jpl.nasa.gov.

137 USGS, "USGS Releases First-Ever Map of Potential for Geologic Hydrogen in the U.S.," January 16, 2025, https://www.usgs.gov/news/national-news-release/usgs-releases-first-ever-map-potential-geologic-hydrogen-us; USGS, "Data Release for Prospectivity Mapping for Geologic Hydrogen," January 16, 2025, https://www.usgs.gov/data/data-release-prospectivity-mapping-geologic-hydrogen.

138 USGS, *Earth Mapping Resources Initiative (Earth MRI)*, https://www.usgs.gov/special-topics/earth-mri/about.

coordination challenge, the DOE NLR is leading a proposed effort to produce an RD&D Roadmap for Geological Hydrogen.[139] This roadmap would provide coordinated pathways needed for acquiring and managing much of the information needed to produce significantly improved geological assessments of U.S. geological hydrogen.

FINDING 2-23: There is currently no funding to support partnerships between the USGS and state geologic surveys for geological hydrogen research. The Earth MRI program could be utilized as a vehicle to provide needed funding and partnership opportunities for state geological surveys as well as university and industry partnerships for research and resource assessments

FINDING 2-24: The federal government currently lacks a plan to capture and archive crucial industry datasets from geologic hydrogen exploration.

Many of the same geologic systems, subsurface conditions, and engineering challenges are shared across oil and gas, geothermal energy, helium, geologic hydrogen, and critical mineral development. These include drilling in high-temperature and high-pressure environments, characterizing subsurface reservoirs, managing fluid flow in porous and fractured media, and interpreting geophysical and geochemical data. Similarly, some geothermal and geologic hydrogen systems as well as helium and geologic hydrogen systems may be colocated. As a result, advances in data collection, subsurface modeling, and field operations in one domain can directly inform and accelerate progress in other domains.

FINDING 2-25: Geological hydrogen research has synergies with essential minerals, oil and gas, helium, and geothermal research and assessment. Federal agencies could use those synergies when collecting data, supporting pilot programs, and performing assessments.

139 Personal communication, 2026.

RECOMMENDATION 2-11: The NPC recommends Congress authorize and fund a national program for geologic hydrogen research, assessment, development, and demonstration. Modeled after the Methane Hydrate Research and Development Act, the program would support DOE-led technological development and field demonstrations and USGS-led resource assessment of both conventional and unconventional (stimulated) geologic hydrogen, in partnership with state geological surveys, research institutions, and industry.

RECOMMENDATION 2-12: The NPC recommends that USGS should consider assessing potential helium resources that might be associated with hydrogen discoveries, as more exploration data from geological hydrogen wells drilled in the U.S. becomes available. Currently the USGS national assessment of recoverable helium resources includes only those found in known natural gas resources.

VIII. DYNAMIC SUBSURFACE STORAGE

As defined in Chapter 1, subsurface storage may take place in engineered voids, such as salt caverns, or within the natural pore space of geologic formations, including depleted oil and gas reservoirs and isolated saline aquifers. These reservoirs support two fundamentally different classes of storage: dynamic storage and permanent storage. Dynamic storage systems—used for oil, natural gas, compressed air, hydrogen, and thermal energy—are designed for repeated injection and withdrawal cycles. Permanent storage—most notably for CO_2 and produced water—will be discussed separately.

A. Current Landscape of Government Initiatives

Federal agencies have made significant progress in assessing subsurface resources for dynamic energy storage. Both the USGS and DOE

have undertaken foundational work to evaluate geologic storage potential across multiple energy systems. In 2025, USGS developed a probabilistic methodology for the evaluation of geologic energy storage capacity for natural gas storage in depleted hydrocarbon reservoirs and a first-of-kind assessment of the potential in the Michigan Basin.[140, 141] The USGS has also developed a methodology for assessing Reservoir Thermal Energy Storage and begun a national assessment focusing on five generalized geologic regions (Basin and Range, Coastal Plain, Illinois Basin, Michigan Basin, and the Pacific Northwest) across the United States.[142] Complementing these efforts, DOE–HGEO recently oversaw the Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project,[143] in partnership with multiple national laboratories. SHASTA developed regional case studies to assess the potential for underground hydrogen storage across different geographies and geologic conditions, including porous media, salt caverns, saline aquifers, and hard rock storage.[144]

State geologic surveys, EIA, and EPA are also essential partners for dynamic underground storage assessments. State geological surveys may assess opportunities for commercial dynamic storage. EIA maintains estimates of underground storage capacity for natural gas and liquids,[145] while EPA regulates subsurface injection of fluids through the Underground Injection Control (UIC) program.[146]

B. Gaps and Challenges

The USGS's probabilistic assessment methodology for quantifying national capacity for subsurface storage of natural gas provides a template for a larger national assessment, which is anticipated to be published in the next year.[147] However, the methodology does not include storage in salt domes and uses a curated, proprietary national database only available to the USGS.[148] This assessment does not incorporate other public data, such as individual state databases.

Opportunities for installing more chemical or thermal storage systems in the United States will require detailed 3D geologic characterization and assessment to evaluate site suitability and viability. As such, future evaluation and deployment of geological storage systems in the United States presents an opportunity for the USGS to engage and contribute its subsurface and geologic expertise.[149]

FINDING 2-26: USGS has developed a probabilistic methodology for quantifying dynamic storage, but its method and data sources are incomplete and the analysis has not yet been applied across the United States.

RECOMMENDATION 2-13: The NPC recommends USGS complete the nationwide assessment of dynamic subsurface storage resources currently in progress. This work should standardize the probabilistic

140 Marc L. Buursink et al., *A Probabilistic Assessment Methodology for the Evaluation of Geologic Energy Storage Capacity—Natural Gas Storage in Depleted Hydrocarbon Reservoirs*, U.S. Geological Survey Scientific Investigations Report 2025–5108 (2025), https://doi.org/10.3133/sir20255108.

141 This was completed under the authority of the 1975 Energy Policy and Conservation Act.

142 Jeff D. Pepin et al., "Reservoir Thermal Energy Storage Pre-Assessment for the United States," *Geothermics* 127 (2025): 103256, https://doi.org/10.1016/j.geothermics.2025.103256.

143 Authorized under Energy Policy Act of 2005.

144 DOE, Hydrocarbons and Geothermal Energy Office, *DOE Three-Year U.S. Underground Hydrogen Storage Assessment Expands Future Opportunities in the Subsurface*, June 4, 2024, https://www.energy.gov/hgeo/articles/doe-three-year-us-underground-hydrogen-storage-assessment-expands-future; EIA, *Petroleum & Other Liquids Data*, https://www.eia.gov/dnav/pet/pet_stoc_typ_d_nus_SAS_mbbl_m.htm.

145 EIA, *Underground Natural Gas Working Storage Capacity: With Data for November 2025* (May 21, 2026), https://www.eia.gov/naturalgas/storagecapacity/.

146 EPA, *Protecting Underground Sources of Drinking Water from Underground Injection Control (UIC)*, https://www.epa.gov/uic.

147 Personal communication, April 2026.

148 Marc L. Buursink et al., *A Probabilistic Assessment Methodology for the Evaluation of Geologic Energy Storage Capacity—Natural Gas Storage in Depleted Hydrocarbon Reservoirs*, U.S. Geological Survey Scientific Investigations Report 2025–5108 (2025), https://doi.org/10.3133/sir20255108.

149 National Academies of Sciences, Engineering, and Medicine, 2018, *Future Directions for the U.S. Geological Survey's Energy Resources Program*. Washington, DC: The National Academies Press. https://www.nationalacademies.org/projects/DELS-BESR-17-02.

methodology, clarify data inputs and quality requirements, and apply the methodology at scale across the United States. USGS should publish a transparent inventory of assessed coverage and remaining data gaps.

RECOMMENDATION 2-14: The NPC recommends USGS and state surveys, in partnership with research institutes, expand existing salt and storage screening datasets into a national, GIS-based layer with location-specific depth, thickness, impurity, and geomechanical properties to improve early-stage site screening and reduce development risk.

The now-completed SHASTA program at DOE provided regional case studies for the underground storage of hydrogen, including porous media, salt caverns, saline aquifers, and hard rock storage. This research provided a good framework, but also verified the need for additional research in areas, including risks of loss of containment from storage reservoirs through biogeochemical reactions, caprock faults, fractures, or leaky wells. A better understanding of the biogeochemical reactions that could result in asset loss or operational and safety risk is required.[150]

FINDING 2-27: Additional research is needed to study containment of hydrogen in dynamic storage reservoirs, including research on biogeochemical reactions and loss of containment through caprock, faults, fractures, or leaky wells.

RECOMMENDATION 2-15: The NPC recommends DOE, working with USGS, national labs, state surveys, and industry, fund an applied R&D program to quantify and mitigate hydrogen containment risks in dynamic storage reservoirs and deliver field-validated best practices for site screening, monitoring, and integrity management.

IX. PERMANENT SUBSURFACE STORAGE

A. Current Landscape of Government Initiatives

Federal agencies play complementary roles in enabling, assessing, and regulating permanent subsurface storage. Currently, most federal research on permanent storage is focused on carbon sequestration, rather than disposal of other materials, including produced water.[151]

The DOE has historically led research, development, and large-scale demonstration efforts for CCS,[152] including programs such as CarbonSAFE and the Regional Carbon Sequestration Partnerships, which have advanced site characterization, pilot injections, and best-practice frameworks. The National Carbon Sequestration Atlas V (2015/2017) and its predecessors compiled nationwide maps of CO_2 storage formations, capacities, and pilot projects. Managed by DOE's NETL, these atlases help identify prime regions for CO_2 injection in oil and gas fields and saline aquifers.

In addition to conventional geologic storage, DOE's ARPA-E Mining Innovations for Negative Emissions Resource Recovery (MINER) program is advancing carbon mineralization approaches that permanently store CO_2 in solid form by reacting it with geologic materials. These efforts include in situ mineralization in basalt and ultramafic formations, as well as ex situ processes using mine tailings, often coupled with recovery of critical minerals such as nickel, lithium, and cobalt. Early projects have demonstrated lab-scale validation and initial field testing, highlighting the potential for permanent storage with cobenefits for domestic mineral supply.

150 NETL, *Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations* (April 2022), https://www.netl.doe.gov/projects/files/SubsurfaceHydrogenandNaturalGasStorageStateofKnowledgeandResearchRecommendationsReport_041122.pdf.

151 NPC, forthcoming report on the beneficial reuse of produced water (December 2026).

152 Under authorization from the Energy Policy and Energy Act of 2020 and Infrastructure Investment & Jobs Act (IIJA) 2021.

USGS and MMA complement DOE's research and demonstration activities by assessing geologic CO_2 storage resources across onshore and offshore domains. The USGS provides national-scale assessments of geologic CO_2 storage capacity, developing standardized methodologies and mapping subsurface formations suitable for long-term storage.[153] These assessments underpin strategic planning by identifying high-potential basins and guiding data collection priorities. USGS also provides an interactive Geologic CO_2 Sequestration Viewer (released 2019) for users to explore potential storage sites and data (e.g., formation depths, porosities, and capacities) online.[154] In 2021,[155] MMA (then operating as BOEM) initiated a national effort to assess carbon dioxide (CO_2) volumetric storage resources in subsurface formations on the OCS. In 2023, the MMA (then operating as BOEM) published a CO2 storage assessment methodology that utilized many of the same components found in the USGS methodology at the time. The MMA has not finalized an OCS-wide assessment of storage resource potential.[156]

Federal agencies also play central regulatory and land-management roles in determining where and how permanent storage projects may proceed. The DOI, through the BLM[157] and MMA,[158] manages access to federal lands and offshore areas for CO_2 storage, including permitting, leasing, and environmental review. The EPA regulates subsurface injection through the UIC program, including Class VI wells for geologic CO_2 sequestration and Class II wells for produced water disposal associated with oil and gas operations. The permitting requirements of these programs effectively define a national standard for site-specific evaluation and appraisal well-data gathering. EPA also supports state primacy, allowing states to assume regulatory authority where programs meet federal standards.

State agencies, particularly state geological surveys and oil and gas regulators, play a central role in implementing UIC programs, managing produced water injection, supporting site characterization, and contributing regional geologic data.

B. Gaps and Challenges

Despite significant progress, key technical, data, and regulatory challenges remain in advancing permanent subsurface storage. Current assessments of CO_2 storage potential are largely at a regional or basin scale and rely on existing datasets that are insufficient for project-level development. While national and regional mapping efforts have identified broad storage resources, they lack the resolution and site-specific data needed to support investment decisions.

Storage resource estimates generally consider pore space, while more advanced estimates[159] consider additional critical features of the storage unit, such as the likely presence or absence of a sealing caprock and whether formation water meets minimum salinity requirements under EPA UIC regulations. Although near-surface geology is relatively well characterized, there is a lack of high-resolution data on deeper formations, including saline reservoirs and confining zones. This limits confidence in storage capacity, injectivity, and long-term containment.

