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WORKSHOP
Basin Scale Issues for Carbon Storage

February 13-14, 2024
U.S. Geological Survey National Center
Reston, Virginia

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Acronyms and Key Terms

AoRs	Areas of review
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CarbonBASE	Carbon Basin Assessment and Storage Evaluation
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
CDR	Carbon dioxide removal
CEQ	The White House Council on Environmental Quality
DOE	Department of Energy
DOI	Department of the Interior
EDX	Energy Data eXchange
EGS	Enhanced Geothermal Shot
EPA	Environmental Protection Agency
FECM	Office of Fossil Energy and Carbon Management
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
OCS	Outer Continental Shelf
R&D	Research and development
SEI	Subsurface Energy Innovations
TexNet	Texas Seismological Network and Seismology Research
UIC	Underground Injection Control
USDWs	Underground sources of drinking water
USFS	United States Forest Service
USGS	United States Geological Survey

Executive Summary

The scale-up of carbon capture and storage (CCS) and storage-based carbon dioxide removal (CDR) deployment, which is required to meet the national carbon dioxide (CO_2) emission reduction goals, is expected to result in deployment of multiple geologic CO_2 storage projects in single basins. To ensure that the carbon storage resources within the nation's onshore and offshore basins are being utilized equitably and responsibly, multiple technical and non-technical challenges need to be addressed in the near-term. To address these challenges, the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) is launching the Carbon Basin Assessment and Storage Evaluation (CarbonBASE) Initiative while the U.S. Department of the Interior's (DOI) multiple bureaus are developing regulatory guidelines, models, and data-sharing tools for the management of Federal land and marine resources.

In February 2024, FECM and DOI's U.S. Geological Survey (USGS) hosted a joint workshop with over 70 participants from multiple Federal agencies, state government agencies, industry, academia, and research organizations. The objective of the workshop was to collect individual and unique feedback on the challenges and research and development (R&D) needs associated with basin-scale carbon storage resource management, which FECM and DOI bureaus can use to inform their respective program development. The two-day workshop took place at USGS National Center in Reston, Virginia. The agenda focused on multiple technical topics related to basin-scale assessment, monitoring, and management of carbon storage resources in the United States. The participants' feedback was collected over two days through eight sessions with breakout group discussions. ***High-level takeaways*** *of the workshop are shown in*

Figure 1.

DOE and DOI have used the individual and unique feedback and perspectives to develop possible next steps within their respective mission spaces and to identify synergistic and collaborative opportunities. The next steps FECM will consider implementing include (1) developing the CarbonBASE technical R&D scope; (2) identifying stakeholder engagement pathways that can inform the CarbonBASE program on key data and information most useful for policymakers; and (3) considering the CarbonBASE scope that includes elements of stakeholder engagement that informs potential future governance of basin-scale resource management. The next steps DOI bureaus will consider implementing include: (1) collecting and sharing basic basin geologic data needed to better characterize storage basins, particularly in federally managed areas; (2) establishing a working group to identify components of monitoring networks on Federal lands and the Outer Continental Shelf (OCS) and potential leveraging opportunities with existing DOI monitoring infrastructure; and (3) initiating development of geologic and computational models for basins within the Federal lands and OCS. In addition to potential next steps within their respective mission spaces, FECM and DOI plan to map out a mutually beneficial collaboration path forward.

Figure 1. Key takeaways from the Basin Scale Issues for Carbon Storage workshop.

Workshop Details

Background

Deployment and scale-up of carbon capture and storage (CCS) technology is expected to result in rapid development and simultaneous operations of multiple geologic CO_2 storage sites within single basins and to overlap with other subsurface activities. The locations of planned CCS projects and Class-VI wells under review (Figure 2) demonstrates that project developers are currently targeting a select few formations and basins. Expansion of CCS deployment will likely continue with this trend.

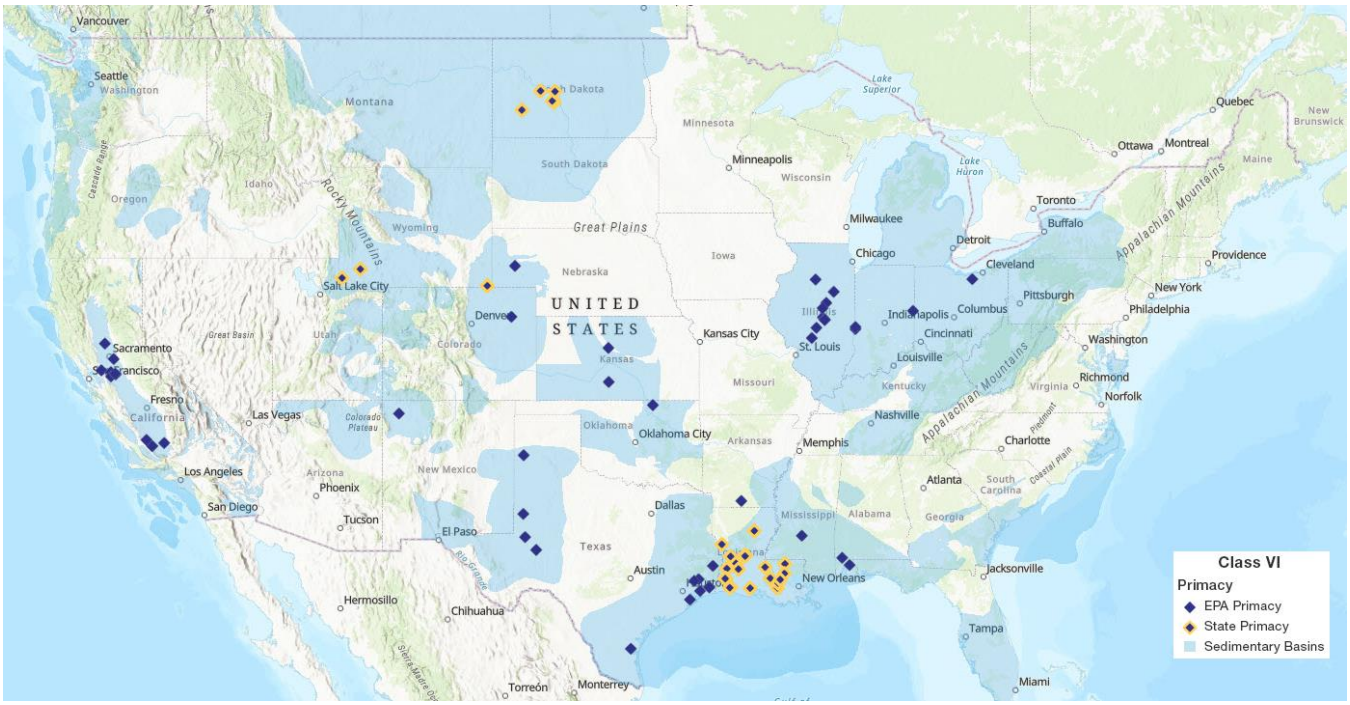

Figure 2. U.S. Map showing locations of current planned CCS projects along with major U.S. saline aquifers. (Data current as of July 2024 are from https://edxspatial.arcgis.netl.doe.gov/webmaps/carbon-management-connect-toolkit-index.html)

The expansion of CO_2 storage projects within a single basin presents new challenges that must be addressed to ensure that at the basin scale, storage resources are being utilized and managed safely and efficiently, with public acceptance and environmental justice considerations in mind. Facilitating the scale-up will also require characterizing the basins that are currently not being utilized, partly due to data uncertainty. The U.S. Department of Energy's (DOE) Office of Fossil Energy & Carbon Management (FECM) has funded R&D addressing the effects of the basin-scale deployment of geologic CO_2 storage, including basin-scale pressure effects (Birkholzer et al., 2009)[1] and recent work on basin-scale risks

[1] J. T. Birkholzer and Q. Zhou, "Basin-scale hydrogeologic impacts of CO_2 storage: capacity and regulatory implications," *International Journal of Greenhouse Gas Control*, Volume 3 (6), 745–756, 2009.

through the National Risk Assessment Partnership (NRAP) Program (Bacon et al., 2023).[2] However, effectively addressing the challenges associated with basin-scale deployment will necessitate:

- Improved characterization of multiple basins and basin-scale effects;
- Development of basin-scale monitoring approaches and technologies;
- Effective and transparent dissemination of basin-wide characterization and monitoring data to facilitate various decision-making processes, including pore-space leasing, site selection and development, permit application evaluation, and basin-wide injection operations; and
- Development of a robust set of tools that consider basin-scale effects to aid and expedite decision-making.

To address the basin-scale CO_2 storage technology deployment-related challenges, DOE has established the Carbon Basin Assessment and Storage Evaluation (CarbonBASE). Meanwhile, Department of Interior (DOI) bureaus and offices are developing regulatory guidelines, conducting basin-scale assessments, and developing models for managing the nation's extensive Federal land and ocean CO_2 storage resources, encompassing multiple storage basins.

