



# Midwest Regional Carbon Initiative

## Final Technical Report

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# Executive Summary

*Regional Initiative to Accelerate CCUS Deployment in Midwestern and Northeastern USA (DE-FE0031836)*, later renamed the *Midwestern Regional Carbon Initiative (MRCI)*. The primary objective of this project is to implement a collaborative Regional Initiative (RI) to accelerate the deployment of carbon capture, utilization, and storage (CCUS) in the Midwest-Northeastern quadrant of the United States covering 20 states and representing multiple geologic provinces and a large fraction of carbon dioxide (CO<sub>2</sub>) emissions in the country. This initiative was built upon more than 20 years of CCUS experience in the region and combines the expertise of two Regional Carbon Sequestration Partnerships (RCSPs). The objectives of the RI include addressing key technical challenges, obtaining and sharing data needed to support CCUS deployment, facilitating regional infrastructure planning, and performing regional technology transfer. In conducting its work, the MRCI has become a key resource for CCUS deployment-specific research in the study region and through knowledge sharing globally.

The six-year long program is funded by the US Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) and managed through the National Energy Technology Laboratory (NETL). This project is co-led by Battelle Memorial Institute (Battelle) in Columbus, Ohio and Illinois State Geological Survey (ISGS) in Champaign, Illinois. The project team includes Indiana University (Indiana Geological and Water Survey), University of Iowa (Iowa Geological Survey), Maryland Geological Survey, Ohio Geological Survey, Pennsylvania Geological Survey, Rutgers University, University of Kentucky Research Foundation (Kentucky Geological Survey), Western Michigan University/Michigan Geological Survey, and West Virginia Geological and Economic Survey. Other technical contributors over the project duration include Los Alamos National Laboratory, Carbon Solutions, Inc., Industrial Economics, Lattis Consulting. The program benefited immensely from data share and in-kind contributions from Marquis, and collaboration and participation from numerous industrial entities.

The MRCI program was conducted under five tasks, as discussed below. While this report briefly summarizes the overall MRCI effort, a series of eight companion reports provide details on individual tasks and subtasks.

**Task 1 – Project Management and Reporting:** This task included oversight of project milestones, deliverables, reporting, and budget, and coordination by the Principal Investigator.

**Task 2 – Addressing Key Technical Challenges:** This is the primary geotechnical and subsurface analysis task, aimed at identifying and mapping geologic carbon storage systems throughout the MRCI region, conducting modeling analyses to quantify the injectivity of selected carbon storage systems to determine their potential to host commercial-scale CO<sub>2</sub> facilities, and evaluate potential storage risks associated with commercial-scale CO<sub>2</sub> storage systems. The outcomes of the subtasks are described in five companion technical reports, submitted to the DOE. The achievements of this collaborative effort with the MRCI GeoTeam members, include a complete redefinition of the CO<sub>2</sub> storage and containment systems across the 20-States and adjacent offshore region, including hundreds of new maps and cross-sections, and a comprehensive new database system to facilitate future work.

**Task 3 – Facilitating Data Collection, Sharing, and Analysis:** Task 3 was aimed at collecting existing technical data from previous CCUS projects and to make the data available to the MRCI project team and other programs such as the National Risk Assessment Partnership (NRAP) and Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART) Initiative, and foster collaboration with other national and international programs. Under this task, the MRCI team also collected legacy seismic data from

private sources. The task results will facilitate improvement of CCUS site assessment, operations, and monitoring for CO<sub>2</sub> storage sites in the MRCI region.

**Task 4 – Evaluating Regional Infrastructure:** The infrastructure requirements for CCUS go beyond the equipment and materials needed to capture, transport, and store CO<sub>2</sub> and include people and policy that make CCUS feasible. This task included assessments of infrastructure readiness for the CCUS buildout; site readiness based on subsurface, infrastructure; regulations and incentives, and social dynamics; jobs, economics, and social characteristics; and tracking of policy and regulations relevant to CCUS development.