It is impossible for a resource assessment to holistically address the full range of economic and technical risks of permanent storage projects without incorporating significant direct data from wells. Verification of confining zone effectiveness and mechanical strength, identification of consequential geochemical interactions, and understanding the impacts of increasing

153 Authorized by the Energy Independence & Security Act of 2007 (EISA) to develop a methodology and conduct a nationwide assessment of CO_2 storage potential.

154 USGS, *Geologic Carbon Dioxide Sequestration Interactive Map* (February 11, 2019), https://www.usgs.gov/tools/geologic-carbon-dioxide-sequestration-interactive-map.

155 Following passage of the Infrastructure Investment and Jobs Act (Public Law 117-58 (IIJA)).

156 BOEM, *Resource Evaluation, Carbon Storage* (2021), https://www.boem.gov/oil-gas-energy/resource-evaluation/carbon-storage.

157 Federal Land Policy & Management Act (FLPMA) authorized BLM to permit CO_2 site characterization, injection, and storage facilities on onshore public lands.

158 Outer Continental Shelf Lands Act (Amended by IIJA 2021) authorized BOEM to grant leases for long-term CO_2 sequestration in offshore federal waters.

159 Peter D. Warwick and M.D. Corum, eds., *Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources*, USGS Open-File Report 2012–1024 (2012), https://doi.org/10.3133/ofr20121024.

pressure under injection conditions all rely on well data.

FINDING 2-28: Current regional- and basin-level storage assessments require more site-specific subsurface data to improve resolution and coverage while addressing unique risks. Key data include additional 3D seismic surveys and well data such as those provided by the CarbonSAFE demonstration program.

Recent DOE programs have enabled demonstration projects in some of the most promising basins and storage formations, with a focus on CO_2 sequestration in saline aquifers, as well as some CO_2 enhanced oil recovery (EOR) projects. Only a few demonstration projects have been carried out in the less mature resource types such as unmineable coal seams, organic shales, and basalt formations.

FINDING 2-29: Additional well and seismic data are needed to characterize deep saline formations and confining zones critical for secure long-term storage. Pilot and demonstration projects, where they exist, do not adequately cover all resource types. More focus is suggested for EOR projects and for less mature storage types.

Finally, there has never been a national-level assessment of permanent storage resources for produced water, the management of which is becoming increasingly critical to U.S. oil production. In principle, most saline aquifers suitable for CO_2 storage are also suitable for water storage, with some adjustment needed in the evaluation due to the different fluid properties and pressure behavior of water injection.

FINDING 2-30: Produced water storage capacity is a critical national resource supporting oil production and represents a major gap in national-level storage assessments. Leveraging subsurface characterization work already underway for carbon dioxide storage assessment can help address this gap. However, there is still a critical need to assess pore pressure variability and compressibility within deep and shallow produced water intervals, particularly in regions such as the Permian Basin, among other key basins across the United States.

RECOMMENDATION 2-16: The NPC recommends that Congress provide funding for USGS to conduct a comprehensive national assessment of subsurface storage capacity in saline aquifers, depleted reservoirs, and other suitable formations for produced water. This effort should build on existing datasets and methodologies.

RECOMMENDATION 2-17: The NPC recommends Congress continue to fund, and DOE continue efforts such as CarbonSAFE to reduce technical risk, uncertainty, and the cost of commercial-storage projects in saline aquifers. Within these programs, additional focus should be placed on understanding play types such as organic shales, basalt formations, unmineable coal seams, and reservoirs associated with composite confining systems.

RECOMMENDATION 2-18: The NPC recommends Congress allocate funding to DOE for demonstration projects targeting carbon dioxide storage in producing oil and gas reservoirs with enhanced oil recovery, to include both conventional and unconventional (organic shale and enhanced coalbed methane) reservoirs.

X. DATA PRESERVATION AND ACCESS

A. Current Landscape of Government Initiatives

Data infrastructure in the United States is distributed across federal, state, academic, and private entities. Federal databases include

both scientific and regulatory datasets, including DOE's EDX, the Geothermal Data Repository, the National Geologic Map Database, EIA's energy production information, and many other resources, as described in prior sections. The primary federal program supporting data preservation is the National Geological and Geophysical Data Preservation Program, which includes the Registry of Scientific Collections and the National Index of Borehole Information.[160] Its purpose is to preserve geological, geophysical, and geochemical data and samples to support modern analysis and resource development through funding of state geological surveys. The program was originally authorized at $30 million per year[161] and has current base funding of $1.5 million per year with 100% match required from the state surveys.[162] The IIJA temporarily increased the annual budget to $6.32 million per year until 2025.[163]

State geological surveys play a central role in data preservation and access. Of the 30 geological surveys that responded to a request for information for this report (a 61% response rate), all provide digital data to the public, though practices vary: Six states make all data fully public, while others maintain portions of data as either permanently (12 states) and/or temporarily (19 states) confidential. All but one state geological survey that responded houses physical data (such as core and samples). Ten geological surveys make all physical data available publicly, three hold some physical data permanently confidential, and 18 hold some physical data confidential temporarily. In some cases, confidentiality is tied to regulatory roles. Funding for these repositories is largely provided by states with limited federal support—primarily through NGGDPP—and through minor contributions from industry or user fees. In the survey, many states expressed concern about the sustainability of this funding.

Academic repositories are often maintained by individual researchers rather than centralized institutional systems, which places valuable collections at risk when researchers retire. In the private sector, data are typically held confidential and are frequently discarded once projects conclude or companies cease operations, which results in the loss of massive, high-quality datasets.

International models provide useful context. Australia has made substantial investments in precompetitive geoscience data and requires submission of exploration data and samples, which are eventually made publicly accessible after short confidentiality periods.[164] Australian companies are required to submit exploration drill core and representative samples in accordance with policy at the state and territory level. These are hosted in public repositories to preserve geoscientific data for future use. For example, in Western Australia, permit holders must submit drill core and cuttings to geological surveys. Samples are retained based on importance, rarity (e.g., depths >1,000 m), and potential for new stratigraphic information. Once in state libraries, cores are available for public access after a minimal confidentiality period. The Western Australia Exploration Incentive Scheme also provides up to a 50% refund for frontier drilling projects if data and core samples are made available to the public.

Canada similarly requires disclosure to the government of exploration, development, and production data for publicly traded companies.[165] This includes data and samples on the geological setting and mineralization, interpretation of these data, exploration activities undertaken (e.g.,

160 Created by the Energy Policy Act of 2005 (Public Law 109-58, Sec. 351) and reauthorized by the Energy Act of 2020 (Consolidated Appropriations Act, 2021) https://www.energy.senate.gov/services/files/32b4e9f4-f13a-44f6-a0ca-e10b3392d47a.

161 U.S. Congress, *Energy Policy Act of 2005*, Pub. L. No. 109–58, 119 Stat. 594 (August 8, 2005), https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf.

162 U.S. Congress, *Energy Policy Act of 2005*, Pub. L. No. 109–58, 119 Stat. 594 (August 8, 2005), https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf.

163 U.S. Congress, Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, 135 Stat. 429 (November 15, 2021), https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

164 The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code) is a professional code of practice that sets minimum standards for public reporting of exploration results, mineral resources, and ore reserves (JORC, 2012, 2025).

165 David J. Szumigala, *Critical Minerals, Strategic Minerals and Minerals in Alaska: A Perspective Towards Future Growth (A Report to the Alaska State Legislature Regarding Critical Minerals)*, Special Report 78 (Alaska Division of Geological & Geophysical Surveys, 2026), https://dggs.alaska.gov/webpubs/dggs/sr/text/sr078.pdf.

geophysical, geochemical, and geological surveys, and drilling), drilling program details, including techniques, depths, and significant results, and interpretation and conclusions regarding the project's potential. The Geological Survey of Canada maintains repositories for oil and gas well cores/cuttings from the western provinces, Yukon, Northwest Territories, and East Coast offshore, but provincial surveys primarily handle mineral exploration core samples. The federal government utilizes the samples stored at provincial surveys for projects such as the Canadian Digital Core Library project, which conducts AI analyses on public core data to generate new interpretations.

B. Gaps and Challenges

The fifth explorer concept highlights the value of cumulative data: "The fifth explorer makes discoveries by leveraging data generated by the previous four."[166] Enabling this concept in the United States depends on strengthening data preservation across three key categories:

- Legacy Data: Converting historical data into modern, accessible formats.
- Public Data: Ensuring data are easily accessible in usable formats.
- Private Data: Maintaining confidentiality for a limited period before public release (currently not required across all industries and settings in the United States).

Investments in data preservation can yield a large return, as the investments provide access to information that may be difficult or impossible to reproduce. Improved data access can accelerate exploration efforts and lower barriers to entry, creating opportunities for startup companies and increasing overall innovation.

At the same time, several key challenges persist. While the U.S. federal government has funded numerous studies of surface and subsurface resources, it does not support a federally managed, centralized repository or portal for preexisting geoscience data that is accessible to the public. This represents a major opportunity area, as relatively modest funding could generate substantial cross-sector benefits. State geological surveys currently host the majority of physical data collections, but funding for data preservation remains limited. The NGGDPP, with a current base funding level of approximately $1.5 million per year, distributes resources across all state geological surveys, leaving state general funds to cover most preservation costs. As a result, data preservation is highly dependent on state budgets, which are often uncertain or declining.

The cost of re-collecting lost or inaccessible data far exceeds the cost of preserving and maintaining existing datasets, making increased investment in data preservation a cost-effective strategy. This need is further amplified by the growing importance of AI, which depends on access to large, high-quality datasets in standardized formats. However, many existing data remain in paper, outdated or inconsistent formats, which limits accessibility and prevents their use in modern analytical tools.

FINDING 2-31: Data preservation is a high-return, low-cost investment that can accelerate exploration and innovation, particularly as AI-driven analysis expands.

FINDING 2-32: The lack of a centralized federal repository with standardized data formats, and limited, fragmented funding—largely dependent on states—create major gaps that restrict access to valuable geoscience data.

Additional challenges arise from policy gaps. Industry data generated on public lands are not consistently required to be submitted or made publicly accessible, and requirements vary widely or may not exist at all. Addressing this inconsistency and evaluating the potential for requiring public access to exploration data from public lands could significantly improve data availability and support more efficient resource development. Industry in all areas associated with resource discovery and characterization has

166 Regina Molloy, "Enabling the 5th Explorer Concept in the US," *Metal Tech News*, January 23, 2026, https://www.metaltechnews.com/story/2026/01/28/op-ed/enabling-the-5th-explorer-concept-in-the-us/2621.html.

substantial nonpublic datasets and samples/cores that are not readily available to others in the governmental or academic communities. In addition to lack of access, these data are in diverse and inconsistent formats, which impedes large-scale assessments.

FINDING 2-33: Limited data availability hinders efficient resource development. Establishing clear, standardized reporting requirements, similar to other countries, could significantly improve access and support U.S. energy dominance.

XI. CROSS-SECTORAL GAPS AND CHALLENGES IN ASSESSMENTS

Across sectors, a consistent set of structural gaps emerges in how federal and state governments assess resource potential.

A. Comprehensiveness

Federal and state governments have developed substantial capabilities to assess the nation's resource base, including geology-based assessments, production and reserves reporting, and extensive regulatory and operational data systems. These efforts provide a strong foundation of publicly accessible information across many resource types and regions. However, assessment activities are limited by human and financial resources and are not able to be consistently applied across the entire country or all resource categories. Instead, efforts are, by necessity, episodic and regionally selective—driven by federal administration priorities or funding opportunities—resulting in significant gaps where many states, basins, and resource types may remain unassessed or only qualitatively characterized.

FINDING 2-34: Assessment efforts are episodic and regionally selective, often limited by funding and capacity. Many states, basins, and resource types remain unassessed or only qualitatively characterized.

B. Integrated Supply Chain

Across multiple sectors, federal and state programs generate valuable data on resource occurrence, geologic setting, and, in some cases, production and reserves. In parallel, recent federal investments have significantly expanded support for deployment, demonstration projects, and downstream manufacturing capacity, accelerating technology commercialization and supply chain development.

However, these efforts are not yet fully aligned. Publicly available resource assessments are often conducted independently of downstream considerations, with limited linkage to processability, extraction feasibility, coproduction opportunities, or broader supply chain risks. At the same time, increased emphasis on deployment and manufacturing has not been matched by comparable investment in upstream activities such as subsurface assessment, exploratory drilling, and data generation. Together, these gaps create a disconnect between resource potential and supply chain readiness, constraining the development of a robust, end-to-end understanding of commercially viable supply.

FINDING 2-35: Across essential minerals, geothermal, and emerging resources such as geologic hydrogen, resource presence may be assessed without sufficient linkage to metallurgical processability, extraction feasibility, coproduction opportunities, and downstream supply chain risks.

FINDING 2-36: Across sectors, federal investment is much greater in deployment, demonstrations, and downstream manufacturing, while upstream subsurface assessment, drilling, and data generation have not seen equivalent funding increases.

C. Application of New Technologies

Rapid advances are being made in the development of quantum sensors, including quantum gravimeters, quantum LiDAR, and quantum-enhanced nuclear magnetic resonance (NMR).