In February 2024, DOE and DOI jointly hosted a basin-scale geologic CO_2 storage resource management workshop, bringing together over 70 participants to discuss associated challenges and R&D needs.

Workshop Objectives

The primary objectives of the workshop included: receiving inputs from a group of technical stakeholders to inform FECM about potential technical R&D needs for the CarbonBASE Initiative; providing DOI bureaus and offices information needed for effectively managing the Nation's Federal land and ocean resources; and discussing effective ways to aggregate and serve data to all stakeholders.

Participants & Agenda

The workshop was held on February 13 and 14, 2024, at the U.S. Geological Survey (USGS) National Center in Reston, Virginia. It was attended by over 70 participants representing Federal and state governmental agencies, industry, academia, national labs, and research organizations. The workshop agenda (**Appendix A. Workshop Agenda**) included eight sessions focused on different thematic topics. Each session included 2–3 short presentations given by experts with knowledge and experience relating to the thematic topic. The presentations were followed by breakout group discussions. To facilitate breakout group discussions, the participants were provided with a set of questions (**Appendix B. Breakout Group**) and were asked to provide feedback on the gaps in the data and knowledge required to answer the questions. Detailed descriptions of each of the workshop sessions and associated breakout discussions are provided in **Appendix C. Summary of Workshop Sessions**.

Workshop Feedback Summary

The feedback received through the breakout discussions highlighted new challenges that may arise with rapid deployment of multiple CCS and carbon dioxide removal (CDR) with storage projects in single

[2] D. Bacon, C. de Toledo, P. Morkner, C. G. Creason, G. Lackey, and R. Haagenson, "Assessing and Managing Risks of Geologic Carbon Storage at the Basin Scale," American Geophysical Union Conference, San Francisco, CA, December 11–14, 2023.

basins. FECM and USGS categorized the workshop feedback along the lines of non-technical issues and technical issues related to characterization, monitoring, models and tools needs, and other issues.

Technical Issues

Basin Characterization

The discussions related to characterization were broadly focused around three themes:

1. Data collection, integration, and analysis';
2. Mapping key basin-specific parameters that inform dynamic storage resource availability with increased utilization of pore-space; and
3. Leveraging opportunities that promote shared benefits in "multi-use" basins.

Data collection, integration, and analysis – Workshop participants stressed that characterization will be needed both for basins currently being targeted by project developers and ones not currently targeted but have storage potential. They identified a broad range of data that will be needed for effective characterization of basins, especially the extent of the basin features, which affect pressure propagation, and basin-scale impacts. Characterization of variability in geology, tectonics, geomechanics, groundwater quality, storage complex geochemistry, and hydrology across basins was identified as key need. Key challenges identified include high expense of collecting new data from new wells, quality checking existing data, creating and applying metadata schemas that ensure consistency and trust, limited availability of proprietary data, the labor-intensive aspect of reviewing data for relevance and value, and digitizing analog data. Workshop participants acknowledged that opportunities exist for cataloging, integrating, and analyzing existing and historic data from different data sources and different subsurface applications. FECM's Energy Data eXchange (EDX[3]) is one example of a data portal that could facilitate data integration and analysis activities. The participants acknowledged that openly sharing vetted and quality-checked information may be of greatest value to the public and the multiple stakeholders with subsurface resource interests.

Mapping key basin-specific parameters that inform dynamic storage resource availability with increased utilization of pore-space – In addition to collecting key subsurface data, participants recommended that a comprehensive set of geospatial maps be generated and made available to the public and stakeholders. These maps could include other dimensions beyond geologic CO_2 storage, thus engaging a broader range of stakeholders. Suggested basin-specific geospatial maps relevant for geologic CO_2 storage included:

- Basement structure, quaternary/other fault locations,
- Pressure maps,
- Permeability architecture,
- Hydrodynamic trends,
- Regional map of stress,
- Salinity variations,
- Lower-most underground sources of drinking water (USDWs),
- Reactive rock deposits (e.g., basalts), and
- Pore-space/surface ownership.

Workshop participants also suggested exploring artificial intelligence and machine learning applications that might assist in building and organizing large, complex, and diverse datasets (given inevitable differences in quality, units, metadata, scale, etc.) and addressing regional data gaps.

[3] https://edx.netl.doe.gov/disco2ver

Leveraging opportunities that promote shared benefits in "multi-use" basins – Discussion related to multi-use basins was largely centered around identifying data that were common for multiple subsurface exploration and utilization interests, which would help increase understanding of all subsurface resources. DOE's Energy Crosscuts and Energy Earthshots[4] are initiatives that seek to address the limited ability to cost-effectively assess, monitor, and access the subsurface and to improve the certainty around subsurface resource utilization. The Subsurface Energy Innovations (SEI) crosscut is one such effort that is taking a holistic approach to identifying common challenges and solutions.

Workshop participants remarked on the wide range of data from various industries (e.g., coal mining, gas storage, cement suppliers, and enhanced oil recovery) that provide parameters to support wellbore integrity, well design, and management practices in the carbon storage industry. Potential opportunities for cross-collaboration were highlighted, including hydrogen production, geothermal, and critical minerals extraction from produced brines. Workshop participants mentioned that the concept of project interferences could be extended to include interference between different types of projects (e.g., CO_2 storage and natural gas storage).

Basin-Scale Monitoring

Workshop participants highlighted various issues related to basin-wide monitoring that FECM and DOI organized into three themes:

1. Key monitoring parameters;
2. Basin-wide monitoring needs and strategies; and
3. Leveraging of existing infrastructure.

Key monitoring parameters – The workshop participants identified pressure (including its initial state and its evolution) as a key parameter that needs to be monitored throughout a basin because pressure propagates over large distances, which introduces the risk of fluid pressure interferences between projects. They acknowledged that pressure interference between projects in and of itself does not necessarily imply the creation of a hazardous condition, but it can affect the areas of review (AoRs) of projects that do not anticipate this interference. They also acknowledged that fluid pressure interference can also affect storage efficiency and injection performance of interfering projects. Participants also discussed the importance of monitoring USDW compositions and baseline seismicity. For offshore basins, establishing baseline and monitoring of environmental resources including the water column, baseline CO_2 levels, and biological resources were highlighted as key needs. Additionally, for offshore basins there is a need for potential environmental monitoring for sound impacts from geological and geophysical activities and seafloor disturbances from multiple storage operations.

Basin-wide monitoring needs and strategies – Deployment of effective basin-wide monitoring networks, especially in areas of the basin that are far-field[5] of CO_2 storage projects, was identified as one of the critical needs by workshop participants. Development of low-cost, higher sensitivity monitoring technologies for measuring far-field-induced dynamic pressure in different types of basins was also suggested. The participants also discussed how basin-specific velocity models would be useful for effective basin-wide monitoring of induced seismicity. Finally, development of effective mechanisms

[4] Energy Earthshots Initiative | Department of Energy

[5] Far-field, as used in this context, refers to areas outside the boundaries where individual projects are required to monitor.

and strategies for making basin-wide monitoring data readily accessible to a wide range of stakeholders was suggested as an important need for facilitating decision-making.

Leveraging existing infrastructure – To alleviate the potential high cost of basin-wide monitoring, it was suggested that opportunities to leverage existing monitoring programs should be explored, including USGS's national seismic monitoring network, various state geologic surveys' seismic monitoring networks, and regional water-well monitoring networks. Utilization of accessible legacy wells drilled for other purposes was suggested as another potential leveraging opportunity. Information for a subset of all wells within the United States has been gathered by the USGS National Index of Borehole Information (NIBI), which can be accessed via (https://webapps.usgs.gov/nibi/).

Models & Tools

Workshop participants suggested various models and tools for effective management of basins, which FECM and DOI organized in the following themes:

1. Geologic models;
2. Basin-scale predictive models; and
3. Modeling and tools to inform decision-making.

Geologic models – According to workshop participants, basin-scale geologic models representing different basin types will be needed to effectively assess storage resources and impacts. Furthermore, these models will need to effectively capture the basin-wide distribution of key geologic and hydrologic characteristics critical for assessing the effects of simultaneous injection of CO_2 by multiple storage projects and associated storage efficiency (or lack thereof). The participants suggested that these types of geologic models could also be useful to a wide range of stakeholders, including those involved in other subsurface activities.

Basin-scale predictive models – In addition to geologic models, workshop participants highlighted the critical need for computationally efficient[6] basin-scale predictive models and modeling approaches. Models will be needed to predict basin-scale dynamics resulting from CO_2 injection, including basin-wide evolution of fluid pressure, inter-project interference, dynamic evolution of individual project AoRs, pressure migration, brine displacement resulting from injection, and geomechanical effects. Additionally, participants also explained the critical need for approaches and models for quantifying basin-scale risks and dynamic evolution of risks. The participants also suggested developing risk assessment approaches and quantification models that take into consideration the unique aspects of the offshore environment for offshore basins.