**Task 5 – Promoting Regional Tech Transfer:** Under this task, the MRCI team leveraged existing and new relationships with critical CCUS stakeholders (national and international stakeholders include state geological surveys, universities, industrial partners and advisors, fossil fuel production and utilization companies, and non-government organizations) within the regional initiative and globally and become a key resource for CCUS information, acceptance, and development. Work included promote acceleration of CCUS deployment by providing general support for commercialization and technology transfer and communicating information from previous tasks to interested stakeholders, and engaging with federal and state governments, industry consortia, non-government organizations, and global institutions. MRCI team developed and maintained the [midwestccus.org](http://midwestccus.org) website, maintained an extensive mailing list, prepared newsletters, and fostered podcasts with CCUS experts. Finally, the team organized three highly attended in-person workshops and two virtual stakeholder meetings, with accompanying workshops and training sessions.

**Summary and Path Forward** - The MRCI region has been subject to CCS research and pilot-scale demonstrations since mid-1990s and is fast transitioning into multiple CCS project clusters, especially in areas such as central Illinois, Indiana, southern Michigan, and parts of the Appalachian Basin. The region has been home to several pilots and demonstrations under the two Regional Partnerships and industrial projects such as the AEP Mountaineer pilots, CO<sub>2</sub>-EOR (Enhanced Oil Recovery) in northern Michigan, FutureGen design studies, and multiple CarbonSAFE or private development projects. As a highly diverse geologic, geographic and industrial region, MRCI is a good microcosm for large-scale development of CCS and a precursor to how CCS will evolve globally over next several decades, beyond the initial “low-hanging fruit”. As described in the MRCI reports, there are many opportunities fostering the ongoing commercial scale deployment, including regions of suitable geology overlying industrial sources of CO<sub>2</sub> in alignment with the enabling regulatory framework. However, there are also significant challenges which could derail the momentum and need continued efforts to resolve in the coming years. These include the need for exploration and validation of sufficient storage resources in the deeper parts of Illinois, Appalachian, and Michigan Basins, which are dominated by carbonate and shale layers. Access to vast potential resources in the mid-Atlantic offshore sediments to help decarbonize eastern US industry and Appalachian Basin shale gas resources. Substantial deployment will also require greater acceptability of local and regional pipeline infrastructure, clarity in ownership of pore space and unitization, suitable carbon pricing and incentives, and greater understanding and acceptability by the local stakeholders. Although the current program under the MRCI will be completed during 2025, further progress will continue with the follow-on programs including those under the Regional Initiative Technical Assistance Partnership (RITAP), CarbonSAFE projects, and the clean Hydrogen Hubs.

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## Acronyms

2D	two-dimensional
3D	three-dimensional
ACT	Accelerating CCS Technologies
AGI	American Geological Institute
AoR	area of review
ASH	Appalachian Storage Hub
BCT	Baltimore Canyon Trough
BHP	bottomhole pressure
BHT	bottomhole temperature
BLS	Bureau of Labor Statistics
BOEM	Bureau of Ocean Energy Management
CCS	carbon capture and sequestration
CCUS	carbon capture, utilization, and storage
CEJST	Climate and Economic Justice Screening Tool
CEQ	Council on Environmental Quality
CEUS	central and eastern US
CNW	commercially navigable waters
CO <sub>2</sub>	carbon dioxide
DOC	Department of Commerce
DOE	Department of Energy
EDX	Energy Data Exchange
EIA	Energy Information Administration
ENSURE	Effective monitoring of long-term site stability for transparent carbon capture and storage hazard assessment
EOR	Enhanced Oil Recovery
FEED	front-end engineer design
FRA	Federal Railroad Administration
FSP	Fault Slip Potential
GHGRP	Greenhouse Gas Reporting Program
HCA	high consequence area
HPA	highly populated area
IMap	interactive map
ISGS	Illinois State Geological Survey