These sensors offer unprecedented sensitivity and precision in detecting, characterizing, and exploiting subsurface geological formations. As the demand for critical minerals continues to rise, quantum sensing technology holds the potential to transform exploration methodologies, enhance resource localization, and reduce environmental impacts. While the mining industry is beginning to use prototype quantum sensors, federal agencies have only just begun (e.g., the ARPA-E ROCKS program)[167] to integrate quantum sensing into their resource assessment toolbox.

FINDING 2-37: Significant progress in migrating the technical readiness levels for the various quantum sensing technologies is critically needed to discover new resources and to further exploit existing resources.

D. Application of Machine Learning and Artificial Intelligence

Industry is rapidly adopting ML and AI approaches in resource modeling and assessments for oil and gas, minerals, and geothermal energy. Federal agencies are aware of these approaches but have made limited use of either ML or AI for resource modeling and assessments, with the exception of the CriticalMAAS program, a collaborative between USGS, ARPA-E, and the Defense Advanced Research Projects Agency. CriticalMAAS has completed its early goals of building AI and ML information technology tools for use across sectors, including academia and industry. However, validation and dissemination of these valuable assets is critically needed for timely application of these new capabilities with the extensive data provided by Earth MRI.

FINDING 2-38: Government resources programs could benefit significantly from expansion of machine learning and artificial intelligence capabilities to capitalize on the full potential of existing and future resource data.

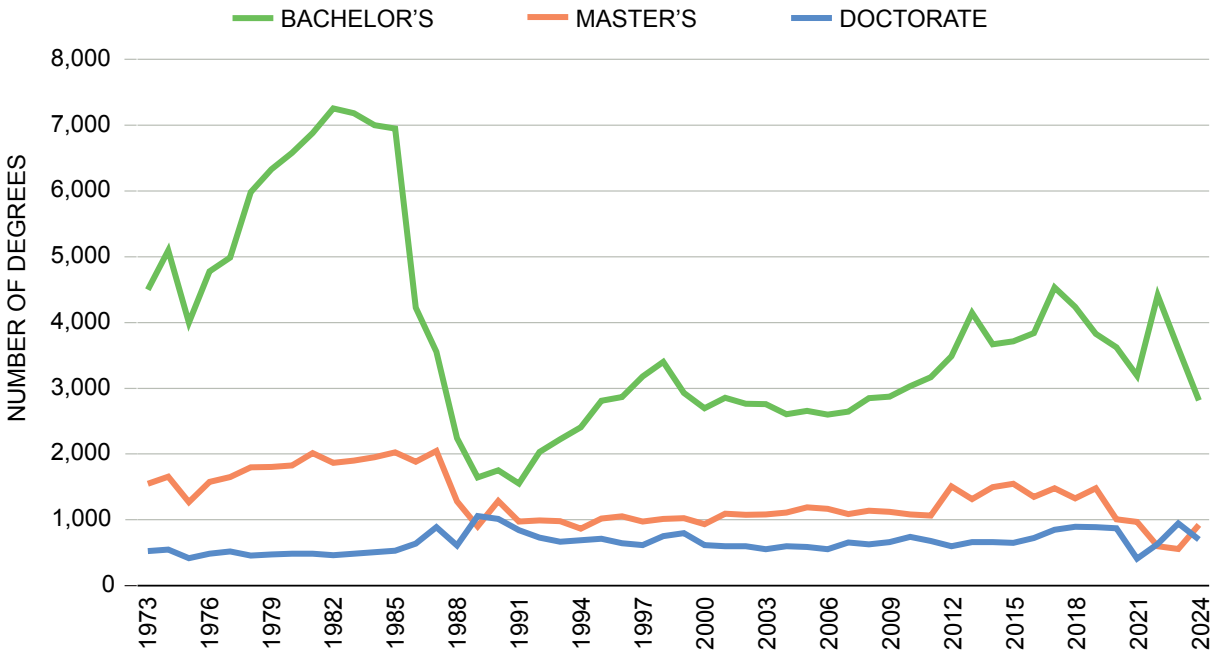
E. Workforce

Robust inventories and syntheses of publicly produced subsurface data and assessments require specialized knowledge developed through formal higher education, postgraduate study, and direct applied experience. Essential expertise includes stratigraphy and sedimentology, structural geology, geophysics, geochemistry, petrology, geomechanics, basin analysis, petrophysics, resource assessment methods, geospatial analysis, and environmental assessment. Essential skills include data conditioning, metadata development, geologic mapping, seismic and well log interpretation, geostatistics, numerical modeling, uncertainty analysis, technical writing, and synthesis of disparate datasets for decision-making. Many of these capabilities are not fully developed through coursework alone; they are typically acquired through hands-on work with real datasets, assessment workflows, field and laboratory programs, computational tools, and applied professional assignments.

Several cross-sectoral challenges limit the nation's ability to maintain, integrate, and use public subsurface data effectively. Geoscience bachelor's degrees have declined in number since peaks in 2017 and the 1980s, and master's degrees have dropped over the last five years (Figure 2-5). Additionally, many curricula have shifted away from traditional subsurface energy resource topics, reducing student exposure to seismic interpretation, basin analysis, stratigraphic correlation, petrophysics, reservoir characterization, and applied resource assessment. At the same time, retirements, competition with the private sector, and constraints in federal and state technical staffing have reduced the number of experienced professionals available to curate legacy datasets, conduct new assessments, evaluate data quality, and synthesize information across agencies, regions, commodities, and resource types.

These workforce gaps are particularly important for assessment systems because modern subsurface work increasingly depends on integration of large, heterogeneous datasets. Today's assessments require fluency in data analytics, geospatial platforms, 2D and 3D visualization, computational modeling, and complex software

167 ARPA-E, *Reliable Ore Characterization with Keystone Sensing (ROCKS)*, August 25, 2025, https://arpa-e.energy.gov/programs-and-initiatives/view-all-programs/rocks.



Source: AGI. 2026. https://profession.americangeosciences.org/research/data/degrees/.

Figure 2-5. *Geoscience Degrees Awarded in the United States*

environments. These tools are needed to integrate geologic maps, seismic data, well logs, geochemical data, sample archives, geophysical surveys, mine records, offshore datasets, and prior assessments. Without sufficient technical capacity, public datasets may remain fragmented, inconsistently documented, difficult to access, or underused in national-scale synthesis.

Existing federal workforce programs provide useful mechanisms for building assessment-relevant skills. At the DOE, the Mickey Leland Energy Fellowship[168] provides undergraduate and graduate students with research experience tied to DOE energy and environmental missions. DOE's HGEO workforce programs[169] are also directly relevant because they support hands-on training, research opportunities, and academic-industry partnerships for hydrocarbon and geothermal resource sectors. The DOE Scholars Program[170] can also be relevant when placements are aligned with DOE offices, laboratories, or projects focused on energy resources, critical minerals, subsurface storage, or related assessment activities.

USGS programs are especially relevant because USGS plays a central federal role in geologic mapping, mineral resource assessment, energy resource assessment, hazards assessment, water science, sample archives, and public geoscience data. USGS internships,[171] recent-graduate opportunities,[172] and Student Services Contractor roles[173] provide mechanisms for students and early career professionals to work directly with public datasets, field programs, science centers, and applied resource assessment projects.

168 Oak Ridge Institute for Science and Education (ORISE), *Mickey Leland Energy Fellowship Program*, https://orise.orau.gov/mlef/index.html.

169 DOE, Hydrocarbons and Geothermal Energy Office, *HGEO Workforce Programs*, https://www.energy.gov/hgeo/hgeo-workforce-programs.

170 ORISE, *DOE Scholars Program*, administered for the U.S. DOE, https://orise.orau.gov/doescholars/.

171 USGS, *Internship, Recent Graduate and Fellowship Opportunities*, Human Capital, https://www.usgs.gov/human-capital/internship-opportunities.

172 USGS, *Students and Recent Graduates*, Human Capital, https://www.usgs.gov/human-capital/students-and-recent-graduates.

173 USGS, *Student Services Contractors*, Youth and Education in Science, https://www.usgs.gov/youth-and-education-in-science/student-services-contractors.

NSF's Non-Academic Research Internships for Graduate Students, or INTERN,[174] is relevant when used to place graduate students with resource-focused federal agencies such as USGS, MMA, DOE offices, national laboratories, or state geological surveys. In that context, NSF INTERN can help graduate students gain applied experience in public data integration, geologic mapping, resource assessment, environmental analysis, and decision-support workflows. NSF's Industry-University Cooperative Research Centers also provide opportunities for students to participate in joint university-industry activities at the cutting edge of resource characterization and exploitation, such as the Center to Advance the Science of Exploration to Reclamation in Mining.[175]

Oak Ridge Institute for Science and Education (ORISE) provides a cross-cutting administrative mechanism for resource-focused internships, fellowships, and research participation programs when appointments are hosted by agencies such as USGS or DOE offices and laboratories working on energy resources, critical minerals, geologic storage, or public geoscience data.[176] Because ORISE supports placements at national laboratories and federal agencies, it can help connect students, recent graduates, postdoctoral researchers, and faculty with applied data, research, policy, and technical projects relevant to public subsurface assessment.

Taken together, these programs demonstrate that the federal government has mechanisms to develop early career technical capacity, but many are broad STEM or general experiential-learning programs rather than pathways specifically designed around subsurface resources, resource assessment, or public geoscience data synthesis. As a result, students and early career professionals may gain valuable research or policy experience without necessarily developing the specialized competencies needed to inventory, integrate, and assess geologic, geophysical, geochemical, well log, sample, offshore, or legacy resource datasets. The remaining gap is therefore not simply a lack of student programs, but a lack of sustained resource- and subsurface-focused alignment across universities; USGS-, DOE-, MMA-, and NSF-supported placements; ORISE-administered programs; state geological surveys; national laboratories; and private sector partners. This gap points to the need for a more intentional pathway—such as a resource- and subsurface-focused residency program—that would connect academic training with applied federal, state, laboratory, and industry assessment work and ensure early career scientists gain practical experience with the datasets, tools, standards, and synthesis methods needed to improve public inventories and assessments.

FINDING 2-39: Advanced computational, mapping, and modeling skills are increasingly essential for subsurface assessment across sectors, but the number of geoscience degrees awarded is declining and a minority of programs offer dedicated subsurface mapping, advanced computational platforms, and modeling coursework.

FINDING 2-40: Growing workforce and skills gaps threaten the capacity of government and industry to meet future needs in critical minerals, energy resource, and subsurface storage assessment, underscoring the need for stronger university-to-workforce training pathways.

F. Holistic Evaluation of Multiple Resources in a Given Area

Although this chapter is organized by assessment of individual resources, it also discusses common baseline datasets, which can support efforts to evaluate multiple, colocated resources at the same time. One such opportunity is the

174 National Science Foundation, *Non-Academic Research Internships for Graduate Students (INTERN) Program*, Directorate for Technology, Innovation and Partnerships, https://www.nsf.gov/tip/intern.

175 National Science Foundation, Industry–University Cooperative Research Centers Program, *Center to Advance the Science of Exploration to Reclamation in Mining (CASERM)*, https://iucrc.nsf.gov/centers/center-for-advanced-subsurface-earth-resource-models/.

176 ORISE, *STEM Internships and Fellowships*, https://orise.orau.gov/internships-fellowships/index.html; ORISE, *U.S. Geological Survey Research Participation Program*, administered for USGS, https://orise.orau.gov/usgs/default.html; DOE, Internships & Fellowships, https://www.energy.gov/internships-fellowships.

potential coproduction of oil, gas, and produced water from the same formation. Another example is the potential colocation of high-temperature geothermal, iron-rich essential minerals, and geologic hydrogen. In this second example, these resources would share common source rocks and an active subsurface water system within an elevated temperature regime. Table 1-2 illustrates that evaluation of these potentially coexisting resources can be done, at least in part, with the same or very similar geophysical, drilling and geochemical analytical techniques. In addition, all resource assessments are dependent on 3D mapping and modeling of the subsurface. A common 3D model of the area of interest could inform assessments of multiple resources, including both existing and emerging resources.

The government agencies that conduct resource assessments have the opportunity to take advantage of rapid advances in technology. Geophysical technology—including quantum sensors, quantum gravimeters, quantum LiDAR, and quantum-enhanced NMR—will significantly increase measurement precision in future resource assessments; use of drones and miniaturization of sensors will improve data acquisition; and fiberoptic acoustic, optical pressure and temperature instrumentation will dramatically enhance downhole assessment.

The ability to process, integrate, and interpret the variety and volume of geophysical, geological, and other datasets necessary to perform holistic assessment of the subsurface will require extensive use of AI and ML as well as traditional and, ultimately, quantum computing. This will require government agencies to rapidly accelerate the future use of these technologies.

FINDING 2-41: Holistic assessment of the subsurface would benefit a broad range of stakeholders, including government assessment and resource management agencies, industry, and the public. It will require improved access to high-quality datasets, use of advanced technology, a highly skilled agency workforce, and a dedicated interagency planning effort.