Modeling and tools to inform decision making – The workshop participants explained the need to develop easy-to-use and computationally fast tools that can be used to make decisions about optimum project siting, pore-space leasing, permitting, monitoring, and safely managing different types of basins. These tools need to be adaptive such that the evolving conditions in a basin resulting from deployment of multiple projects can be easily accommodated. In addition, models for assessing effectiveness of basin-management strategies such as pressure management through brine extraction, techno-economic impact of project interference, including dynamic valuation of pore-space, were also highlighted.

[6] In this context, "computationally efficient" means models that run rapidly because they consider only the most sensitive paraments and do not necessarily account for all physical processes.

Field Tests, Data Sharing & Risk Mitigation Technologies

In addition to the issues mentioned above, the workshop participants highlighted other issues related to basin-scale deployment, which FECM and DOI organized in following themes:

1. Field tests and experiments;
2. Basin-scale risk mitigation strategies; and
3. Data sharing and data standardization.

Field tests and experiments – The workshop participants suggested the need for field experiments and field tests to generate data and information for better understanding of basin-scale effects, quantify sensitivities to critical risks, and test basin-wide monitoring technologies and strategies. Field experiments will be needed for both onshore and offshore environments given their differences.

Basin-scale risk mitigation strategies – To ensure safe management of basins and mitigate potential risks arising from basin-scale deployment, risk mitigation strategies and approaches need to be developed. These include brine production and management to reduce induced seismicity risk (with the additional advantages of improving pore-space utilization and beneficial use of treated brine), exploring concepts of alternate storage (such as stacked storage, buffer storage, or micro-storage) to alleviate fluid pressure increase and interference, de-risking of existing wells to reduce leakage risks, and developing basin-wide safety protocols.

Data sharing and data standardization – Developing protocols, mechanisms, and tools for making the data and information available to a wide range of stakeholders, including the public, was identified by the workshop participants as one of the critical aspects of facilitating the decision-making process for safe and efficient utilization of basin-scale resources, including and beyond CO_2 storage. Platforms such as FECM-funded EDX was mentioned as one potential tool. Effective data sharing will also require addressing topics such as standardization of data including metadata, aggregation of data, consistent data storing and metadata frameworks across government agencies (state and Federal), and other issues.

Non-technical Issues

While the workshop was intended to gather technical feedback, several non-technical challenges related to siting decisions, leasing decisions, permitting, and legal issues associated with trespass, liability, and pore-space value degradation were also addressed. Some participants noted that decision-making paradigms for project siting, leasing, and permitting are project-centric. The need for consideration of the dynamic evolution of basin-wide conditions as multiple CO_2 storage projects begin operating was highlighted. Some participants also noted that increased competition for subsurface pore-space, arising from multiple ongoing and planned uses of subsurface resources, will add further complexities to decision making. Timely information-sharing between various decision makers will be crucial. Some workshop participants also suggested that public-private partnerships and new regional entities may be needed to facilitate basin-scale deployments.

Key Takeaways and Possible Next Steps

After considering all individual perspectives, DOE and DOI identified the following key takeaways:

- There is a need to improve characterization data for both onshore and offshore basins to ensure efficient utilization of basin-scale CO_2 storage resources. This effort could refine the current understanding of basin-scale storage resources and provide information needed for multiple projects operating within single basins. This data need persists even in basins where multiple projects are already under development. Additionally, there is a need to accelerate the characterization of basins with storage options, such as basalts.
- Accurate measurements of in-situ fluid pressure and its evolution across a basin as multiple projects become operational are crucial to ensure safe and efficient utilization of basin-scale storage resources. These measurements will also be necessary to determine pressure interference between projects, pressure trespass across ownership boundaries and to assess the present and future economic value of storage resources.
- There is a need to develop and deploy monitoring technologies and infrastructure to assess basin-scale impacts of CO_2 injection. This monitoring effort is especially needed in the parts of the basins outside of the AoRs of individual projects. Potential leveraging opportunities could exist with present regional and national monitoring infrastructure, such as USGS's seismic network.
- There may be ambiguities in decision-making processes that need to be addressed regarding potential project interferences when multiple projects are deployed in a single basin.
- Transparent sharing of basin-wide data and information without compromising data sensitivity is crucial to support decision-makers. Furthermore, transparent information sharing could promote public trust in the integrity of CO_2 storage projects.
- With growing competition for subsurface resources, current resource management approaches will need to be reconsidered to ensure the successful deployment of technologies and efficient utilization of all subsurface resources.
- There are opportunities to leverage the collection of CO_2 storage related characterization and monitoring data as various basins within the United States are increasingly being utilized for diverse subsurface energy and environmental applications.

FECM Possible Next Steps

Building on the key takeaways highlighted above, FECM has identified three potential next steps for implementation in the near term.

1. CarbonBASE Technical R&D Scope Development

The workshop's main objective for FECM was to gather input from workshop participants to identify priority research areas for the development of the technical R&D scope of CarbonBASE. As highlighted in the key conclusions, the immediacy of implementing a basin-wide carbon storage resource management strategy is paramount if CCS and storage-based CDR industries are to grow at the pace needed to meet decarbonization goals. In light of the workshop outcomes, FECM has identified the following high-priority elements that could be incorporated into the CarbonBASE R&D scope:

- Develop a data collection strategy aimed at addressing existing data gaps;
- Prioritize fluid pressure modeling and monitoring as a key aspect of basin-wide carbon storage resource utilization management;
- Create informational resources and tools to guide decision making;
- Ensure data accessibility to the public; and
- Consider leveraging various subsurface energy activities, such as geothermal, critical minerals extraction, and oil and gas production to enhance data collection.

2. Engagement to Inform Policy

Some workshop participants' views aligned with the notion that the laws, policies, and regulations governing carbon storage may be ambiguous about the various interferences that can arise between projects (e.g., converging pressure fronts, pore-space encroachment, pore-space economic value degradation, competing uses of subsurface resources, etc.). Moreover, onshore and offshore carbon storage can cross state and jurisdictional boundaries. These issues could be exacerbated as geologic storage resource utilization rapidly expands within any given basin. Therefore, it is important to understand the ambiguities and gaps that could create barriers for basin-wide deployment of CO_2 storage projects.

Given these circumstances, the near-term next steps FECM could take to help inform stakeholders about effective and efficient management of basin-wide storage resources include identifying engagement pathways with key stakeholders to inform the CarbonBASE program about the data needs and tools that will be most useful to policymakers and instill public confidence in the integrity of CO_2 storage projects.

3. Future Governance of Basin-Wide Carbon Storage Resources

An outcome of the workshop was the recognition that effective management of carbon storage resources in the United States will require oversight and monitoring of multiple geologic basins with carbon storage resources, each with its own unique geology and rate of storage resource utilization as multiple projects or hubs deploy over time. The footprint of a basin can be a patchwork of Federal, state, and private land ownership, each having its respective pore-space rights to utilize or lease pore-space for carbon storage. Workshop participants acknowledged there is no single organization or government agency/office that has clear jurisdiction or authority to act as a steward of carbon storage resources within individual geologic basins of the United States. Rather, carbon storage resource management can involve competing interests from multiple stakeholders that if not addressed may impact scale-up of CCS/CDR with storage projects.

The White House Council on Environmental Quality (CEQ) issued guidance on carbon capture, utilization, and storage (CCUS) in 2022,[7] which included a recommendation for appropriate government agencies to implement, when feasible, a national program for monitoring deep geologic carbon sequestration. Given the diverse landscape of stakeholders and interests, a monitoring program would need to be based on an understanding of the information and data that enable a storage resource management framework. Therefore, a near-term next step FECM could take to help address the governance issue is to consider scope within the CarbonBASE program that includes elements of engagements with various stakeholders, including representatives from Federal agencies and state government offices, to

[7] "Carbon Capture, Utilization, and Sequestration Guidance," Council on Environmental Quality [CEQ–2022–0001] 8808 F.R. Vol. 87, No. 32, at 8810 (https://www.govinfo.gov/content/pkg/FR-2022-02-16/pdf/2022-03205.pdf), 2022.

understand and inform potential future governance needed to address basin-scale issues, as well as considerations related to regional policies and authorities.