KGS	Kentucky Geological Survey
LCA	life cycle analysis
LCI	Lettis Consultants International
MGSC	Midwest Geologic Sequestration Consortium
MMP	Minimum Miscibility Pressure
MMt	million metric tonnes
MPAC	Marine Protected Areas Center
MRCI	Midwest Regional Carbon Initiative
MRCSP	Midwestern Regional Carbon Sequestration Partnership
NETL	National Energy Technology Laboratory
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRAP	National Risk Assessment Partnership
NRHP	National Registry of Historic Places
ONMS	Office of National Marine Sanctuaries
OPA	other populated area
PAD-US	protected area dataset of the United States
PHMSA	Pipeline and Hazardous Material Safety Administration
PISC	post-injection site case
psi	pound per square inch
RCSP	Regional Carbon Sequestration Partnership
SCADA	Supervisory Control and Data Acquisition
SMART	Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications
SOC	Standard Occupational Code
SWD	saltwater disposal
TDS	total dissolved solids
UIC	underground injection control
USA	unusually sensitive area
USDW	underground source of drinking water
USEPA	United States Environmental Protection Agency
WHPA	wellhead protection area
WSM	World Stress Map

## 1.0 Introduction

### 1.1 MRCI Project Objectives

The objective of the Midwest Regional Carbon Initiative (MRCI) project was to implement a collaborative Regional Initiative to accelerate the deployment of carbon capture, utilization, and storage (CCUS) in the Midwest-Northeastern and Mid-Atlantic areas of the United States. This area encompasses a 20-state region with much of the country’s carbon dioxide (CO<sub>2</sub>) emissions. The MRCI project is co-led by Battelle Memorial Institute (Battelle) in Columbus, Ohio, and the Illinois State Geological Survey (ISGS) in Champaign, Illinois, and benefitted from the experience these organizations have acquired over the past 10-plus years leading two Department of Energy (DOE) Regional Carbon Sequestration Partnerships (RCSPs): the Midwestern Regional Carbon Sequestration Partnership (MRCSP), led by Battelle, and the Midwest Geologic Sequestration Consortium (MGSC), led by the ISGS. The initiative also engaged state geological surveys and universities from across the MRCI region (the Geoteam), industrial partners and advisors from fossil fuel production and utilization companies, non-governmental organizations, and international research groups. The various participants, supporters, and program leads are shown in the organization chart (Figure 1-1)