FINDING 2-42: Assessments of emerging resources are generally not well funded by Congress or emphasized by administrations, probably because they are poorly understood. Yet history has shown that emerging resources, such as shale oil and gas, can become major contributors to the U.S. economy and energy supply security. Holistic assessments by government agencies could be particularly valuable in improving the assessment of emerging resources and in frontier areas where less-resource-specific data are available. ■

CHAPTER 3 | CROSS-SECTORAL RECOMMENDATIONS

I. INTRODUCTION

Chapter 3 sets out strategic cross-sectoral recommendations to strengthen the United States' capacity to assess, manage, and develop subsurface resources in a more integrated, efficient, and forward-looking manner. Building on the findings of earlier chapters, these recommendations call for a coordinated national approach that harnesses advances in data, assessments, technology, workforce, and interagency long-term planning processes. Together, these actions support a National Cooperative Subsurface Assessment Program that can strengthen energy security, support economic growth, and ensure responsible stewardship of subsurface resources amid evolving energy and environmental priorities.

OVERARCHING RECOMMENDATION:
The NPC recommends that Congress authorize and appropriate a National Cooperative Subsurface Assessment Program that builds on existing federal and state agency authorities for resource assessments, data acquisition and management, technology development, and workforce capacity to strengthen the nation's ability to holistically evaluate subsurface resource potential and support a secure energy and economic future.

The establishment of a National Cooperative Subsurface Assessment Program will require a phased progression from near-term actions to implementation of a fully integrated long-term vision. As shown in Figure 3-1, early efforts should focus on advancing targeted assessments of emerging resources, strengthening foundational data and methodologies, and improving coordination and long-term planning across existing capabilities. Over time, these efforts can evolve into broader, more integrated assessments that consider multiple subsurface resources and uses within shared geologic systems. The ultimate vision is a sustained national program that holistically evaluates all subsurface resources within a specified volume of the subsurface. This program will support informed decision-making and enable the United States to better understand and manage its subsurface resources for energy security, economic competitiveness, environmental stewardship, and long-term national security.

Rigorous estimation of required appropriation levels and economic analyses of the recommendations presented in this report were beyond the scope of this study. However, based on existing funding levels for similar programs, and indicative costs for data acquisition, field pilot projects, staffing, and other capital-intensive components, we estimate that the recommendations would require new appropriations between $500 million and more than $1 billion per annum. Although this investment would be significant, the combined expected value return to the federal government would be on the order of 10x to >50x, based on comparison with similar resource-focused initiatives. State and industry benefits would be

in addition to this. Moreover, these recommendations would lead to more secure value chains for energy, minerals, and subsurface storage in the United States; further strengthen U.S. leadership in subsurface resource exploration and production; grow and evolve its capabilities for the future to keep pace with rapid advancements in technology; and address concomitant needs for a highly skilled workforce for subsurface assessment.

Development and implementation of the National Cooperative Subsurface Assessment Program will require a holistic approach linking advanced data acquisition and management, development of new technologies, new approaches to resource assessment, and investment in workforce development. This will require significant coordinated upfront investment. Some high-cost elements include drilling and testing deep wells, the acquisition of high-resolution remote sensing data, building and operating the pilot tests sites needed to develop advanced technology, and support for workforce development. All these elements are critical because it is the combination that will support rapid advancement of U.S. domestic energy and mineral supplies, and subsurface storage.

As analogous indicators of expected return on investment, Geoscience Australia commissioned Deloitte to conduct an analysis of the value of government investment in precompetitive data in 2021–2022 to support subsurface resource exploration and extraction and calculated that the investment of $AU 151 million in new data acquisition and facilitated provision of legacy data returned $AU 5.5 billion in resource exploration value and $AU 70.5 billion in resource extraction (minerals and oil and gas).[177] A report published by the American Geosciences Institute analyzed the return of investment of geologic mapping in the United States from 1994 to 2019 and estimated that the investment of $1.99 billion during this period fostered $20.61 billion[178]—more than 10x increase in value.

177 Deloitte Access Economics, *The Economic Value of Government Precompetitive Geoscience Data and Analysis for Australia's Resources Industry*, prepared for Geoscience Australia, 2023.

178 American Geosciences Institute, *Economic Analysis of the Costs and Benefits of Geologic Mapping in the United State of America* (2025), https://www.americangeosciences.org/static/pdf/GeoMapAnalysis.pdf.

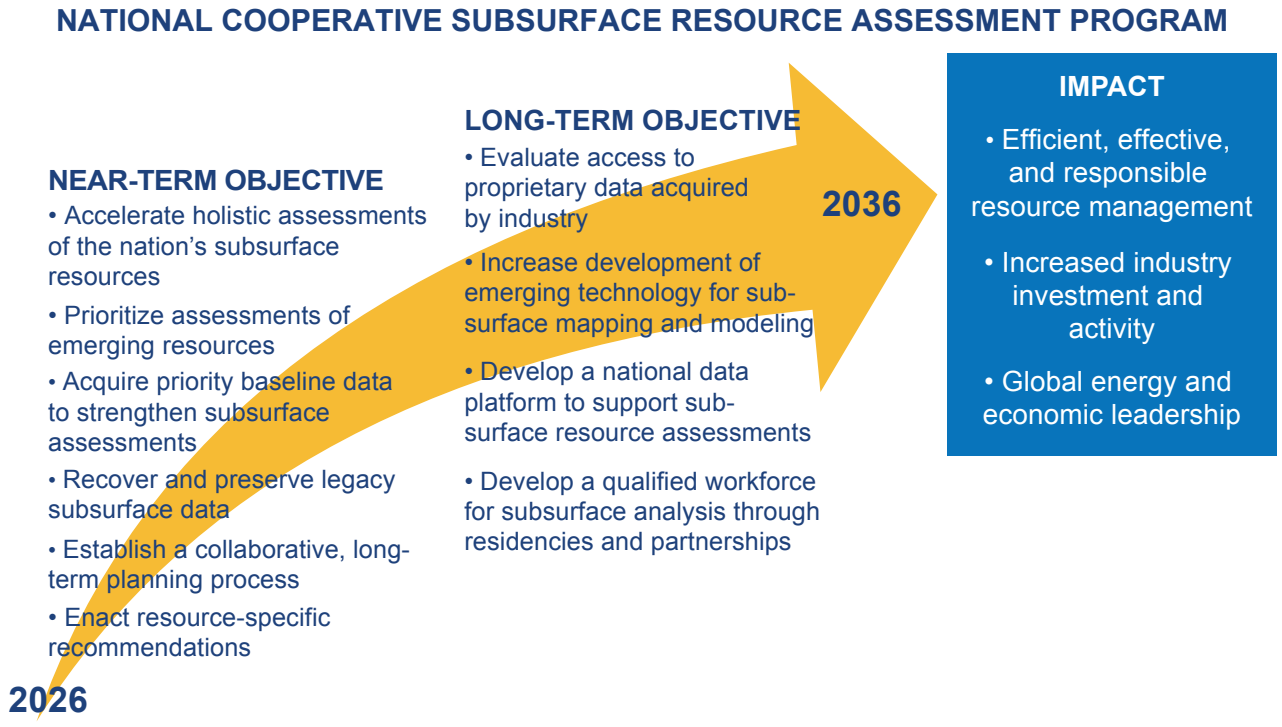


Figure 3-1. *Goals to Implement the Ultimate Vision of Establishing a National Cooperative Subsurface Assessment Program*

Recommendation 1
Accelerate Holistic Assessments of the Nation's Subsurface Resources

Recommendation: The NPC recommends that the USGS and Marine Minerals Administration,[179] working in collaboration with the state surveys, accelerate the development of holistic, multiresource assessments that leverage DOE technology and pilot project support, advanced 3D subsurface maps and models, AI, and emerging sensor integration.

1. Detailed Explanation

In addition to its proven and probable subsurface resources of energy and minerals, the United States has immense contingent and potential oil and gas and conventional mineral resources, as well as emerging and unconventional energy and mineral resources. Currently, most subsurface resources are assessed individually using only a subset of the potentially available data and technology. The United States would benefit significantly from developing a holistic evaluation of subsurface resources at the state, regional, and national levels. Most regions have a variety of existing and emerging subsurface resources that are potentially near each other. For example, oilfields and natural gas fields, permanent and dynamic storage, low-temperature geothermal, and minerals contained within produced water are often closely associated. Another example of potentially associated resources are ultramafic and granitic mineral deposits, geothermal reservoirs, natural and stimulated geologic hydrogen, and helium.

Geological, geochemical, geophysical, petrophysical, and remote sensing data collected for the assessment of exploration and development of one resource can be useful for the assessment of other resources in the vicinity. Table 1-2 shows examples of the overlap in data types used for the exploration, assessment, and development of different resources. If these data can be made available to users through integrated and cross-referenced database systems, other resources in the area can be assessed with the same data, eliminating the need to acquire similar assets for assessing other resources in the area and saving time and money.[180] When new baseline data are required, these assets could be acquired through a more systematic and strategic acquisition process that incorporates the needs of multiple users and resources. This process has potential for evaluating both conventional and unconventional existing and emerging resources. Taking this approach should provide a catalyst for advancing the timetable for development of emerging and unconventional resources while expanding the development of existing resources.

Rapid advances in sensor technologies, combined with machine learning (ML)/AI and advanced (and emerging quantum) computing, are transforming subsurface analysis. These advances can significantly improve assessments of both individual resources and the subsurface as an integrated system. Coupled with expanded access to 3D seismic data, they will enable more accurate, integrated 3D subsurface models. Although developing these 3D models will require sustained investment, computational capacity, and interagency coordination, they should be a priority output of a National Cooperative Subsurface Assessment Program.

A holistic approach to resource assessment requires strong coordination among key agencies, along with access to emerging technologies, resource economics, and diverse datasets. These include data from pilot and experimental programs and historical exploration and production records maintained by state, regional, and federal agencies, including DOE.

179 The Marine Minerals Administration (MMA) was formerly the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

180 For the sake of clarity, this report is not advocating for new compulsory licenses of privately held data.

Coordination among primary assessment bodies—such as USGS, MMA, and state geological surveys—and research, development, and reporting agencies is essential. The DOE (including the national labs, Energy Information Administration and Advanced Research Projects Agency–Energy (ARPA-E)), along with the National Science Foundation (NSF), state regulatory agencies, Bureau of Land Management (BLM), and National Oceanic and Atmospheric Administration (NOAA), all play critical roles.

2. Key Findings

- Data collected for conventional resources often are beneficial for emerging resources at a later date.
- Holistic assessment of the subsurface would benefit a broad range of stakeholders, including government assessment and resource management agencies, industry, and the public. It will require improved access to high-quality datasets, use of advanced technology, a highly skilled agency workforce, and a dedicated interagency planning effort.
- Assessments of emerging resources are generally not well funded by Congress or emphasized by administrations, probably because they are poorly understood. Yet history has shown that emerging resources, such as shale oil and gas, can become major contributors to the U.S. economy and energy supply security. Holistic assessments by government agencies could be particularly valuable in improving the assessment of emerging resources and in frontier areas where less-resource-specific data is available.

3. Benefits

A holistic approach to resource assessment would benefit a broad spectrum of users—including industry, local, state, and federal governments—as well as the public. Benefits include providing crucial information to inform permitting processes, infrastructure development, freshwater management, disposal and storage management, and resource development priorities.

At its core, this holistic approach strengthens the technical foundation for decision-making by providing fundamental subsurface information needed for resource modeling, including thermal and pressure gradients, structural and stratigraphic frameworks, and fluid properties. Ultimately, the holistic approach produces foundational 3D maps of the subsurface that provide the framework for characterizing and quantifying multiple resources. The approach also supports assessment and evaluation of both conventional and unconventional resources by making more affordable baseline datasets available, such as 3D seismic, gravity, and magnetic data. These data enable more effective early-stage play and prospect screening, helping identify where to focus more detailed exploration and/or pilot projects.

Beyond improving individual resource assessments, a holistic subsurface data approach creates opportunities for improved efficiency and coordination. For example, where colocated resources are identified, shared infrastructure models could reduce development costs while minimizing environmental impacts. In addition, because subsurface datasets often extend across jurisdictional boundaries, data repositories (see Recommendation 4) can support more consistent assessments and improved coordination among jurisdictions involved in resource exploration and development.

This integrated approach to resource assessments has the potential to improve management of all subsurface resources, including oil and gas, geothermal, minerals, geologic hydrogen, and storage by enabling more informed, efficient, and coordinated decisions.

4. Actions Required To Implement

- Develop collaborative organizational structures and capacity to provide holistic assessments in key resource and research agencies, including USGS, DOE, NSF, BLM, MMA, and state agencies (see Recommendation 8).

- Expand technological development and support and pilot projects funded and managed by DOE (see Recommendation 7).
- Develop USGS- and MMA-led data-derived models, metadata standards, and database architectures—working with DOE, state geological surveys, state oil and gas commissions, BLM, other relevant regulatory agencies, industry, and professional societies—to enable holistic resource assessments.
- Establish funding and training to build capacity across government resource agencies to deploy and interpret advanced sensing and analytics, such as quantum sensing, ML, and AI.
- Establish dedicated federal and state funding mechanisms to support holistic subsurface resource assessments.
- Publish integrated 3D models of the subsurface for various properties (e.g., water resources and reservoir temperature).