DOI Possible Next Steps

Based on the feedback from the workshop and guidance from the land management bureaus, DOI has identified three major themes for potential future work:

1. Detailed Storage Resource Evaluation for Federal and Other Lands

The U.S. Government land management bureaus act as stewards to a vast area onshore and offshore, but not all this land contains the geologic conditions that are suitable for safe, long-term CO_2 storage. There is a need for rigorous estimates of geologic CO_2 storage resources for areas that are likely to be developed. Particular attention could be paid to deconflicting carbon storage lease siting with energy, mineral, and other surface and subsurface uses, including of the OCS. The near-term next steps DOI bureaus could take include:

- Expanding the collection and sharing of basic basin geologic data that are needed to better characterize storage basins particularly in federally managed areas.
- Working with stakeholders to facilitate the digitization of legacy data from paper (digitize the analog) and hold geologic storage workshops, trainings, data/knowledge sharing avenues, etc., for Federal and state land management agencies.

2. Subsurface Monitoring Infrastructure

DOI needs infrastructure in place to perform detailed subsurface monitoring in federally managed areas before and after CO_2 storage project development. Monitoring data are needed for subsurface fluid pressure variations, ground water quality, and for CO_2 injection-related induced seismicity. Particular sets of risks need to be accounted for when storing CO_2 in Federal waters in OCS environments. Research could focus on understanding the impacts to the natural environment of potential CO_2 leakage to benthic communities, water geochemistry, commercial fisheries, infrastructure, human safety, and other areas. In addition, environmental monitoring is needed for all physical (e.g., geological, water, air), biological (e.g., benthic communities, marine mammals, fish), sociological, and cultural environmental resources, as well as human safety. Environmental monitoring will be needed for more than just the potential of CO_2 leakage, but for all potential environmental impacts, such as sound impacts from geological and geophysical activities, vessel strikes, seafloor disturbances from drilling and infrastructure installation, and related issues. Therefore, a near-term next step that DOI bureaus could take is to establish a working group to identify components of monitoring networks on Federal lands and OCS and potential leveraging opportunities with existing DOI monitoring infrastructure.

3. Computational Simulations

Computational simulations are important methods for assessing the migration of CO_2 in the subsurface, the fluid pressure buildup associated with injection, and the potential for leakage out of the storage formation into overlying formations, the waters above the sediment-water interface in offshore storage, or to the atmosphere.

Pressure management is a crucial component of the successful rollout of multiple CO_2 storage projects on Federal lands. Injection wells and storage projects will increase the fluid pressure in the subsurface. To estimate the subsurface flow of different fluids in porous media and how the pressure generated by injection wells and storage projects might interact in the subsurface, there is a need for accurate models

to manage the pressure buildup under Federal lands. There is also a need to understand how the production of formation water or other pressure mitigation approaches will impact CO_2 storage projects.

Workshop participants suggested that a pilot CO_2 storage project in Federal waters would help to identify the models, storage methods, and monitoring techniques that work best in the offshore environment.

A near-term next step for DOI bureaus may be to initiate development of geologic and computational models for basins within the Federal lands and OCS as well as associated risk-assessment models.

DOE/DOI Potential Synergies

Based on feedback from workshop participants, DOE FECM and DOI see the opportunity to work cooperatively in areas of mutual interest and benefit while conforming to their respective agency missions. The goal of the FECM CarbonBASE initiative is to provide the capabilities and information to assess, manage, and monitor the nation's carbon storage resources for enabling the safe, equitable, and environmentally responsible scale-up of the CCS and storage-based CDR industries. This effort will take FECM in new R&D directions in subsurface characterization, modeling, and monitoring technologies, as well as data organization and sharing. The DOI mission includes several programs that have the potential to align well with this initiative. These include:

- **USGS Energy Resources Program** – conducts basic and applied research on geologic energy resources and on the environmental and economic impacts of their production and use, including evaluation of pore space availability and suitability for multiple types of storage.
- **USGS National Geospatial Program/3D Elevation Program** – provides digital elevation data and products for the nation.
- **USGS Mineral Resources Program/Earth Mapping Resources Initiative**[8] – collects foundational geoscience data on the Nation's surface and subsurface, including geophysical surveys important to the study of pore space.
- **USGS Advanced National Seismic System** – includes a national backbone network, the National Earthquake Information Center, the National Strong Motion Project, and 15 regional seismic networks operated by USGS and its partners.
- **USGS National Index of Borehole Information**[9] – compiles USGS and state geological surveys' locations and data from existing boreholes and related subsurface resource data.
- **USGS National Water Quality Program –** provides an understanding of water quality conditions and how natural features and human activities affect those conditions.
- **USGS National Cooperative Geologic Mapping Program –** provides a national geologic framework model of the Earth through geologic mapping and associated research.
- **Bureau of Land Management (BLM) Lands, Realty & Cadastral Survey –** administers leases, permits and right-of-way authorizations (ROWs) support for energy development, film production and other economic activities.
- **Bureau of Ocean Energy Management (BOEM) Resource Evaluation Division –** provides support for all of BOEM's program areas, both energy and non-energy, through critical technical and economic analysis.

[8] https://www.usgs.gov/centers/gmeg/science/minframe-methodological-infrastructure-needed-resource-assessment-modeling-and
[9] https://webapps.usgs.gov/nibi/

- **Bureau of Safety and Environmental Enforcement (BSEE) Office of Offshore Regulatory Programs –** provides strategic guidance in support of BSEE's regulatory oversight and enforcement mission.

These DOI programs, among others, are designed to serve the national interest in understanding, protecting, and utilizing the Federal subsurface resources for the responsible stewardship of these resources in the benefit of the public. Each of these programs represent an opportunity for integrating data and information with CarbonBASE in support of the safe deployment of CCS/CDR for meeting the nation's decarbonization goals. In recognition of this, FECM and DOI bureaus plan to meet regularly to identify lanes of alignment within their respective programs and to map out a cooperation plan that mutually benefits and strengthens their respective mission spaces.

Appendix A. Workshop Agenda

Basin Scale Issues for Carbon Storage

Joint Department of Energy – Department of Interior Technical Workshop

February 13 & 14, 2024

Main Auditorium, USGS National Center

12201 Sunrise Valley Drive

Reston, Virginia

Day 1 (February 13, 2024)

7:30 am – 8:15 am **Registration, Security Check-in, Refreshments**

8:15 am – 8:25 am **Welcome**

David Applegate, Director, United States Geological Survey

Amanda Raddatz, Division Director, Fossil Energy Carbon Management, Department of Energy

8:25 am – 8:40 am **Workshop Objectives**

Rajesh Pawar, Fossil Energy Carbon Management, Department of Energy

Sean Brennan, United States Geological Survey

8:40 am – 10:20 am **Session 1: Basin-scale effects**

- Presentations identifying issues/current state of the art (10 minutes each)
  - Jens Birkholzer – Lawrence Berkeley National Laboratory
  - Volker Oye – NORSAR
  - Robert Dilmore – National Energy Technology Laboratory
- Facilitated discussion in breakouts (40 minutes)
  - What are the required data? What are the key knowledge/data gaps? What tools/models can be useful?
  - Report out/ follow-on discussion - 30 minutes

10:20 am – 10:35 am Break

10:35 am – 12:05 pm **Session 2: Project siting considerations (onshore/offshore)**

- Presentations identifying issues (10 minutes each)
  - Tara Righetti, University of Wyoming

  - Melissa Batum, Bureau of Ocean Energy Management
- Facilitated discussion in breakouts (40 minutes)
  - What are the major technical issues? What are the data needs? What types of models/tools can be useful?
  - Report out/follow-on discussion – 30 minutes

12:05 pm – 1:30 pm Lunch (on your own)

1:30 pm – 3:00 pm Session 3: Effective basin management for different types of basins

- Presentations identifying issues (10 minutes each)
  - Randy Locke, Illinois State Geological Survey
  - Sue Hovorka, Bureau of Economic Geology
- Facilitated discussion in breakouts (40 minutes)
  - What are major issues? What are required data? What are knowledge/data gaps? What types of models/tools can be useful?
  - Report out/follow-on discussion – 30 minutes

3:00 pm – 3:15 pm Break

3:15 pm – 4:15 pm Session 4: Industry perspectives on basin-management issues

- Presentations identifying issues (10 minutes each)
  - Chris Walker, BP
  - Robin Ozah, Talos Energy
  - Joseph Jephson, Carbon Terravault
- Facilitated discussion (30 minutes)
  - What are major issues? What are major data needs? What types of models/tools can be useful?