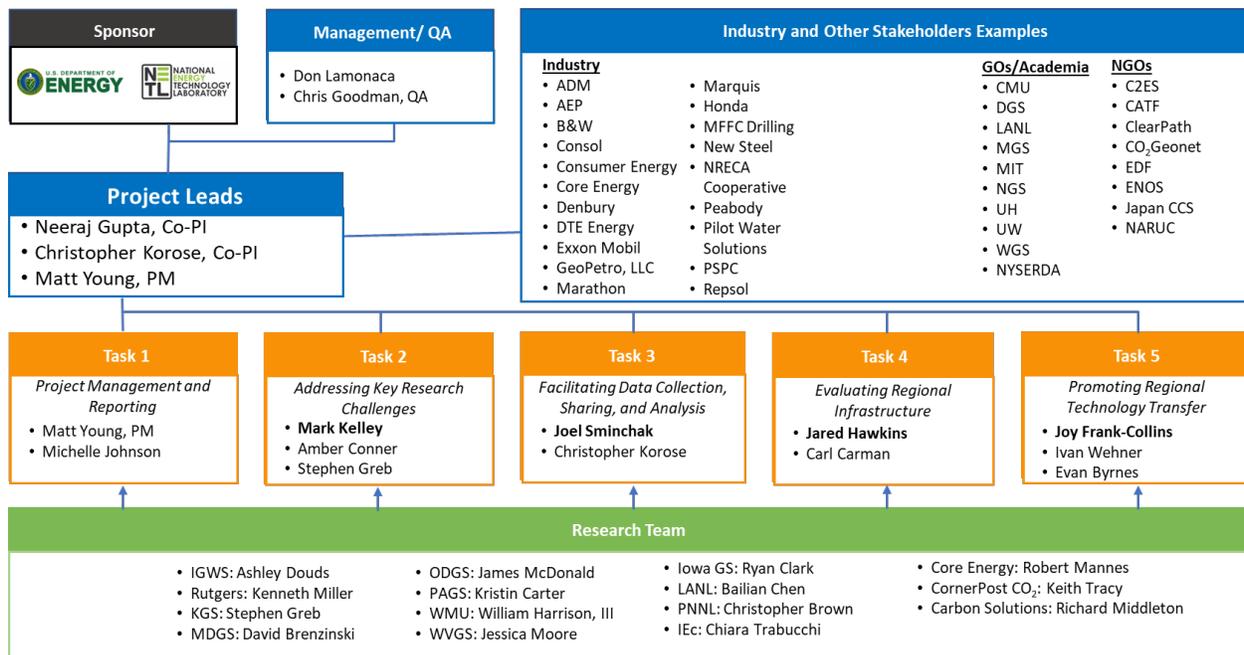


Figure 1-1. The MRCI study Organizational Chart

Specific objectives of the MRCI included addressing key technical challenges; obtaining and sharing data needed to support CCUS deployment; facilitating regional infrastructure planning; and performing regional technology transfer. The ultimate expectation of the program was to serve as a long-term resource for CCUS deployment in the region through continued research in the study region and engaging in global knowledge-sharing to address key issues and fill in critical data/information gaps.

## 1.2 MRCI Study Area

The MRCI region encompasses the combined 11-state areas of the former MRCSP and MGSC (Delaware, Indiana, Illinois, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, West Virginia) plus three states in the midcontinent (Wisconsin, Iowa, Missouri) and six states in the northeastern United States (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut), and the Mid-Atlantic and north-Atlantic offshore region (Figure 1-2). The offshore region of the study area includes the Bureau of Ocean Energy Management (BOEM) North-Atlantic Outer Continental Shelf planning area (BOEMRE, 2010) as well as the southern portion of the Baltimore Canyon Trough (BCT) as mapped by Battelle (2019).