5. Support And Challenges For Implementation

Implementation can build on strong federal and state capabilities, including USGS and MMA assessment expertise, DOE technology programs, state geological survey data, and advances in sensing, AI/ML, advanced computing, and 3D modeling. The primary challenges are sustained funding and persistent siloes among the resource-specific assessment programs. Progress should begin with targeted regional pilots that integrate data across resource types, test shared workflows, and demonstrate the value of holistic assessment before scaling to broader state, regional, and national applications.

6. Case Studies

Several international programs demonstrate the feasibility and strategic value of simultaneous subsurface assessments integrating geothermal, critical mineral, hydrogen, and hydrocarbon resources. These initiatives illustrate how unified data architectures and multiresource workflows—linking geophysical, geochemical, mineralogical, and fluid datasets—can optimize exploration efficiency, infrastructure planning, and environmental stewardship. They provide templates for the development of a prototype holistic assessment methodology that could be built through an expansion of the USGS Earth Mapping Resources Initiative (Earth MRI) framework.

- Europe—CHPM2030 and CRM Geothermal Projects (2016–2027): The Combined Heat, Power, and Metal Extraction (CHPM2030) concept merged enhanced geothermal systems with in situ metal recovery from deep mineralized formations. Pilot sites integrated geothermal reservoir data, ore body mineralogy, hydrogeochemical fluid chemistry, and geophysical imaging to evaluate coproduction of heat, power, and metals. The Critical Raw Materials (CRM) Geothermal project expands this approach, linking geophysical, geochemical, and mineral system datasets for simultaneous mapping of geothermal and critical mineral potential.
- Australia—Exploring for the Future Program (2016–present): Led by Geoscience Australia, this national initiative conducts basin-scale mapping of geothermal, hydrogen, critical mineral, and petroleum systems across northern and central Australia. It integrates airborne magnetic, radiometric, and electromagnetic surveys; magnetotelluric transects; geochemical sampling; and fluid rock analyses to characterize subsurface structure, thermal gradients, and mineralized brine systems. The resulting datasets support colocation assessments for geothermal energy, hydrogen storage, and mineral recovery, providing a unified platform for cross sector resource planning.

Recommendation 2
Prioritize Assessments of Emerging Resources

Recommendation: The NPC recommends that the DOI prioritize national assessments of emerging resources and collaborate with DOE and state surveys to integrate emerging and existing technologies into these assessments. Current emerging resources include unconventional sources of critical and essential minerals, methane hydrates, and geologic hydrogen, as well as subsurface porous media storage capacities for oil and gas, hydrogen, carbon dioxide, and wastewater management. Establishing assessment priorities for emerging resources should include consideration of data availability to allow for adequate subsurface characterization and understanding of the key mechanisms governing the distribution and recoverability of the resource.

1. Detailed Explanation

Subsurface assessments produced by government entities tend to focus on static resource characterization, providing foundational information that reduces uncertainty and supports informed decision-making for all stakeholders. Prioritizing efforts to assess emerging resources—and integrating advanced technologies—will further reduce risk and uncertainty, improve investment confidence, and enable more efficient and responsible resource development.

Assessments of evolving resource systems—such as unconventional critical minerals, methane hydrates, geologic hydrogen, and subsurface storage capacities—require more dynamic, data-rich, and technology-enabled approaches. By prioritizing these assessments in the context of data availability, addressing gaps in understanding the mechanisms controlling distribution and recoverability, and increasing collaboration between DOI and DOE, the federal government can better integrate resource evaluation with technology needs, including advances in sensing, modeling, and data analytics.

In doing so, the government can realize complementary benefits across energy production, transport, storage, and waste management while ensuring the subsurface is managed as a strategic national asset that supports economic strength, environmental sustainability, and energy independence. Strategic public investment in subsurface assessment, data management, and technology maturation can similarly accelerate development of emerging resources—including geothermal systems, hydrogen storage, critical minerals, carbon storage, and unconventional resources—helping to de-risk private investment, strengthen domestic supply chains, and expand the long-term economic value derived from the nation's subsurface.

2. Key Findings

- Government resource assessments are most useful in the early stages of resource exploration, or where new concepts or technologies open opportunities for revitalizing resource development.
- Static assessments of in-place resources are the foundation of publicly available long-term, cross-sectoral data. When conducted rigorously and supported by robust datasets, these assessments can remain valuable for generations, enabling diverse industries to explore the subsurface as technologies evolve and new pathways emerge for technically and economically recoverable resources.

3. Benefits

The emergence of new subsurface resource opportunities such as geologic hydrogen, produced water storage, and unconventional sources of minerals and hydrocarbons highlight the growing importance of the subsurface as a strategic national asset. Developing and managing these resources can strengthen energy security and diversify supply while advancing lower-emissions energy solutions and enhancing long-term system resilience. At the same time, these subsurface resources present significant opportunities for economic growth, domestic industry development, and the expansion of U.S. technological leadership in subsurface characterization, extraction, and storage. As a result, the management of this asset will be crucial in supporting the growth of these resources.

4. Actions Required To Implement

- Use the collaborative, long-term planning process established in Recommendation 8 to set national priorities for emerging resources.
- Complete static assessments of in-place characteristics for emerging resources, using probabilistic methods wherever possible.
- Complete technically recoverable/storage capacity assessments for more mature, developing resources. Coordinate research, development, and deployment of technologies with DOE (Recommendation 6) to integrate those emerging technologies within the assessments at DOI and state surveys.

5. Support And Challenges For Implementation

The government can build on a strong foundation of existing capabilities to advance emerging subsurface resources, including extensive subsurface datasets, established R&D programs, and long-standing collaboration among agencies. The United States also benefits from a highly experienced oil and gas industry with transferable expertise in drilling, reservoir characterization, and infrastructure development—as well as a network of data-rich basins and existing wells, pipelines, right of ways, etc., that can be repurposed for emerging applications.

At the same time, significant challenges must be addressed to realize this opportunity. Emerging subsurface resources such as methane hydrates, geologic hydrogen, and critical minerals remain undercharacterized, introducing technical and economic uncertainty, which limit investor confidence. High upfront capital requirements, long lead times, and incomplete or siloed subsurface data further complicate implementation. In addition, public concerns regarding environmental risks, such as induced seismicity and groundwater protection, underscore the need for transparent monitoring and stakeholder engagement. Overcoming these barriers will require coordinated federal and state leadership, regulatory modernization, integrated data systems, and targeted risk sharing to mitigate uncertainty and enable large-scale deployment of emerging subsurface resources and storage solutions.

Recommendation 3
Acquire Priority Baseline Data to Strengthen Subsurface Assessments

Recommendation: The NPC recommends that Congress authorize and appropriate dedicated, ongoing funding for a coordinated federal-state data acquisition initiative—led by the USGS with DOE, Marine Minerals Administration, and state geological surveys partners—to close critical gaps in baseline subsurface data.

The initiative should prioritize:

- Nationally consistent, geophysical mapping (airborne magnetic, radiometric, gravity, and targeted seismic where appropriate).
- Strategic drilling, coring, and downhole logging to calibrate and validate geophysical interpretations.
- Standardized geochemical, mineralogical, and metallurgical sampling and analysis (including produced water chemistry where relevant).
- Rapid publication of quality-controlled data and metadata in interoperable public repositories.

1. Detailed Explanation

High-quality, publicly accessible subsurface datasets are the foundation of credible national resource assessments. Across resource types, the primary constraint is not geologic potential, but the lack of consistent, spatially coherent baseline data needed to reduce uncertainty to decision-grade levels. This is particularly true for emerging resources and applications (e.g., essential minerals in unconventional settings, geologic hydrogen, unconventional geothermal, and subsurface storage), where investors and regulators require reliable subsurface characterization before advancing pilot projects or making permitting decisions.

A national data acquisition initiative should prioritize the minimum dataset needed for multiresource evaluation: regionally consistent geologic mapping and remote sensing; airborne geophysical surveys (magnetic, radiometric, gravity, and, where appropriate, electromagnetic and targeted seismic methods); and calibration from wells (cores, cuttings, modern logs, temperature/pressure, and fluid and rock geochemistry) to tie interpretations to ground truth. Standardized mineralogical and geochemical datasets—particularly for essential minerals—are also critical to characterize resource quality, quantify recoverable elements, and inform process design.

To maximize impact, funding should be directed using transparent, repeatable criteria (e.g., multiresource potential, supply chain relevance, colocation opportunities, and deployment readiness). Competitive awards should be paired with interagency pilots (e.g., USGS-DOE) to test integrated acquisition workflows and new sensing approaches. All programs should require standardized metadata, rigorous quality assurance/quality control (QA/QC) protocols, and timely release of nonproprietary datasets through interoperable repositories to ensure each campaign produces durable, compounding value for future assessments.

2. Key Findings

- Regionally consistent baseline datasets (geologic mapping and geochemical characterization, geophysical imaging, targeted drilling) are repeatedly identified as high-value inputs across essentially all subsurface resource types and stages of development.
- While recent initiatives under the National Cooperative Geologic Mapping Program, Earth MRI, and related programs have significantly advanced the collection of baseline geologic and geophysical data, more surveys are required to reduce extensive gaps in areal coverage. These gaps include

regionally consistent and regularly spaced geophysical surveys (gravity, magnetic, resistivity, hyperspectral, passive seismic, seismic reflection, geodetics, etc.), which will enhance opportunities to apply machine learning and artificial intelligence.

- Gaps in seafloor mapping and subsurface sediment characterization limit the United States' ability to assess offshore mineral and energy resources, a challenge compounded by the loss of the JOIDES Resolution and the resulting hiatus in U.S.-led ocean drilling.

3. Benefits

Improved baseline data collection directly increases the accuracy, confidence, and usefulness of both public and private subsurface resource decisions. For industry, publicly available regional datasets could reduce early-stage uncertainty and screening costs, helping teams focus investment on the most promising areas and avoid redundant acquisition. For government and regulators, consistent datasets improve permitting efficiency, hazard identification (e.g., induced seismicity, groundwater pollution), and the ability to evaluate cumulative impacts across colocated subsurface uses (e.g., production, storage, geothermal, and minerals).

Expanded temperature measurements, heat-flow constraints, and calibrated 3D structural models would improve assessments of where viable geothermal resources are most likely to occur and reduce drilling risk for geothermal. Additional wells, seismic surveys, and caprock characterization would enable progression from broad capacity estimates for subsurface storage to project-ready sites with quantified containment risk. Integrated geophysics plus standardized geochemical/mineralogical sampling accelerates discovery of essential minerals and improves understanding of metallurgical uncertainty earlier in the project life cycle. Standardized geochemical data would improve resource assessments for produced water and other fluids, reuse planning, and environmental management.

4. Actions Required To Implement

- Establish an interagency acquisition steering group within the Office of Science and Technology Policy (OSTP) National Data Task Force made up of DOI, DOE, and state surveys to set standards, define priority metrics, and coordinate annual project selections.
- Publish a national subsurface data gap and opportunity map (geophysics, drilling/coring, temperature, geochemistry) and update it on a regular basis to guide investments.
- Fund regional acquisition projects through competitive Notice of Funding Opportunities (NOFOs) that require open data release, standardized metadata, and documented QA/QC workflows.
- Deploy targeted drilling/coring/logging campaigns specifically designed to calibrate geophysical surveys and enable 3D modeling products.
- Require that all federally funded acquisition projects deliver data products into the National Data Portal (Recommendation 4) within a defined release timeline.

5. Support And Challenges For Implementation

Implementation of a coordinated federal-state subsurface data acquisition initiative can build on strong existing programs (e.g., USGS Earth MRI and state survey mapping and core repositories), established interagency partnerships, and demonstrated stakeholder demand for consistent baseline datasets. In many regions, substantial legacy data and infrastructure (existing wells, core and sample libraries, geophysical archives, and university and laboratory capabilities) can be leveraged to reduce cost and accelerate delivery. The key enablers are sustained multiyear funding, clear governance, and a disciplined "open by default" publication approach so that each acquisition campaign produces compounding value for assessments, permitting, and private investment.

Likely obstacles include fragmented governance across federal and state entities; inconsistent standards for metadata and QA/QC; procurement and permitting lead times for airborne surveys, drilling, and land access; and limited workforce capacity in state surveys and federal programs to manage, curate, and publish data at scale. Practical avenues to address these challenges include establishing an interagency steering group with decision authority and adopting a minimum national metadata standard and QA/QC standards.

Recommendation 4
Develop a National Data Portal to Ease Access to Subsurface Data

Recommendation: The NPC recommends Congress fund a National Data Portal to ease access to interoperable public repositories for subsurface data. This portal, designed in consultation with an OSTP National Data Task Force, would be implemented by the USGS. The task force of key federal agencies—with input from academia, industry, state, Tribal, and federal stakeholders—would establish data standards and governance processes to optimize public data access to enable resource development and management.