4:15 pm – 4:30 pm Day 1 Recap

Day 2 (February 14, 2024)

7:45 am – 8:30 am Security Check-in, Refreshments

8:30 am – 8:45 am Day 2 Overview

8:45 am – 10:15 am Session 5: Regulatory aspects/Safe management (onshore/offshore)

- Presentations identifying issues (10 minutes each)
  - Onshore – Molly McEvoy, United States Environmental Protection Agency
  - Offshore – Stacey Noem, Bureau of Safety and Environmental Enforcement
- Facilitated discussion in breakouts (40 minutes)
  - What are the major data needs? What types of models/tools can be useful?
  - Report out/follow-on discussion – 30 minutes

10:15 am – 10:30 am Break

10:30 am – 12:00 pm Session 6: Characterization of conventional/unconventional resources to reduce data scarcity and uncertainty

- Presentations identifying current status and needs (10 minutes each)
  - Peter Warwick, United States Geological Survey
  - Jessica Moore, American Association of State Geologists
- Facilitated discussion in breakouts (40 minutes)
  - What data are required? What are major data gaps? How should data collection efforts be prioritized (which data and where)?
  - Report out/follow-on discussion – 30 minutes

12:00 pm – 1:30 pm Lunch (on your own)

1:30 pm – 3:00 pm Session 7: Multi-resource related opportunities

- Presentations identifying issues (10 minutes each)
  - Matthew Merrill, United States Geological Survey
  - Julien Caubel, Office of the DOE Under Secretary for Science & Innovation
- Facilitated discussion in breakouts (40 minutes)
  - What are synergy opportunities? What are major data needs?
  - Report out/follow-on discussion – 30 minutes

3:00 pm – 3:15 pm Break

3:15 pm – 4:45 pm Session 8: Data sharing approaches/platforms

- Presentations identifying issues (10 minutes each)
  - Kelly Rose, National Energy Technology Laboratory
  - Sean Brennan, United States Geological Survey
- Facilitated discussion in breakouts (40 minutes)
  - What types of tools/approaches can facilitate effective data sharing?
  - Report out/follow-on discussion – 30 minutes

4:45 pm – 5:15 pm **Recap and Adjourn**

Appendix B. Breakout Group Questions

Session 1: Basin-scale effects

- What are the required data? What are the key knowledge/data gaps? What tools/models can be useful?
  - Considerations for discussions may include but are not limited to….
    - Variability in formation characteristics and in-situ conditions across the basins
    - Pressure/plume interference
    - Poro-elastic effects
    - Horizontal brine migration
    - Effects beyond target reservoirs (vertical/horizontal directions)
    - Opportunities for targeted field experiments for collecting data
- Please identify high-priority items

Session 2: Project siting considerations (onshore/offshore)

- What are the major technical issues? What are the data needs? What types of models/tools can be useful?
  - Considerations for discussions may include but are not limited to….
    - Data that will aid effective leasing, site screening and site selection process – from basin-scale perspective
    - Effective tools for site-developers as well as decision-makers (e.g. private, government lease holders) for selecting sites where competition for storage resource utilization exists
    - Tools to help with leasing decisions that ensure optimal use of storage resource
- Please identify high-priority items

Session 3: Effective basin management for different types of basins

- What are major issues? What are required data? What are knowledge/data gaps? What types of models/tools can be useful?
  - Considerations for discussions may include but are not limited to….
    - Needs for developing basin-scale earth models for different types of basins
    - Site selection criteria and processes for different types of basins
    - Future technologies needed to effectively monitor basin-scale impacts for different basin-types (direct and in-direct)
    - Opportunities for developing or leveraging national/regional level monitoring infrastructure
    - Project development and management strategies to ensure optimal and efficient use of basin-scale storage resources
- Please identify high-priority items

Session 5: Regulatory aspects/safe management (onshore/offshore)

- What are the major data needs? What types of models/tools can be useful?
  - Considerations for discussions may include but are not limited to….
    - Management of leakage/induced seismicity risks beyond individual project's AoR

    - Tools that allow regulators to evaluate permit applications with consideration to potential project interferences and aggregated impacts
    - Basin-scale earth models and computational simulations
    - Differences between project-level safety and basin-scale safety
- Please identify high-priority items

Session 6: Characterization of conventional/unconventional resources

- What data are required? What are major data gaps? How should data collection efforts be prioritized (which data and where)?
    - Considerations for discussion may include but are not limited to….
        - Key characterization needs and data gaps in basins where projects are currently being deployed
        - Key characterization needs to facilitate CO2 storage development in data-sparse basins (leading to higher uncertainty in project costs)
        - Leveraging opportunities with other ongoing characterization/data collection efforts?
        - Relevant legacy data and avenues for their curation/effective utilization (digitization)
- Please identify high-priority items

Session 7: Multi-resource related opportunities

- What data from other resource industries are unavailable, needed?
- What data act as bridges between industries, what could be improved?
- How do we approach data deserts – areas with little oil and gas data?
- Is infrastructure data a high value data point to target?
- How do we define multi-resource basins?
    - 2D is not sufficient – inherently 3D resource set
- Define by fluid flow? Or some other characteristic? How we deal with ‘edges’?

Session 8: Data sharing approaches/platforms

- What types of tools/approaches can facilitate effective data sharing?
    - Considerations for discussion may include but are not limited to….
        - Metadata strategies
        - Data aggregation strategies, e.g. geo-spatial (e.g. ArcGIS Online or AGOL) versus unstructured data (Data Lake)
        - Approaches to ensure data trust
        - Efficient data sharing infrastructure for use by different stakeholders for multiple purposes
- Please identify high-priority items

Appendix C. Summary of Workshop Sessions

Each workshop session included a set of presentations and breakout group discussions. To facilitate the breakout group discussions the workshop participants were provided a set of questions which are documented in Appendix B. The summaries of presentations and breakout group discussions for each of the workshop sessions are provided below.

Session 1: Basin-scale effects

Presentations

- *Managing a Gigatonne CCS Future: Basin-Scale Storage Challenges*, Jens Birkholzer (Lawrence Berkeley National Laboratory)
- *Basin-scale impacts from Gigaton CO_2 storage: A short recap on the improving of earthquake detection and location capabilities to prepare for safe CO_2 storage*, Volker Oye (NORSAR)
- *Assessing and Managing Risks of Geologic Carbon Storage at the Basin Scale: Perspective from the U.S. DOE's National Risk Assessment Partnership*, Robert Dilmore (National Energy Technology Laboratory (NETL))

Presentations Summary

The session on basin-scale effects of gigaton carbon dioxide (CO_2) storage featured three presentations focusing on the implications and dynamics of large-scale simultaneous injections within a basin. Jens Birkholzer emphasized the importance of regional coordination and far-field characterization to mitigate risks such as pressure interference among neighboring storage sites within the framework of large basins with multiple sites. Additionally, it was emphasized that the gigaton CCS future in the United States is starting to materialize, as evidenced by the map showing projects that have submitted U.S. Environmental Protection Agency (EPA) Class VI permit applications or been publicly announced. Specifically in California, CCS projects with cumulative injections range from 3.8 to 71 million metric tons (MMT) of CO_2. Furthermore, Birkholzer addressed the ongoing DOE project at LBNL on developing a framework for simulation-based storage management at the basin scale. Birkholzer concluded by emphasizing the need for new ideas to efficiently monitor basin-scale impacts, such as fault activation in caprocks.

Volker Oye provided an overview of seismicity challenges associated with gigaton-scale carbon storage, emphasizing the necessity of preparing for increased pressure and fault encounters while also stressing the importance of public perception management and cost-effective monitoring solutions, including emerging technologies like fiber-optic monitoring for offshore sites. Robert Dilmore discussed NRAP and its tools — such as the Open Integrated Assessment Model (NRAP-Open-IAM), State of Stress Analysis Tool (SOSAT), Operational Forecasting of Induced Seismicity (ORION) and Risk-Based Adaptive Monitoring Planning (RAMP) — emphasizing their role in evaluating basin-scale risks such as leakage, geomechanical instability and induced seismicity. Dilmore identified computational expense, model limitations, data collection constraints, and uncertainties as primary challenges in basin-scale modeling and risk assessment. Dilmore advocated for enhanced data collection, geologic characterization, and comparative studies to facilitate the success of basin-scale CCS deployment.

Breakout Discussions

The breakout discussions identified a broad range of data (as well as their variability within basins) that will be needed for effective characterization of basins and basin-scale impacts, including information on

geology, tectonics, groundwater quality, storage complex geochemistry and hydrology. The characterization data needs could be addressed through new, fit-for-purpose stratigraphic characterization wells and a range of geophysical technologies including, seismic, InSAR, and electromagnetic surveys. It was noted that exhaustive new data collection campaigns may be cost-prohibitive and review of existing data to aid in characterization of basins will be essential. In addition to data to characterize basins, data needs related to public land suitability and legacy wells were also highlighted.

Specific tools/models identified through the breakout discussions included: basin management tools; easy-to-use tools/models to inform operations as injection progresses; and effective ways to incorporate basin-scale modeling and boundary conditions within individual project-scale models.