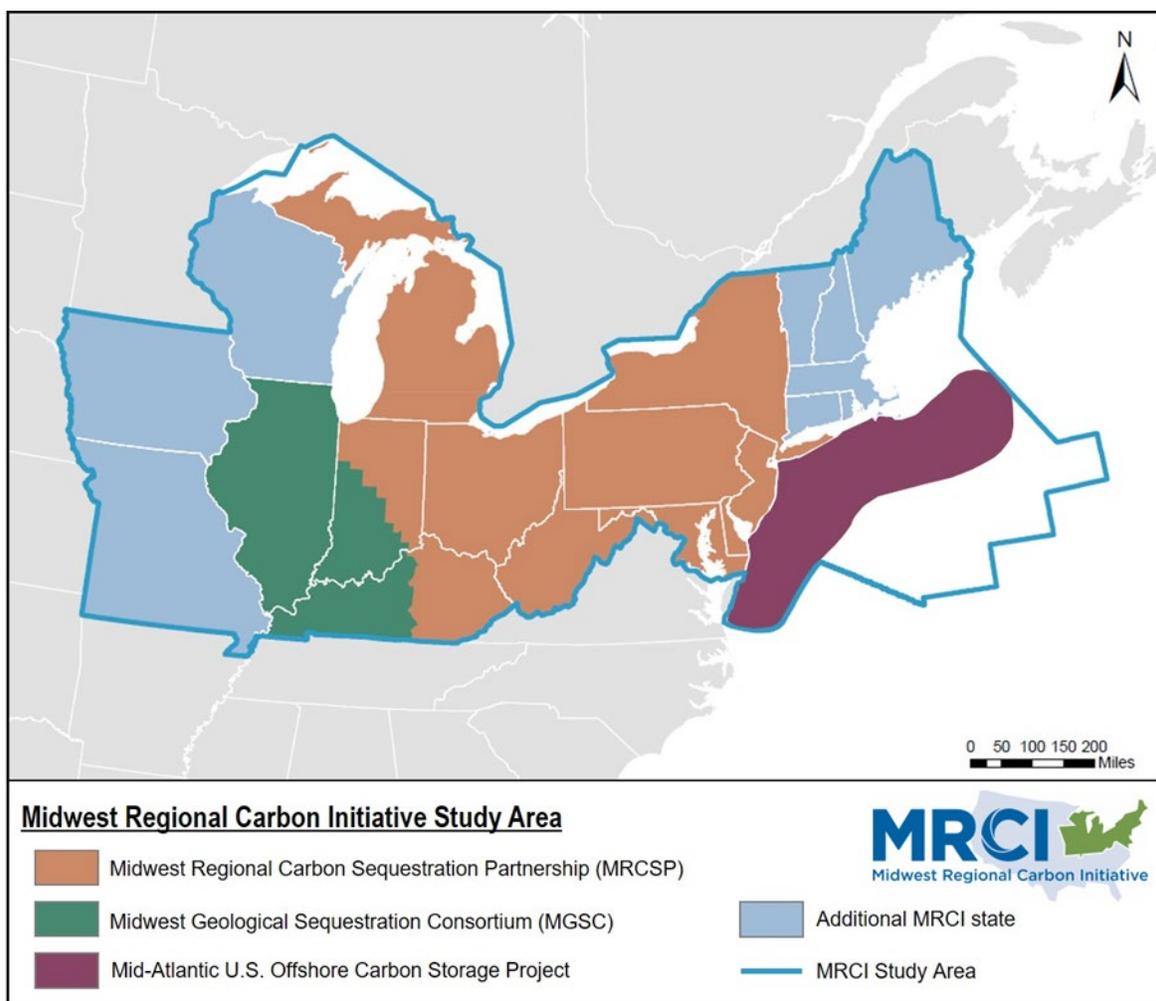


Figure 1-2. The MRCI study area composed of previous project regions of MRCSP (orange) and MGSC (green), the previous DOE-sponsored project region for the Mid-Atlantic Offshore (mauve), and states added to the effort (blue).

## 1.3 Organization of the MRCI Project

The MRCI project was co-led by Battelle in Columbus, Ohio, and ISGS in Champaign, Illinois. The project team also includes the Geoteam, which is comprised of the Indiana Geological and Water Survey, Iowa Geological Survey, Maryland Geological Survey, Ohio Geological Survey,

Pennsylvania Geological Survey, Rutgers University, Kentucky Geological Survey, Western Michigan University/Michigan Geological Survey, and West Virginia Geological and Economic Survey. The project was divided into five tasks as shown below:

- Task 1 – Project Management and Reporting
- Task 2 – Addressing Key Technical Challenges
- Task 3 – Facilitating Data Collection, Sharing, and Analysis
- Task 4 – Evaluating Regional Infrastructure
- Task 5 – Promoting Regional Tech Transfer

Tasks 2 through 5 comprise the technical tasks, which are briefly described below.

**Task 2** – The overall objective of Task 2 was to identify and map geologic carbon storage systems throughout the MRCI region, conduct modeling analyses to quantify the injectivity of selected carbon storage systems to determine their potential to host commercial-scale CO<sub>2</sub> facilities, and evaluate potential storage risks associated with commercial-scale CO<sub>2</sub> storage systems. Task 2 includes five subtasks:

- Defining carbon storage systems (2.1);
- Defining Precambrian basement faulting/stress (2.2);
- Developing industrial partnerships and regional technical collaborations (2.3);
- Conducting regional/subregional analyses (2.4); and
- Assessing and managing risk for potential commercial-scale storage complexes (2.5).