1. Detailed Explanation

A national, federated data portal integrating federal and state subsurface data would transform how geologists, engineers, and policymakers analyze the subsurface. Subsurface assessments rely on diverse datasets, including well data (logs, temperature, pressure, flow, cores, and samples), geophysical surveys (seismic, magnetic, magnetotelluric, radiometric, gravity, electromagnetic), remote sensing (radar, hyperspectral, LiDAR), geologic mapping, and geochemical, rock, fluid, and gas analyses. These data are distributed across federal and state repositories, as well as state geological surveys and regulatory agencies, and significant proprietary datasets remain with industry.

A national data portal would serve to enhance access and discoverability across these distributed sources.[181] Rather than serving as a master repository, it should establish common standards and a centralized access point to enable seamless data integration and use in subsurface assessments. The portal should be flexible and scalable to incorporate emerging data types (e.g., fiber-optic sensing, quantum sensors) and support advanced analytics, including ML/AI applications. Design of the National Data Policy should be based on consultation with the OSTP National Data Task Force with input from the Federal Geographic Data Committee within the DOI.

2. Key Findings

- Establishing a national data exchange standard (common schema and application programming interfaces [APIs]), shared identifier conventions, and routine federal-state reconciliation would enable consistent integration and use of subsurface data for national-scale analysis.
- A national, interoperable data architecture—spanning geologic, geophysical, geochemical, and mineralogical datasets—is essential for modern mineral resource assessments but remains underdeveloped and inconsistently implemented across federal and state systems.
- Across all major hydrocarbon-producing states, produced water data systems are robust for volumes and operations but systematically lack standardized geochemical data and integrated reuse frameworks, limiting their utility for resource assessment and beneficial reuse.

3. Benefits

A National Subsurface Data Portal would enable regional and national assessments to inform strategic planning for resource availability and development. By reducing the time and effort to locate and assemble data, it would shift the work time and effort from data gathering to high-value interpretation and prediction—accelerating resource evaluations and strengthening environmental safeguards. Efficiency gains are potentially tremendous. A unified federal-state dataset would also support ML/AI applications trained on comprehensive national data, improving consistency, reproducibility, and risk assessment through

181 For the sake of clarity, this report is not advocating for new compulsory licenses of privately held data.

standardized APIs, nomenclature, and quality control protocols.

An integrated platform would enable cross-jurisdictional analysis, reflecting the reality that subsurface systems span state boundaries. Seamless integration of datasets—such as federal 3D seismic with state well records—would likely improve basin modeling, reservoir simulation, and assessments across energy, storage, water, and mineral resources.

The portal would also provide transparent, continuously updated data for regulators, researchers, and investors, with the goal to responsibly accelerate resource development aligned with U.S. energy goals of safe, affordable, reliable, and sustainable energy.

Primary industry benefits include:

- Oil and gas: Potentially accelerating basin-scale mapping, reservoir characterization, and prospecting.
- Geothermal: Improved resource assessment and reduced exploration risk.
- Storage: Enhanced site screening, risk assessment, and performance monitoring.
- Geologic Hydrogen: Targeted identification of prospective systems using integrated datasets.
- Mining: Improved resource modeling, reserve estimation, and colocation analysis for coal and critical minerals.

4. Actions Required To Implement

- Congress authorizes and appropriates funding for a National Data Portal for subsurface data to facilitate assessments.
- A National Data Task Force, composed of federal agencies, is funded and convened to design and implement a standardized, interoperable subsurface data ecosystem across onshore and offshore U.S. jurisdictions, including private, state, Tribal, and federal lands.
- The task force engages with industry, academic, state, Tribal, and federal stakeholders.
- USGS implements the National Subsurface Data Portal, including clear goals and performance metrics.

5. Support And Challenges For Implementation

Developing a National Subsurface Data Portal will face several challenges. The scale and diversity of datasets require multidisciplinary expertise to establish consistent protocols and standards. Data are highly fragmented across federal and state agencies, necessitating a coordinated effort to catalog, map, and enable access to these datasets. Establishing an integrated system will take years and depend on sustained congressional funding for development and maintenance.

Recommendation 5
Recover and Preserve Legacy Subsurface Data

Recommendation: The NPC recommends Congress:

- Increase annual funding to the USGS National Geological and Geophysical Data Preservation Program (NGGDPP) to the originally authorized $30 million per year.
- Reduce the state matching requirement to 25%.
- Fund an Office of Science and Technology Policy National Data Task Force to develop a data preservation and recovery strategy that builds on the NGGDPP and establish best practices and budget recommendations for collecting, preserving, and serving data from industry and public sources.

1. Detailed Explanation

Data supporting subsurface resource assessments are distributed across federal, state, academic, and private entities. As such, legacy data, including well data, geochemical analyses, geophysical datasets, and physical samples such as well cores and cuttings, are not consistently collected, archived, and managed and are at risk of being lost or discarded.

Preservation offers high returns as it provides access to information that may be difficult or impossible to reproduce. For example, rock cores, cuttings, and geophysical logs collected for one resource (e.g., oil and gas) can be used in assessments of other resources (e.g., subsurface storage) and are often virtually irreplaceable due to access and cost. Improved preservation, archiving, curation, and access to these data can accelerate exploration efforts and lower barriers to entry, creating opportunities for startup companies and increasing overall innovation. This represents a major opportunity area, as relatively modest funding could generate cross-sector benefits and a high return on investment. State geological surveys currently host most physical data collections, but funding for data preservation remains limited. The NGGDPP, originally authorized at $30 million per year[182] but currently funded at about $1.5 million annually, distributes modest support across all state surveys, leaving preservation largely dependent on constrained state budgets.

The cost of re-collecting lost or inaccessible data far exceeds the cost of preserving and maintaining existing datasets, making investment highly cost effective. This need is further amplified by AI, which depends on access to large, high-quality datasets. Many existing data remain in analog or outdated formats, limiting accessibility and usability.

Increasing NGGDPP funding to the $30 million per year level, as originally authorized, would provide a near-term bridge while a longer-term strategy is developed. Reducing the current 100% (1:1) state matching requirement to 25% would further expand NGGDPP reach and impact.

2. Key Findings

- Data preservation is a high-return, low-cost investment that can accelerate exploration and innovation, particularly as AI-driven analysis expands.
- The requirement for matching funds by the state geological surveys has had both positive and negative effects. Matching funds have leveraged federal funds allowing for more productivity but also have limited opportunities for some state geological surveys to participate.

3. Benefits

Preserving subsurface data is essential for effective resource characterization and

182 U.S. Congress, *Energy Policy Act of 2005*, Pub. L. No. 109-58, 119 Stat. 594 (August 8, 2005), https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf.

assessment. Government-maintained datasets provide industry with a credible, independent baseline that reduces uncertainty, informs exploration strategy, and supports long-term investment decisions. Preservation also helps de-risk early-stage investment, particularly in frontier and underexplored basins where private data are limited.

Comprehensive preservation—including recovery, curation, digitization, standardized metadata, and improved accessibility—ensures that legacy and new data remain usable over time. In many cases, preserved data can prevent unsuccessful drilling and unnecessary expenditures.

Digitized subsurface data also enable use of advanced analytical tools, including AI/ML applications, which improves subsurface modeling, interpretation, and assessment while extending the long-term value of existing datasets.

4. Actions Required To Implement

- Increase congressional funding for the NGGDPP.
- Fund and convene a steering group to develop a data preservation and recovery strategy building on NGGDPP.
- Incorporate recovered NGGDPP data into the National Subsurface Data Portal (Recommendation 4).

5. Support And Challenges For Implementation

While digital access would streamline data use, improve subsurface assessments, and enable advanced AI/ML analysis and modeling, legacy data and physical samples (e.g., well cores and cuttings) remain fragmented across state and federal agencies. Collecting and systematically compiling these data will require sustained multimillion-dollar funding over several years.

Recommendation 6
Evaluate Access to Proprietary Data Acquired by Industry

Recommendation: The NPC recommends that the DOI commission a focused review of state, federal, and select international policies governing industry sharing of proprietary subsurface data—including well, seismic, and other geophysical data—to identify best practices and develop recommendations. The review should also evaluate incentives for early data release, giving due consideration to R&D and commercial investments and intellectual property rights, and impacts on operators and data/information service companies.

1. Detailed Explanation

Subsurface assessments depend on access to high-quality subsurface and supporting data. In the United States, most of these data—including well logs and geophysical surveys—are collected by industry, some at considerable cost following years of sustained R&D investment during exploration, appraisal, development, and production activities on federal, state, Tribal, and private lands. However, requirements for data submission, retention, and public release vary widely by jurisdiction and data type. For example, the Marine Minerals Administration (MMA) requires submission of well and seismic data from the Outer Continental Shelf but releases well data after two years and seismic data after 25 years. State policies for submission and retention vary by state. A detailed comparison of state, federal, and international data submission and retention policies could help establish best practices that balance R&D, commercial investments, and intellectual property rights with broader public access and potentially encourage resource exploration and development.

2. Key Findings

- Limited data availability hinders efficient resource development. Establishing clear, standardized reporting requirements, similar to other countries, could significantly improve access and support U.S. energy leadership.
- Three-dimensional seismic and well data are critical datasets for conventional oil and gas; timely public access to these data can stimulate exploration and development activity.

3. Benefits

Most subsurface data are acquired by industry. Enabling access to industry data after submission to the relevant state or federal regulating agency benefits subsurface resource assessments and may support further investment and activity by industry. Many of these data (e.g., well data) may have utility across multiple resource sectors. For example, wells drilled for oil and gas may contain data relevant to geothermal, fluid storage, or minerals. Broader access to legacy geophysical survey data, including reflection seismic data acquired by industry would benefit multiple resource sectors.

4. Actions Required To Implement

- DOI should conduct a one-year study to identify best practices and develop nonbinding recommendations to improve industry data access across the United States while respecting R&D, commercial investments, and intellectual property rights.
- DOI should utilize national coordination networks, such as the Interstate Oil and Gas Compact Commission and Interstate Mining Compact Commission, to gather information from states relative to requirements for submission and retention of industry data.
- DOI should report findings to other federal agencies and relevant state regulators.

5. Support And Challenges For Implementation

Because of potential opposition due to commercial sensitivities related to investment incentives, data ownership, and data licensing, it will be important to accurately compile and assess existing regulatory requirements and understand implications to the private sector with respect to proposed recommendations.

Recommendation 7
Increase Development of Emerging Technology for Subsurface Resource Extraction, Mapping, and Modeling

Recommendation: The NPC recommends that DOE, in coordination with USGS, increase investment in emerging technologies, through both public/private partnerships and direct research and development funding, to improve resource extraction technologies and subsurface resource mapping and modeling. Such investment should support new technologies, such as miniaturizing and ruggedizing existing technologies; developing new sensing technologies; improving drilling and recovery technologies; advancing hydraulic fracturing and stimulation technologies; advancing 3D models; and leveraging artificial intelligence and machine learning capabilities to capitalize on the full potential of current and future resource data.

1. Detailed Explanation

Emerging technologies such as quantum sensing, real-time monitoring systems, fiber-optic deployments, graphics processing unit (GPU)-accelerated reservoir simulation and modeling, nodal and advanced ocean bottom networks for seismic data collection, high pressure/temperature and extended reach drilling and stimulation equipment, wellsite automation, and AI/ML applications are becoming increasingly important for generating, collecting and accurately interpreting large volumes of high-quality data. As these data and subsequent interpretations underpin resource assessment accuracy, improving resource assessments, specifically subsurface mapping and modeling, is intrinsically related to emerging technology development and advancement.

Complementing these advances, the miniaturization and ruggedization of sensors is enabling devices that consume less power, operate more reliably in extreme environments, and provide greater measurement sensitivity. Emerging deployment platforms—including small autonomous vehicles, small satellites, handheld scanners, fiber-optic systems, and downhole tools—further enhance the ability to deploy these miniaturized sensors in challenging environments while reducing cost and increasing coverage.

Similarly, new advances in engineering and materials science provide opportunities to improve resource extraction and increase resource recovery. R&D incorporating fundamental research as well as laboratory and field testing are paramount for unlocking resources that previously were uneconomic to develop.

Additional DOE investment in emerging technologies, which can be accomplished through direct R&D funding and private/public partnerships (e.g., national labs, academia), is therefore recommended to fully capitalize on current and future resource data in these sectors. USGS should be the key federal agency partner for advancing 3D subsurface models and related AI/ML tools and a key partner for validating and testing emerging technologies.

2. Key Findings

- Significant progress in migrating the technical readiness levels for the various quantum sensing technologies is critically needed to discover new resources and to further exploit existing resources.
- Government resources programs could benefit significantly from expansion of ML and AI capabilities to capitalize on the full potential of existing and future resource data.
- Basic research, development, and deployment are needed to further advance the unconventional geothermal field. This could occur through the development of public-private partnerships.