In addition to data and models, other highlighted technical issues included strategic monitoring to reduce basin-scale risks; strategies for de-risking legacy wells; development of far-field monitoring techniques; better understanding of environmental impacts in offshore settings; better characterization of pressure interference and truthing of models with real data. Specific ideas for targeted field projects included: basin-specific experiments including in offshore settings to quantify sensitivities to critical risks (e.g., induced seismicity, environmental effects of CO_2, and injectivity, etc.).

Related to non-technical gaps, it was noted that a regulatory process that addresses simultaneous multi-project deployment was needed. The need to make private data publicly available (e.g., seismic monitoring data, pressure data) was identified as an important challenge, especially since there are multiple stakeholders with potentially competing needs.

Session 2: Project siting considerations (onshore/offshore)

Presentations

- *Onshore Project Siting Considerations*, Tara Righetti (University of Wyoming)
- *Carbon Sequestration on the Outer Continental Shelf*, Melissa Batum (BOEM)

Presentations Summary

Tara Righetti provided insights into critical considerations for siting onshore projects within the basin-scale geologic CO_2 storage framework. Righetti explored the complexities surrounding Federal and tribal lands, including ownership, management, and authority issues. Challenges such as coordination hurdles, multi-resource conflicts, and regulatory fragmentation were discussed, emphasizing the need for harmonization and cooperation. Additionally, the presentation highlighted the significance of fair market value assessments, especially regarding pore-space, and the need for basin-scale appraisals. Righetti concluded the presentation with strategic considerations for storage project operators, stressing the transition from exclusivity-driven frameworks to cooperation-centric approaches for risk and liability management.

Melissa Batum's presentation highlighted critical science and data needs for offshore leasing and planning decisions. It outlined decision steps and emphasized adherence to legal, regulatory, and policy frameworks governed by BOEM and BSEE. The presentation stressed the importance of considering national and regional resource assessments, environmental impacts, and operational requirements for safe and environmentally responsible carbon sequestration activities on the Outer Continental Shelf.

Breakout Discussions

The breakout discussions revealed that the site selection process for basin scale deployment involving multiple projects will be complex, due to many interrelated factors that need to be taken into consideration. One of the identified overarching issues was how to utilize storage space most-effectively to avoid creation of "wasted" storage areas between projects. Project-specific, technically usable storage needs to be identified which involves knowledge of factors such as the permeability architecture of sites and possible compartmentalization. Fluid pressure propagation needs to be understood, including impacts of possible pressure barriers and faults and the potential role of non-net reservoirs to alleviate pressure. Additional issues to consider included impacts of legacy fluid injection (e.g., produced water disposal) on pore-space availability, impacts of producing brines required for pressure management, potential setbacks from exploration for other subsurface resources, impacts of surface ownerships on site development, non-traditional/unconventional storage targets.

Multiple non-technical issues related to siting were identified, including pore-space ownership and the need for assessing fair market pore-space value, particularly for marginal storage resources, reportable storage resource (i.e., capacity) for lease valuation, and deconfliction of stacked resource utilization (e.g., hydrocarbon extraction, brine disposal, CO_2 storage, rare earth mineral extraction, etc.). Legal issues include pressure trespass, forced unitization, and long-term liability. Regarding data needs, there was considerable discussion in the roundtables related to the need for standardized data sets and data access. Specific suggestions included:

- Concerted, specific effort to identify different requirements for onshore vs offshore with respect to requirements for required data and model inputs.
- Build a readily accessible data commons and promote reuse of existing resources.
- Utilize EPA Class VI permit data.
- Digitization of historical published studies and existing state agency data.
- Easy to access surface ownership maps on basin scale.

The breakout discussions also yielded specific suggested data needs, including reservoir and containment/seals data, depositional sequence stratigraphy, chemical engineering data for injected fluid, cement integrity testing data, pipeline data — capacity accessibility, seismic data, legacy well data, data on underground sources of drinking water (USDWs), and microseismicity data.

In addition to the tools related to data accessibility discussed above, the roundtable discussions suggested a variety of models/tools useful for siting: a caprock analysis tool, a site-screening and site-selection tool incorporating uncertainty and risk, geologic/reservoir multiscale models for offshore, socio-economic impact assessment tools, and public communication tools development of applicable tools/designs to ensure CCS is not restricted to specific regions, potentially "stranding" sources outside those regions.

Session 3: Effective basin management for different types of basins

Presentations:

- *Illinois Basin Characteristics and Issues*, Randy Locke (Illinois State Geological Survey)
- *Effective basin management for different types of basins*, Sue Hovorka (Bureau of Economic Geology)

Presentations Summary:

Randy Locke's presentation started with an overview of the Illinois Basin's storage potential, stratigraphy, structure of the storage complex, and generalized reservoir properties. The presentation covered technical challenges at various scales, from unit to system-wide considerations. Addressing the need for improved data resolution, Locke proposed a comprehensive airborne geophysical survey to enhance understanding and mapping of the subsurface geology of the remaining 85% of the state. Key recommendations for effective basin management included establishing interagency oversight committees, fostering coordination between Federal, state, and local governments for permitting and regulation, clarifying pore-space ownership rights, and enhancing public engagement to ensure informed decision-making in CCUS activities.

Sue Hovorka presented perspectives on managing subsurface space limitations in the Gulf Coast Region. Hovorka emphasized the importance of understanding basin-specific parameters in setting injection limits, highlighting strategies such as stacked storage to manage permeability and thickness constraints and locating injectors far from faults to manage geomechanical limits. Management mechanisms for boundary conditions involved pressure relief through brine production and the presence of large amounts of non-reservoir rocks. The presentation also addressed challenges such as accurately forecasting pressure, which requires considering all projects that might be in communication, and the additional limitations on pressure due to seismicity risk. Hovorka also acknowledged the difficulties arising from limited data, experience, and the heterogeneous state of stress in managing these challenges.

Breakout Discussions

One overarching issue identified in the breakout discussions was the need for basic basin characterization data and improved knowledge of in-situ properties and their spatial variability. The discussions identified a variety of technical activities that could be undertaken to fill knowledge/data gaps:

- Preliminary data collection for each basin: gravity/magnetic survey to establish depth to basement, a deep well with a full log suite, and water salinity profile all the way to basement.
- Basin-wide monitoring of local water wells for changes in water levels.
- Studies to determine if basins of different age respond differently to elevated fluid pressure.
- Advancing USGS and state seismic monitoring arrays within a basin prior to storage operation.
- Development of physics-based reduced order models (ROMs), geocellular models to understand the basin-scale sensitivities.
- Development of basin-wide seismic velocity models.
- Basic studies of geomechanics properties of different lithologies - sandstones, limestones, mudstones, etc.
- Studies to assess efficacy of mixed slurry (non-supercritical) injection that might be proposed for mixed mafic layers in sedimentary basins.

Data accessibility and data management were identified as important issues; it was noted that most projects do not currently enlist professional data management personnel. Suggested approaches to address data issues included: creation of a basin injection authority regulatory body that enforces data sharing; development of a collaborative industry government framework for monitoring data; collection and sharing of pre-existing EPA Class I data; development of publicly available, easy to use web-based

apps; making recorded seismic events publicly available; and development of standards for reporting monitoring data.

Session 4: Industry perspectives on basin-management issues

Presentations

- *Basin Scale Issues for Carbon Storage*, Chris Walker (BP)
- *Industry Perspective – Basin Management Issues*, Robin Ozah (Talos Energy)
- *Basin-Scale Effects of Carbon Storage*, Joe Jephson (Carbon Terravault)

Presentations Summary

This session featured three speakers offering industry perspectives on basin-management issues. Chris Walker mentioned that CCUS value chains are complicated due to the involvement of multiple parties from source to sink; the technical transfer of molecules, ownership and risk and liability between counterparties. Investment timelines are often long (three-plus years from investment to start up) and projects involve long-term commitments (on scale of decades). Walker noted that basin management of storage projects in Federal waters should be technically simpler due to a single surface and mineral owner, although overlapping leases will need careful coordination to co-exist in an efficient fashion (e.g., carbon storage and wind power plant). In contrast, onshore basins are more complicated due to a patchwork of many surface and mineral owners and general public opposition to development. Academia and government can assist by ensuring compatibility of monitoring data collected by private operators; establishing common monitoring networks; and providing factual information to stakeholders on groundwater protection, induced seismicity and pipeline safety.