**Task 3** – The overall objective of Task 3 was to collect existing technical data from previous CCUS projects and to make the data available to the MRCI project team and other programs such as the National Risk Assessment Partnership (NRAP) and SMART (Science-informed Machine Learning to Accelerate Real Time Decisions in Subsurface Applications). The task results will facilitate improvement of CCUS site assessment, operations, and monitoring for CO<sub>2</sub> storage sites in the MRCI region. The objectives of Task 3 were achieved through seven subtasks, as shown below.

- Inventory available data and analyses (3.1)
- Facilitate data collection, sharing (3.2)
- Plan and execute additional analyses (3.3)
- Engage NRAP/National Energy Technology Laboratory (NETL) (3.4)
- Engage national laboratories (3.5)
- Advise machine learning for CCUS (3.6)
- Participate in SMART Initiative (3.7)

**Task 4** – The goal of Task 4 was to determine the infrastructure requirements to enable CCUS throughout the MRCI study area. The infrastructure requirements go beyond the equipment and materials needed to capture, transport, and store CO<sub>2</sub> and include people and policy that make CCUS feasible. This objective was achieved through four subtasks.

- Infrastructure Readiness: Strategizing the buildout of capture, transport, and storage infrastructure in the Midwest-Northeast and Mid-Atlantic Offshore.
- Site Readiness: Determining the CCUS readiness of each state in the MRCI region in the categories of subsurface readiness; infrastructure readiness; regulations, permitting, and incentives; and social dynamics.

- Jobs, Economics, and Social Characteristics: Quantifying the economic potential, job opportunities, and training opportunities for CCUS as well as the social characteristics of the region with a focus on energy and environmental justice issues.
- Policy and Regulations: Providing an updated accounting of the CCUS-relevant policy and regulations in the MRCI region.

**Task 5** – The goal of Task 5 was to leverage existing and new relationships with critical CCUS stakeholders (national and international stakeholders include state geological surveys, universities, industrial partners and advisors, fossil fuel production and utilization companies, and non-government organizations) within the regional initiative and globally and become a key resource for CCUS information, acceptance, and development. Work under Task 5 was categorized into four actions:

- Promote acceleration of CCUS deployment by providing general support for commercialization and technology transfer
- Compile and communicate information from previous tasks to interested stakeholders
- Engage with federal and state governments, industry consortia and non-government organizations
- Engage with global institutions

The remainder of this report provides a summary of the work performed under the technical tasks, i.e., Tasks 2, 3, 4 and 5. More detailed documentation of the work performed and results obtained can be found in the following reports:

**Task 2 Reports:**

- Midwest Regional Carbon Initiative task 2 – Task 2 Addressing Key Technical Challenges - Executive Summary Report (Battelle, 2024a)
- Midwest Regional Carbon Initiative Subtask 2.1 – Defining Sub-Regional Carbon Storage Systems Final Technical Summary Report (Battelle, 2024b)
- Midwest Regional Carbon Initiative Subtask 2.2 – Precambrian Basement Faulting and Stress Final Technical Summary Report (Battelle, 2024c)
- Midwest Regional Carbon Initiative Subtask 2.3 – Developing Industrial Partnership and Regional Technical Collaboration (Battelle, 2024d)
- Midwest Regional Carbon Initiative Subtasks 2.4/2.5 – Regional/Subregional Analysis and Risk Assessment Final Technical Summary Report (Battelle, 2024e)

**Task 3 Report:**

- Midwest Regional Carbon Initiative – Facilitating Data Collection, Sharing, and Analysis (Task 3) (Battelle, 2024f)

**Task 4 Report:**

- Midwest Regional Carbon Initiative – Evaluating Regional Infrastructure (Task 4) (Battelle, 2024g)

**Task 5 Report:**

- Midwest Regional Carbon Initiative – Promoting Regional Technology Transfer (Task 5) (Battelle, 2024h)