3. Benefits

Advancing technologies for subsurface resource extraction, mapping, and modeling will deliver significant benefits across a wide range of energy and mineral resources, including hydrocarbons, geothermal systems, critical minerals, and subsurface energy storage. Improved imaging, sensing, and data integration—particularly through AI/ML—will enable higher-resolution and more accurate characterization of subsurface formations, thus reducing uncertainty and improving decision-making. For hydrocarbon resources, this translates to optimized well placement, increased recovery efficiency, and fewer wells, which will lower costs and environmental impacts. In geothermal applications, especially superhot systems, advanced sensing and modeling will improve resource identification and reservoir evaluation, supporting more effective development strategies. For critical minerals, enhanced detection and characterization technologies can accelerate discovery and reduce the time and risk associated with bringing new resources into production.

Subsurface storage applications will benefit from improved understanding of reservoir integrity, fluid behavior, and long-term containment, which will also enable safer and more reliable operations. At the same time, advances in miniaturized sensors, autonomous deployment platforms, and real-time monitoring systems will expand access to challenging environments while reducing operational costs. Across all resource types, these innovations may support more efficient and environmentally responsible development by minimizing surface disturbance and improving monitoring capabilities.

4. Actions Required To Implement

- DOE should increase Notice of Funding Opportunities (NOFOs) for academic and national lab collaboration.
- USGS should accelerate the application of emerging technologies in assessments.

5. Support And Challenges For Implementation

The loss of skilled practitioners at the USGS has hindered the process of validation and verification of AI/ML tools developed through the USGS- Defense Advanced Research Projects Agency collaboration, limiting full use of Earth MRI datasets. Rebuilding a workforce with expertise in geoscience, data science, and advanced analytics is essential to test, validate, and deploy these tools effectively. Public-private partnerships, including Cooperative Research and Development Agreements, can also help leverage specialized expertise and accelerate emerging technologies for resource assessments.

At the same time, fundamental technology R&D is often conducted in the private sector and may be difficult to share across stakeholders, while commercialization can take years. National laboratories play a critical role at early technology readiness levels by advancing foundational research, de-risking emerging technologies, and providing testing environments that bridge the gap between basic science and applied deployment. For example, the Critical Minerals Innovation Hub brings together government, industry, and academia to further develop critical material supply chains and recovery from secondary sources. National labs also support technology development through commercialization agreements, strategic partnerships, cooperative R&D, and technology licensing.

6. Implementation Case Studies

ARPA-E has established the Reliable Ore Characterization with Keystone Sensing (ROCKS) program to advance cutting-edge technologies in drilling, sensing, and analytical technologies to enable rapid, high-resolution, and cost-effective assessment of ore deposits. ROCKS will pursue technology that targets order-of-magnitude improvements in characterization. These advances will shorten the timeline for feasibility assessments of rare

earth elements and critical mineral deposits, leading to increased access to resources. These innovations are expected to deliver significant improvements in orebody delineation and characterization and shorten the timeline from discovery to production.[183]

183 Advanced Research Projects Agency–Energy, *Reliable Ore Characterization with Keystone Sensing (ROCKS)*, August 25, 2025, https://arpa-e.energy.gov/programs-and-initiatives/view-all-programs/rocks.

Recommendation 8
Establish a Collaborative, Long-Term Planning Process

Recommendation: The NPC recommends that Congress establish a long-term planning process within the OSTP that convenes federal agencies involved in subsurface resources, alongside a Federal Advisory Committee Act (FACA) committee chartered by OSTP, DOE, DOI, representing Tribal governments, state geological surveys, industry, academia, and other stakeholders. The planning process should incorporate the FACA's input to identify national subsurface resource assessment priorities—including opportunities for holistic, multiresource assessments—and recommend funding, as well as periodically update priorities and recommended actions to maximize the relevance, impact, and timeliness of assessment activities.

1. Detailed Explanation

Effective implementation of a long-term holistic subsurface assessment program will require clear coordination across federal, Tribal, state, and private-sector entities. Responsibilities for data collection, resource assessment, research, and regulation are distributed across multiple agencies and organizations, often with limited integration. Existing planning efforts focused on specific program areas are important, but it will be beneficial to supplement them with an efficient, comprehensive planning process that defines roles, focuses on evolving priorities, strengthens interagency collaboration, and aligns federal and state efforts. Strong partnerships with industry are also critical to ensure access to high-quality data and to translate assessments into practical resource development. Establishing a long-term planning process within OSTP that also involves interested stakeholders can achieve these objectives.

2. Key Findings

- Holistic assessment of the subsurface would benefit a broad range of stakeholders, including government assessment and resource management agencies, industry, and the public. It will require improved access to high-quality datasets, use of advanced technology, a highly skilled agency workforce, and a dedicated interagency planning effort.

3. Benefits

The suggested comprehensive planning process is essential in order to ensure that the nation sets priorities for subsurface resource assessments after considering all options. Improving decision-making in this manner will benefit both stakeholders interested in particular resources and society at large.

4. Actions Required To Implement

- Congress should appropriate funding sufficient to enable implementation of this recommendation.
- OSTP should convene federal agencies interested in subsurface resource assessments to jointly develop and participate in a comprehensive, long-term planning process for assessment of subsurface resources.
- OSTP, DOE, and DOI should establish a FACA that includes Tribes, state geological surveys, industry, academia, and other interested stakeholders to inform the planning process.Priorities and recommended actions identified during the planning process should be reviewed and updated at least every five years.
- Staff from congressional committees responsible for agency oversight (e.g., House Committee on Natural Resources; House Committee on Science, Space, and Technology; Senate Committee on Energy and Natural Resources; Senate Committee on Commerce, Science and Technology); and House and Senate committees on appropriations (e.g., Subcommittee on Interior, Environment, and Related Agencies;

Subcommittee on Energy and Water; Subcommittee on Commerce, Justice, Science, and Related Agencies) should stay informed about the results of the planning efforts in order to understand the reasons for various priorities and recommended actions.

5. Support And Challenges For Implementation

Different agencies have different missions. This can naturally lead to communication challenges as well as differing ideas about the value of different options. However, these differences need not get in the way of increased collaboration and integration of efforts. The missions of the resource agencies are not in fundamental conflict, and the agencies can build on a long history of cooperation. A joint planning process will provide opportunities for increased cooperation.

Long-term planning is challenging under the best of circumstances, and it becomes more difficult when funding is either uncertain or inadequate. A comprehensive planning process that clearly articulates the reasons for selected priorities is likely to convince Congress and stakeholders of the value and strategic importance of improving subsurface resource assessments. This may result in more consistent and higher funding levels, which in turn would improve both the planning process and outcomes.

Implementing the above recommendations, such as the holistic resource assessment program proposed in Recommendation 1, will require coordination across agencies with different missions, authorities, and funding structures. A comprehensive planning process can help align priorities, clarify roles, and guide implementation over time.

Recommendation 9
Develop a Qualified Workforce for Subsurface Analysis Through Residencies and Partnerships

Recommendation: The NPC recommends that DOI and DOE coordinate with NSF, academic institutions, state geological surveys, national laboratories, and private-sector partners to identify priority subsurface analytical skillsets. They should then establish a residency program linking universities to professional practice while expanding fellowship and internship opportunities focused on developing these competencies. These steps will send a signal to universities that these skills are highly valued and create the durable pipeline of highly skilled early-career geoscientists and advanced computational analysts essential for progressing national priorities in resource extraction and storage.

1. Detailed Explanation

Robust subsurface resource assessment depends on expertise developed through a combination of higher education, postgraduate study, and years of applied experience. Essential competencies span stratigraphy, structural geology, geophysics, geochemistry, petrology, geomechanics, petrophysics, and subsurface operations, alongside technical skills such as seismic interpretation, well log analysis, geostatistics, numerical modeling, data analytics, and scientific communication. Increasingly, geoscientists must also be proficient in advanced computational platforms used for 2D and 3D visualization, property modeling, and fluid-flow simulation—capabilities that require specialized training and sustained professional development.

Several converging trends threaten the long-term workforce pipeline. Geoscience programs have declined in number, and many university curricula have shifted away from subsurface disciplines, reducing exposure to foundational resource assessment skills. At the same time, retirements and recent federal workforce reductions have further eroded technical capacity.

Addressing these gaps will require coordinated action among universities, state geological surveys, national laboratories, federal agencies, and industry. Priority efforts should include identifying critical workforce gaps; expanding internships, fellowships, scholarships, and applied training opportunities; and establishing a dedicated fellowship program—modeled on the Department of Defense Science, Mathematics, and Research for Transformation (SMART) Scholarship-for-Service program—to build and sustain expertise in subsurface characterization and assessment. Such a program, the Subsurface Training and Residency (STAR) Program, would comprise a federally funded scholarship-for-service initiative designed to build a pipeline of highly trained geoscientists and advanced computational analysts with deep expertise in subsurface assessment—critical for energy security, critical minerals, and storage. The program would begin with university juniors and seniors or master's students in geology, geophysics, petrophysics, or related fields, and would include internships and rotations in applied project work, culminating in guaranteed employment (Table 3-1).

2. Key Findings

- Advanced computational, mapping, and modeling skills are increasingly essential for subsurface assessment across sectors, but the number of geoscience degrees awarded is declining and a minority of programs offer dedicated subsurface mapping, advanced computational platforms, and modeling coursework.
- Growing workforce and skills gaps threaten the capacity of government and industry to meet future needs in critical minerals, energy resource, and subsurface storage assessment, underscoring the need for

stronger university-to-workforce training pathways.

3. Benefits

A coordinated program linking higher education with professional experience would strengthen the subsurface workforce by attracting students, supporting enrollment growth, and building practical skills early in careers. Training in areas such as data analytics, seismic interpretation, 3D subsurface mapping, petrophysics, and geochemistry would provide broadly transferable expertise across energy, mining, waste sequestration, and other subsurface industries, as well as improving workforce resilience as national priorities evolve. Such a program would also directly support federal priorities, including critical minerals development and U.S. energy security.

4. Actions Required To Implement

- Identify priority knowledge and skill area gaps related to subsurface resource assessment.
- Through the DOI and DOE, develop a fellowship program—STAR—focused on building and maintaining key knowledge and skills for students and professionals in subsurface characterization.

5. Support And Challenges For Implementation

Implementation would be supported by clear national demand for subsurface expertise, existing institutional capacity across DOI, DOE, state geological surveys, national laboratories, universities, and private-sector partners, and proven models for scholarship-for-service workforce development. The proposed fellowship and residency structure could build on these assets by aligning academic training with applied professional experience and by creating a visible pathway into federal and partner roles. Key challenges will include securing sustained federal funding, coordinating responsibilities across multiple agencies and partners, identifying priority skill gaps in a way that remains current as technologies evolve, and ensuring that universities have sufficient faculty, curriculum, and software resources to deliver advanced training in areas such as seismic interpretation, 3D mapping, data analytics, and numerical modeling. Successful implementation will therefore require dedicated program governance, predictable funding, strong mentor participation, and mechanisms to regularly assess workforce needs and program outcomes.

PHASE 1 Academic Fellowship	PHASE 2 Residency	PHASE 3 Guaranteed Employment
• 1-2 years of fully funded study at a designated partner university • Full tuition and dedicated faculty mentor and agency/industry co-mentor	• Summer rotations at USGS, MMA, state geological surveys, DOE national labs, or private sector partners • Mentored, applied project work	• 2- to 3-year placement at a sponsoring agency • One-for-one service commitment • Competitive GS-level or equivalent pay

Table 3-1. *Structure of Subsurface Training and Residency Program*

■

Appendix A |

REQUEST LETTER, DESCRIPTION OF THE NPC, AND MEMBER ROSTER

The Secretary of Energy
Washington, DC 20585

June 30, 2025

Mr. Alan Armstrong
Chair
National Petroleum Council
1625 K Street, NW
Washington, DC 20006-1656

Dear Mr. Armstrong:

Many of President Trump's directives, including Executive Order 14156, ***Declaring a National Energy Emergency***, Executive Order 14154, ***Unleashing American Energy***, and Executive Order 14213, ***Establishing the National Energy Dominance Council***, underscore the critical role of domestic energy and natural resources in powering the Nation's economic prosperity and national security. Meeting future energy needs will require ingenuity, innovation, and market-based solutions.

Accordingly, I request that the National Petroleum Council (NPC) undertake a broad ***Future Energy Systems*** study with subcomponent deliverables designed to recognize and leverage the vast potential of domestic oil and natural gas resources and industry expertise to advance Administration goals for increasing the availability of affordable, reliable, and secure energy for American consumers and our allies. The scope of this study should be developed with key objectives, deliverables, and timelines mutually determined between the NPC and the Department. Please work with Deputy Assistant Secretary Ryan Peay from the Office of Fossil Energy and Carbon Management (FECM) to delineate the preliminary scope and subcomponent deliverables within the next 30 days.