Robin Ozah presented a technical take on issues related to carbon storage and transport. Ozah mentioned that overlap of pressure and CO_2 plumes between nearby leases could lead to unfavorable scenarios. There is an identified need to develop a unitization for CO_2 front and pressures, to pre-develop alignment of neighboring projects, and to encourage data and results sharing during monitoring. Regarding legacy wells, alternative cost-effective and low-impact materials are needed to replace CO_2-resistant cement. Seismic is needed over large areas and may require frequent imaging. 2D imaging may miss details in shallow sections while 3D imaging is expensive and time consuming — combinations of both may provide a more cost-effective and detailed solution. Full wave inversion (FWI) has the potential to provide greater coverage than vertical seismic profile (VSP)/VSP distributed acoustic sensing (DAS). Regarding transportation and pipelines, only a handful of existing CO_2 pipeline networks exist and are not rated for CO_2 of mixed or high impurity, while the whole endeavor is expensive for point source projects in general. Carbon dioxide pipeline networks will need to be expanded with midstream and major developers and shipping will need to be developed for offshore projects.

Joe Jephson presented an overview of issues facing basin management. The presentation notes that "the best basins" are already crowded, and there are many project risks such as technical, regulatory/policy uncertainty, overcapitalization, and confidentiality. Projects could conduct early stakeholder engagement and bias themselves toward action with a balanced approach. Jephson's proposed philosophy includes prioritizing near-term actionable projects and consolidated hubs, considering interpretation and uncertainty during basin-level characterization, accelerating de-risking and scaling efficiencies, risk management, and developing the supporting science to inform legal/policy framework. Jephson suggested various topics for FECM to consider for the CarbonBASE Initiative,

including field validation of subsurface characterization and performance; supporting advancing permits; exploring basin-scale efficiencies in monitoring, response, and financial assurance; risk-based basin development strategies; and revisiting the Brine Extraction Storage Test (BEST) Program and supporting pressure management for beneficial water use.

Breakout Discussions

There were no associated breakout group discussions.

Session 5: Regulatory aspects/safe management (onshore/offshore)

Presentations

- *Onshore – UIC Class VI Permitting*, Molly McEvoy (EPA)
- *Offshore,* Stacey Noem (BSEE)

Presentations Summary

Molly McEvoy provided an overview of the Underground Injection Control (UIC) Class VI permitting process. As of February 2024, U.S. EPA agency has received 127 UIC Class VI permit applications across 43 projects. In the cases where projects are located near each other, McEvoy emphasized the significance of accurate site characterization for these permits. However, information from pending Class VI projects, such as the location of injection wells and specific operational parameters, is often protected through a Confidential Business Information agreement. Consequently, project developers face challenges in assessing areas of review (AoR) overlap and pressure interaction from CO_2 injection activities of nearby projects.

Stacey Noem provided an overview from an offshore perspective. Noem mentioned that BSEE is currently in the rule making process related to CO_2 storage on OCS. BSEE is currently performing studies focused on identifying CO_2 storage potential in OCS and will be sharing its results. Noem mentioned that while offshore storage options are less complicated in terms of pore-space ownership as well as leasing and regulatory authorities compared to onshore, offshore settings pose their own significant challenges. A number of basin-scale related challenges for offshore settings will be similar to those in onshore settings, including fluid pressure propagation, interference, plume migration and basin-scale resource management, however a few environmental monitoring requirements will be different. Noem noted that as deployment of OCS projects increases, BSEE will update the CO_2 storage related rules as needed.

Breakout Discussions

The breakout group discussions identified a broad range of required data to assess the uncertainty of basin-scale effects. Data are needed to identify the established storage complexes and geologic boundary conditions (stratigraphic traps, faults) and to characterize variations of geomechanical properties across the basin. The review of existing well test data (average porosities, permeabilities, brine salinities, etc.) and monitoring data in every monitoring sphere (deep geosphere, shallow geosphere, hydrosphere, atmosphere/marine biosphere) is desired. Additional focus was given to data related to materials for offshore pipelines and facilities.

For the management of leakage/induced seismicity risks beyond an individual project's AoR, the discussions highlighted the complex nature of basins, which are not singular flow systems but rather compartmentalized to varying degrees. Therefore, it was recommended to categorize the basin into sub-basins regions, wherein regulators and operators would carry out best practices at the multi-

project-scale level. One of the identified overarching issues for these sub-basins was to demonstrate the implications of interproject impact. Another aspect to consider is how effectively injection zones in stacked reservoirs are regulated to prevent project overlap. Adaptive monitoring strategies, baseline monitoring, and basin-level monitoring interaction were identified in the roundtable discussion as technical knowledge gaps. Basin-scale strain measurements (remote sensing, above-zone monitoring) were identified as important tools for assessing time-dependent deformations. In offshore environments, acoustic sound source permitting for seismic surveys were desired to address basin-scale safety. Related to non-technical gaps, it was noted that jurisdiction of the scale effects is not well understood. Specific suggestions included:

- Determine the regulatory agency or designated applicant accountable for addressing interference in basin-scale injection projects.
- Establish responsibility attribution in cases of brine containment failure, including identification of the operator(s) contributing to pressure irregularities and their respective liabilities.

In addition to the data needs discussed above, there was considerable discussion on the need for data accessibility and data projection to ensure transparency across multiple operators. Specific suggestions included:

- Identifying effective strategies for restricting cross-border injection within a specified region or jurisdiction.
- Determine the feasibility and mechanisms for operators to furnish voluntary well information on an anonymized grid system (e.g., Texas Seismological Network and Seismology Research [TexNet]).
- Develop a derivative data product that safeguards the precise location of injection sites while providing essential information for analysis and monitoring.

Specific ideas for targeted field projects included saltwater injection under Class II in the Permian basin and stacked storage projects under Class I and II for handling AoR, penetrations, corrective action and monitoring. Specific management tools/models identified included state-run, basin-scale monitoring platforms for operators (e.g., TexNet); Models to assess AoR interference from multi-project interaction (e.g., Enhanced Analytical Simulation Tool [EASiToo]).

Session 6: Characterization of conventional/unconventional resources to reduce data scarcity and uncertainty

Presentations

- *Subsurface Carbon Storage Resource Assessments and Proposed CO_2 Injection wells in the United States*, Peter Warwick (USGS)
- *Characterization of Conventional and Unconventional Resources: Reducing Data Scarcity and Uncertainty*, Jessica Moore (American Association of State Geologists)

Presentations Summary

This session featured two speakers discussing characterization efforts of conventional and unconventional resources to reduce data scarcity and uncertainty. Peter Warwick provided an overview of static CO_2 storage assessments conducted to date, which suggest vast available storage resources within the United States; however, dynamic assessments, such as volumetric and pressure-limited

assessments and simulated brine injection rates, are necessary to better define physical constraints of injection activities and more accurate storage estimates. Warwick noted that a large number of Class VI permits have been submitted nationwide across 16 states, with the majority in Louisiana, California and Texas. To better understand U.S. CO_2 mineralization potential, proposed efforts include more characterization of suitable subsurface rocks and mine tailings for mineralization, assessing and estimating potential CO_2 mineralization volumes in those resources, and conducting airborne magnetic surveys to identify more suitable areas for mineralization.

Jessica Moore provided an overview of state survey involvement and opportunities as research partners for Federal carbon storage efforts. Challenges include determining the data required, the major data gaps, and the prioritization of data collection needed for basin characterization in relation to CO_2 storage efforts. Opportunities to leverage current efforts include utilizing networking from the DOE funded "Regional Initiative to Accelerate Carbon Capture, Utilization, and Storage (CCUS) Deployment: Technical Assistance for Large-Scale Storage Facilities and Regional Carbon Management Hubs". The initiative supports 16 active projects across 14 states (Plains CO_2 Reduction [PCOR] Partnership, Carbon Utilization Storage Partnership [CUSP], Midwest Regional Carbon Initiative [MRCI], Southeast Regional Carbon Sequestration Partnership [SECARB]), featuring locally tailored technical assistance and enhanced stakeholder engagement. The Earth Mineral Resources Initiative (EMRI: USGS and state geological surveys cooperative activity) regularly conducts geochemical reconnaissance studies and airborne geophysical surveys across the nation, including magnetic, radiometric and hyperspectral surveys. Finally, the USGS and state geological surveys are actively seeking out historical samples and data for preservation, which may spur new interest and opportunity in previously investigated (but potentially forgotten) locations or prevent unnecessary duplication of sampling or drilling.

Breakout Discussions

One overarching issue identified in the breakout group discussion was the need to evaluate the economic feasibility of unconventional[10] storage formations, aiming to optimize resource utilization, and to comply with Class VI permitting requirements. Field data acquisition in unconventional and underexplored basins are desired. Prospects located outside hydrocarbon-producing basins will require new capture and finance drivers (e.g., removal technologies) to reduce the pipeline reliance of these projects. Pressure management practices were recommended to improve operational efficiency and reduce costs. Unconventional targets identified by the respondents include depleted hydro-fractured reservoirs with low permeability zones, basalts, karst formations, and surface mineralization. To facilitate CO_2 storage development, "practical" storage estimates were considered more reliable than regional storage resource estimates when assessing storage capacity. Factors such as limitations imposed by surface activities, geological conditions specific to each site, and cost considerations (e.g., "practical" limit on the number of wells) will require validation at a regional level.

Karst formations (meaning formations containing caves) were of significant interest due to the potential for storage of large volumes of CO_2 with potentially very little fluid pressure increase in the storage formation. On the other hand, CO_2 plume movement and potential pressure increase are still not well understood in Karst formations due to their unique morphology. These predictions are used to establish the extent of the AoR and to comply with Class VI regulations. Similar modeling challenges in basalt formations were noted.

[10] Such as basalts as well as other mafic and ultramafic rocks

The breakout discussions identified the need for baseline characterization data, including the development of USDW maps across basins. Data needs for baseline characterization include basement faults, cores of caprock, shallow water quality data, geochemical compatibility of injected fluids of reservoirs and seals, in-situ continuous from temperature and pressure profiles. Data needed to characterize mineralization in basalts (e.g., water-rock-CO_2 interactions, brine composition) were also mentioned.

There was considerable discussion related to the need for standardized data sets and avenues for their curation and effective utilization. Specific suggestions included:

- Establish a comprehensive data system for organizing information by basin and formation to facilitate carbon storage development.
- Explore strategies for integrating disparate metadata standards to enable cohesive functionality.
- Implement protocols for standardizing geologic stratigraphic names and codes to ensure consistency and clarity.
- Construct a platform capable of aggregating existing data sources while preserving their metadata integrity in a specialized format.

Session 7: Multi-resource related opportunities

Presentations

- *Multi-resource/ Multi-use Resource Assessments at USGS*, Matthew Merrill (USGS)
- *Subsurface Energy Innovation*, Julien Caubel (DOE)

Presentations Summary

This session featured two speakers who discussed multi-resource-related opportunities. Matthew Merrill discussed how there is opportunity to organize and unify traditionally siloed data so that it can be used more efficiently and flexibly, with the goal that unified data can be used in perpetuity by future endeavors. The USGS currently has a working group dedicated to the problem facing CO_2 storage and multi-resource opportunities, with the two major challenges being a lack of foundational basin data and existing project structure. Projects are currently not operator-focused, but this could be addressed by those that fund data collection or plan work on multiple resources in basins over the long term. The current tower model (silo) of resource assessment published a single static product that needs to be redone every several years. A new model is proposed that fits all existing assessment methods together and adjusts them to build a unified multi-resource product (the castle model). This new model focusses on building a solid data foundation by digitizing existing information, populating data with spatial metadata, and providing long-lived storage and access capability.

Julien Cauble touched on the needs and opportunities regarding national data aggregation and collection. Within DOE, the Science and Energy portfolio is centered around two departmental coordination mechanisms: crosscuts and Earthshots, both responsible for R&D. Crosscuts are meant for interdepartmental collaboration and cooperation and have broad missions. Earthshots are more targeted with specific quantifiable goals. The Subsurface Energy Innovation (SEI) Crosscut includes six offices with diverse equities in the subsurface space. One of them, the Enhanced Geothermal Shot (EGS), has a goal of reducing the cost of geothermal energy by 90% by 2035. EGS is led by the Geothermal Technologies Office but leverages the SEI structure to align staff and resources from across the department. The SEI focuses on four key mission areas: geothermal energy, geologic carbon

storage, geologic hydrogen storage and critical mineral sourcing. These technical areas are often still considered and developed separately, even though needs and resources overlap. They are united by the limited ability to assess, monitor and access the subsurface, and improving the certainty around our interactions with the subsurface can benefit all these critical energy areas. The SEI crosscut has identified four major pillars that represent the common scaffolding for the various technology solutions: (1) characterization; (2) drilling; (3) monitoring; and (4) engineering. The mission of the crosscut is to ensure that each pillar is addressed and developed holistically. The presentation concludes with some immediate opportunities that include aggregating, harmonizing, storing and distributing datasets at a national level; targeting exploration and assessment methods for multi-resource outputs; standardizing data collection; and creating multi-resource-focused funding mechanisms (e.g., cost-shared drilling).

Breakout Discussions

The breakout discussions covered a wide range of data from various industries (e.g., coal mining, gas storage, cement suppliers, and enhanced oil recovery [EOR]) that provide parameters to support wellbore integrity, well design, and management practices in the carbon storage industry. Potential opportunities for cross-collaboration were highlighted in the blue hydrogen, wind energy, and geothermal sectors. Project-specific critical minerals need to be identified. This involves brine analysis of resident brines and the development of machine learning tools for correlating critical mineral concentrations. Other recommendations included the assessment of AoR during multi-project development and the amalgamation of existing county-scale water resource data across the basin.

The discussions also highlighted that data collection would need to be encouraged by the permitting authorities at the Federal or state level to ensure its preservation. In addition, respondents noted that data standardization and aggregation initiatives are desired for improving the usefulness of future data. These efforts need to undergo scientific scrutiny rather than solely relying on the tools of data collection. Well logs were identified as particularly useful for their continuous data and context, enabling users to make their own interpretations.

Session 8: Data sharing approaches/platforms

Presentations

- *Data Science and Innovation to Bridge the Digital Divide*, Kelly Rose (NETL)
- *Data Sharing Approaches*, Sean Brennan (USGS)

Presentations Summary

The session featured two speakers who discussed data sharing approaches, challenges, and current platforms. Kelly Rose provided an overview of the FECM-funded Energy Data eXchange (EDX) system and the development of the disCO_2ver platform, an integrated user interface within the EDX system for connecting stakeholders with CCS-priority data, tools, and models. Rose highlighted that EDX hosts the world's largest open-source carbon storage dataset and a variety of data computing resources. There is a notable need to advance the system for democratized use and useability via data preservation, artificial intelligence (AI)/machine learning (ML)/natural language processing (NLP)-enhanced tools and enabling geospatial data and carbon storage web mapping for select CCS resources. Relevant data science tools include RokBase, CO_2-Locate Database, Class VI Data Support Tool, CCS-EJ-SJ Database, CCS Pipeline Route Planning Database, and CS Technical Viability Database. Applied AI for CCS data has been used to evaluate community attitudes of local CCS projects and to evaluate and identify safe and sustainable routes for CO_2 pipelines. AI has also been employed to find and aggregate disparate

wellbore data from authoritative sources, is being used to integrate Class VI data into a data visualization dashboard tool and is being utilized to improve subsurface property predictions. EDX can accommodate the needs of data anonymization and communicating uncertainty in data and models. EDX's recent move to cloud computing allows for data curation, ease of access, and accessibility of carbon storage and subsurface data assets.

Sean Brennan discussed data sharing approaches with the goal of identifying data gaps, determining how to fill those gaps, and making the data and metadata publicly available as efficiently as possible to meet the needs of stakeholders. Many datasets are currently diffuse, in multiple formats, and behind clunky interfaces. How to effectively extract and serve this data for ease-of-use is a major challenge. Data aggregation and centralization can utilize application programming interfaces (APIs) and other tags (metadata) to make them visible to machines. There is a need to make data repositories comprehensive through the combination of datasets, such as those regarding the subsurface, surface, ecosystem, endangered species, other resources, commercial considerations, environmental justice considerations and others.

Breakout Discussions

The breakout discussions identified a need for standardization of metadata and the establishment of a unified or harmonized metadata framework. This framework could include standardized formats and clearly defined terminology regarding aspects such as spatial location, temporal coverage, data source, data quality, and any other metadata standards. The purpose, approach, and permitted use of the data should be included in metadata. This framework could be implemented across agencies so that public data can be easily queried and compiled for any purpose. The elimination of barriers to efficient data access and usage could be prioritized.

Regarding general data, workshop participants noted a need to develop and promote use of a general data recording guideline. Private sector companies could be consulted and coordinated with to develop approaches to prioritize the integration of newly created data with existing platforms.

Workshop participants asked: when aggregating data, are there current ways to aggregate proprietary data in standard formats that could be useful for basin analysis? Aggregating data from multiple platforms will require quality control and an appreciation of the resource used to acquire the data. Tools could be developed that tie data to specific publications and topics.

Workshop participants noted there is a need to better develop monitoring efforts to inform basin scale static and dynamic models used to express uncertainty and test for unacceptable responses to pressure increase from injection. Workshop participants identified a need to develop proxy and analogue studies of pressure evolution. Basin or sub-basin scale models will need validation via monitoring to provide reasonable boundary conditions for individual projects. Specific suggestions included:

- Development of comprehensive platforms for quantifying basin-scale responses from injection activities, including metrics and techniques for measurement.
- Organized data on natural and induced under and overpressure occurrences in various geologic settings, alongside historical records, to facilitate matching observations and understanding their implications.

Finally, it was also noted there is a need for amalgamating and digitizing relevant data from other UIC wells and making it accessible to support Class VI permitting efforts.