For the initial deliverables within the ***Future Energy Systems*** study, I am requesting the NPC address two priority topics immediately, with reports delivered to me by December 2025. These topics are crucial to advancing the priorities outlined in President Trump's energy agenda and require prompt and focused attention:

Oil and Natural Gas Infrastructure Permitting. Streamlining and expediting permitting is essential for all parts of the energy value chain and for building infrastructure to meet future energy needs. Re-evaluating and updating the permitting section of the NPC's 2019 Dynamic Delivery study report with practical recommendations based on current legislation and regulations can provide meaningful input to support the effective redesign of government systems and siting of new energy infrastructure. The advice of the NPC on this topic will be particularly helpful in concert with the work of the National Energy Dominance Council. Important also will be insights regarding factors that affect industry's ability to attract and retain private sector investment or rapidly deploy new technologies that increase safety, integrity, or operational efficiency.

Gas-Electric Coordination. A failure of natural gas infrastructure to keep pace with growing natural gas demand has created natural gas supply challenges and revealed new risks to the reliability of interconnected natural gas and electric power systems. A misalignment between the electric power and natural gas markets has exacerbated these risks resulting in inadequate access to natural gas and cost impacts to power consumers. The misalignment is rooted in fundamental market differences that influence decision making and the pace of infrastructure development made worse by legacy decarbonization mandates and the rapid growth of electricity demand. The NPC, working with both natural gas suppliers and electric power producers, can bring forward unique insights regarding the growth of natural gas demand in the United States and resolution of the misalignment of the natural gas and electric markets that if not addressed could threaten energy security, reliability, and affordability. This study should assess how rising natural gas and electricity demand and shifting load patterns are straining natural gas pipelines in key regions of the United States; examine what impact these strains can have on energy reliability; and recommend actionable strategies to address the misalignment between these two industries that can prevent or mitigate reliability impacts. The study will fill an important gap and complement ongoing gas-electric reliability and coordination initiatives involving industry and/or government by specifically focusing on the energy reliability risk viewed from the perspective of natural gas infrastructure operations and capabilities.

For the broad ***Future Energy Systems*** study, I request the NPC consider other additional subcomponents for which it can deliver high-value, actionable, and timely advice. Topics that may meet these criteria include energy security, infrastructure security, and analyses supporting U.S. energy trade and competitiveness globally.

I welcome continued dialogue with the NPC as we work together to shape a new era of American technology leadership and energy dominance. Please keep me advised of progress on the efforts addressed in this letter.

Sincerely,

Chris Wright

Chris Wright
Secretary of Energy

cc: Ryan Lance
Vicki Hollub

Wednesday, January 14, 2026 at 11:46:40 AM Eastern Standard Time

Subject: Future Energy Systems Study Request
Date: Wednesday, November 26, 2025 at 11:10:26 AM Eastern Standard Time
From: Haustveit, Kyle
To: John Dabbar
CC: Ryan Peay, Blair Pasalic, Stephanie Plith, James Slutz, Margo Regier, Deen, Toby, Cohen, Derek

John,

Thank you for coming in to brief us on the status of the NPC studies earlier this month. Following our discussion, I wanted to provide additional information and clarity on what we'd like to see in the larger, overarching *Future Energy Systems* study that the NPC will work on subsequent to the December 3rd meeting:

- We'd like the Future Energy Systems study to focus on affordability, both in terms of supply (break-even pricing) and demand (average U.S. household impact).
- As part of the broader study, we'd like to see a number of additional shorter-term studies, including, but not limited to:
    - **Produced water**: A short-term study on alternatives to disposal with a focus on the Permian would be very helpful to the Department as it looks at future project and program planning. For desalination, a review of potential commercial uses for the desalinated water would be helpful.
    - **Gas storage demand**: We would value a short-term study that focuses on natural gas storage demand through the lenses of reliability and volatility in relation to production, consumption, and exports. An examination of crude storage solutions is not needed, as this is already largely in-place.
    - **Resource mapping**: We would value the NPC members' opinions on the possibility of a government-led national resource mapping effort of all federal lands, and a template that states could follow for best practices in resource mapping. We are not expecting the NPC to conduct resource mapping.

Within these guideposts, we welcome the NPC members' thoughts on the best ways to proceed.

Look forward to seeing you next week for the NPC meetings.

Thank you,

Kyle Haustveit
Assistant Secretary
Hydrocarbons and Geothermal Energy Office (HGEO)

DESCRIPTION OF THE NATIONAL PETROLEUM COUNCIL

In May 1946, the President stated in a letter to the Secretary of the Interior that he had been impressed by the contribution made through government/industry cooperation to the success of the World War II petroleum program. He felt that it would be beneficial if this close relationship were to be continued and suggested that the Secretary of the Interior establish an industry organization to advise the Secretary on oil and natural gas matters. Pursuant to this request, Interior Secretary J. A. Krug established the National Petroleum Council (NPC) on June 18, 1946. In October 1977, the Department of Energy was established and the Council's functions were transferred to the new department.

The purpose of the NPC is solely to advise, inform, and make recommendations to the Secretary of Energy and the Executive Branch on any matter requested or approved by the Secretary, relating to oil and natural gas or the oil and gas industries. Matters that the Secretary would like to have considered by the Council are submitted in the form of a letter outlining the nature and scope of the study. The Council reserves the right to decide whether it will consider any matter referred to it.

Examples of reports of studies undertaken by the NPC at the request of the Secretary include:

- *Bottleneck to Breakthrough: A Permitting Blueprint to Build (2025)*
- *Reliable Energy: Delivering on the Promise of Gas-Electric Coordination (2025)*
- *Charting The Course – Reducing GHG Emissions from the U.S. Natural Gas Supply Chain (2024)*
- *Harnessing Hydrogen: A Key Element of the U.S. Energy Future (2024)*
- *Principles, and Oil & Gas Industry Initiatives and Technologies for Progressing to Net Zero (2022)*
- *Petroleum Market Developments – Progress and Actions to Increase Supply and Improve Resilience (2022)*
- *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage (2019)*
- *Dynamic Delivery: America's Evolving Oil and Natural Gas Transportation Infrastructure (2019)*
- *Supplemental Assessment to the 2015 Report – Arctic Potential (2018)*
- *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources (2015)*
- *Enhancing Emergency Preparedness for Natural Disasters (2014)*
- *Advancing Technology for America's Transportation Future (2012)*
- *Prudent Development: Realizing the Potential of N. America's Abundant Natural Gas & Oil Resources (2011)*
- *One Year Later: An Update On Facing the Hard Truths about Energy (2008)*
- *Facing the Hard Truths about Energy: A Comprehensive View to 2030 of Global Oil & Natural Gas (2007)*
- *Observations on Petroleum Product Supply (2004)*
- *Balancing Natural Gas Policy – Fueling the Demands of a Growing Economy (2003)*
- *Securing Oil and Natural Gas Infrastructures in the New Economy (2001)*
- *U.S. Petroleum Refining—Assuring the Adequacy and Affordability of Cleaner Fuels (2000)*

The NPC does not concern itself with trade practices, does not lobby, nor does it engage in any of the usual trade association activities. The Council is subject to the provisions of the Federal Advisory Committee Act of 1972.

Members of the NPC are appointed by the Secretary of Energy and represent all segments of the oil and gas industries and related interests. The NPC is headed by a Chair and a Vice Chair, who are elected by the Council. The Council's operations are supported entirely by voluntary contributions from its members. Additional information on the Council is available at www.npc.org.

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Appendix B | STUDY GROUP ROSTERS

STUDY PARTICIPATION

Participants in this study contributed in a variety of ways, ranging from work in all study areas, to involvement on a specific topic, to reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all the statements, findings, and recommendations in this report. Additionally, while U.S. government participants provided significant assistance in the identification and compilation of data and other information, they did not take positions on the study's recommendations.

As a federally appointed and chartered advisory committee, the NPC is solely responsible for the final advice provided to the Secretary of Energy. However, the NPC believes that the broad and diverse participation has informed and enhanced the study and advice. The NPC is very appreciative of the commitment and contributions from all who participated in the process.

This appendix lists the individuals who served on this study's Coordinating Subcommittee and Task Groups, as a recognition of their contributions. In addition, the NPC wishes to acknowledge the numerous other individuals and organizations who participated in some aspects of the work effort. Their time, energy, and commitment significantly enhanced the study, and their contributions are greatly appreciated.

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2. Resource Assessment Coordinating Subcommittee Roster
3. Task Group 1: Value of Assessments
4. Task Group 2: Existing Federal and State Initiatives

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Appendix C | RESOURCE ASSESSMENT METHODS

DIRECT MEASUREMENTS

- Geologic Mapping: Field-based observation and documentation of surface rock types, stratigraphy, and structural features (e.g., faults, folds) are fundamental for inferring subsurface conditions. Geologic mapping establishes the regional framework that guides drilling, geophysical survey design, and resource interpretation.
- Well Logs: Downhole measurements of physical properties—such as resistivity, density, porosity, temperature, and pressure—used to characterize formations in situ. These logs are essential for determining lithology, fluid presence, and reservoir properties.
- Core Data: Continuous cylindrical rock samples retrieved during drilling, typically from reservoir intervals. Core analysis enables direct measurement of porosity, permeability, mineralogy, mechanical properties, and fluid saturation. Core data are considered the benchmark for calibrating other subsurface measurements.
- Geological Cuttings: Rock fragments generated during drilling and transported to the surface by drilling fluid. While less continuous and detailed than cores, cuttings provide cost-effective information on lithology, mineral composition, and stratigraphic changes with depth. They are widely used for real-time geological interpretation and preliminary assessments.
- Petrophysical Data: Quantitative measurements derived from well logs that describe rock and fluid properties. Common open-hole logs include gamma ray, resistivity, density, neutron, sonic, and nuclear magnetic resonance (NMR). These are used to identify lithology and hydrocarbon- or fluid-bearing zones. In developed wells, cased-hole logs (e.g., pulsed neutron, production logs, temperature logs) are used to monitor fluid movement, identify producing zones, and diagnose issues such as water breakthrough.
- Mud logs: Continuous records gathered during drilling that integrate cuttings descriptions, gas measurements, and drilling parameters. Mud logs support real-time decision-making, hazard identification, and early detection of hydrocarbons.
- Production Data: Measurements of fluid volumes (oil, gas, water) produced over time. These data provide insight into reservoir performance, pressure depletion, and recovery efficiency, and are essential for calibrating reservoir models and forecasting future production.
- Drill Stem Tests (DSTs): Temporary downhole tests that isolate specific formations to measure

pressure, permeability, and fluid type. DSTs provide early, direct estimates of reservoir productivity and are critical for evaluating commercial viability.

- Geochemical Analysis: Laboratory analysis of rock, fluid, or gas samples to determine composition, origin, maturity, and potential resource presence.
- Pump Tests: Controlled fluid extraction or injection tests used to evaluate permeability, pressure response, and reservoir connectivity.

INDIRECT OR REMOTE SENSING MEASUREMENTS

- Seismic Imaging: Seismic surveys use acoustic waves to image subsurface structures and stratigraphy. Reflections from rock interfaces are recorded and processed to generate subsurface images.
  - 2D seismic: Provides cross-sectional views along survey lines.
  - 3D seismic: Generates volumetric datasets for detailed structural and stratigraphic interpretation.
  - Time-lapse (4D) seismic: Tracks changes over time, supporting reservoir monitoring and storage integrity assessments.
- Gravity Survey: Measure small variations in Earth's gravitational field caused by density contrasts in subsurface rocks. Useful for identifying large-scale features such as sedimentary basins, salt bodies, and structural highs.
- Magnetic Surveys: Detect variations in Earth's magnetic field associated with different rock types. Commonly used to map basement structures, igneous bodies, and mineral systems.
- Resistivity Surveys: Active electrical methods that inject current into the ground and measure resulting voltage differences to determine subsurface resistivity.
- Electromagnetic Surveys: Methods that use time-varying electromagnetic fields (active or passive) to measure subsurface conductivity.
- Magnetotelluric Surveys: A subset of EM methods that uses naturally occurring electromagnetic fields (passive source) to image deep subsurface resistivity structures—particularly effective for crustal-scale imaging and geothermal systems.
- Radiometric Surveys: Measure natural gamma radiation (e.g., from potassium, uranium, thorium) to map near-surface lithology and alteration patterns.
- Radar-Based Imaging: Satellite-based method that measures ground deformation by comparing repeated observations of the same area. Phase differences between acquisitions are used to detect very small surface displacements over time, supporting analysis of subsurface processes such as fluid movement, reservoir compaction, and fault activity.
- Optical-Based Imaging: Satellite and aerial imagery (multispectral and hyperspectral) used to map surface geology, structural features, and mineral alteration zones. These datasets are valuable for early-stage reconnaissance and regional assessments.
- Thermal Infrared Imaging: Detects surface temperature variations associated with fluid flow, geothermal activity, or material differences, aiding in identifying active systems or anomalies.
- Laser-Scanning (LiDAR): High-resolution topographic mapping using laser pulses to detect subtle geomorphic features, fault traces, and structural patterns that may not be visible in traditional imagery.
- Sonar-based imaging: Acoustic imaging methods (e.g., multibeam sonar offshore) used to map the seafloor and near-subsurface features, supporting offshore geological and geomorphological characterization. ■

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