## 2.0 Addressing Key Technical Challenges (Task 2)

Task 2 focused on addressing key technical challenges to implementing CCUS in the MRCI region. The technical challenges addressed in this study include:

- The geologic framework for CO<sub>2</sub> storage needs to be characterized for the entire MRCI region; previous geologic characterization work for CCUS (e.g., MRCSP and MGSC) did not cover all 20 states in the MRCI region;
- The injectivity of potential storage formations in the MRCI region needs to be defined (quantified), previous work focused on defining CO<sub>2</sub> storage capacity, but injectivity is a better metric for assessing true storage potential and determining operational parameters such as number and spacing of injection wells required to achieve the injection target and the area of the CO<sub>2</sub> plume;
- The impacts and likelihood of key risks associated with CO<sub>2</sub> storage in the MRCI region need to be understood and tools suitable for evaluating these risks need to be identified.

The first challenge was addressed by developing several new geology resources and tools for the MRCI region; these include regional geologic cross sections, regional structure and thickness maps, stratigraphic charts, written summaries of the geology of the carbon storage systems, a comprehensive map database, and a rock properties database.

The second challenge was addressed by conducting a screening-level assessment of injectivity for a wide variety of storage formations in the region, followed by a focused but detailed injectivity assessment for a small number of potential storage formations using numerical modeling to simulate a commercial-scale CO<sub>2</sub> injection operation defined as 1 million metric tons of CO<sub>2</sub> per year for 30 years.

The third challenge was addressed by modeling two potential leakage pathways for multiple model sites, including vertical migration of CO<sub>2</sub> and brine via (abandoned) wells that penetrate the storage reservoir and vertical migration of CO<sub>2</sub> and brine across an unfractured caprock. In addition to evaluating potential leakage risks, induced seismicity risk was evaluated for one model site to evaluate the feasibility of the process for evaluating induced seismicity risks at other sites.

This section is organized into three parts, each addressing one of the key technical challenges addressed in this study. Section 2.1 describes the geologic framework of the MRCI region and describes the new geologic resources and tools that were developed. Section 2.2 describes the methods and results of the injectivity assessments, including the screening-level assessment and the detailed numerical modeling assessment. Section 2.3 describes the assessment of leakage risks and induced seismicity risks.

### 2.1 Geology of the MRCI Region and Identification of CO<sub>2</sub> Storage Opportunities

A primary objective of Addressing Key Technical Challenges under the MRCI project was to better define the geology within the MRCI area as it pertains to CCUS and to document this information in a form that can be easily accessed by others seeking to conduct CCUS in the region. This effort included development of new regional maps and cross sections, stratigraphic charts, and a geologic map database and a rock properties database for key storage reservoir and caprock formations. In addition, a written description of the carbon storage systems and

## 2.0 Addressing Key Technical Challenges (Task 2)

individual geologic formations within the carbon storage systems that are potential CO<sub>2</sub> storage reservoirs was developed for each major basin and arch region within the MRCI boundaries.

As part of the final products, seven new regional maps were developed that connect individual reservoir and caprock layers across the region in terms of structure and thickness. This work also extended to the Precambrian basement, where structure contour mapping, fault mapping, and stress mapping were completed for the region. Additionally, a catalog of historical earthquakes was developed that includes earthquakes from 1568 to 2020. Three new cross-sections were developed, one of which covers the Georges Bank Basin offshore the East Coast, one of which spans north-south in the Illinois Basin, and one of which spans east-west across the Forest City Basin, Western arches, and Illinois Basin. Finally, the subsurface was divided into 48 subregions within the MRCI region, with unique stratigraphic columns defining the geology across these 48 subregions. The 48 regional divisions of the geology in the area provided a basis for defining potential storage reservoirs and caprocks within localized subsets of the MRCI area. These assemblages of storage reservoirs and caprocks are grouped into five CCUS systems which are classified by age.

### 2.1.1 Regional Carbon Systems and Structural Divisions of the MRCI Region

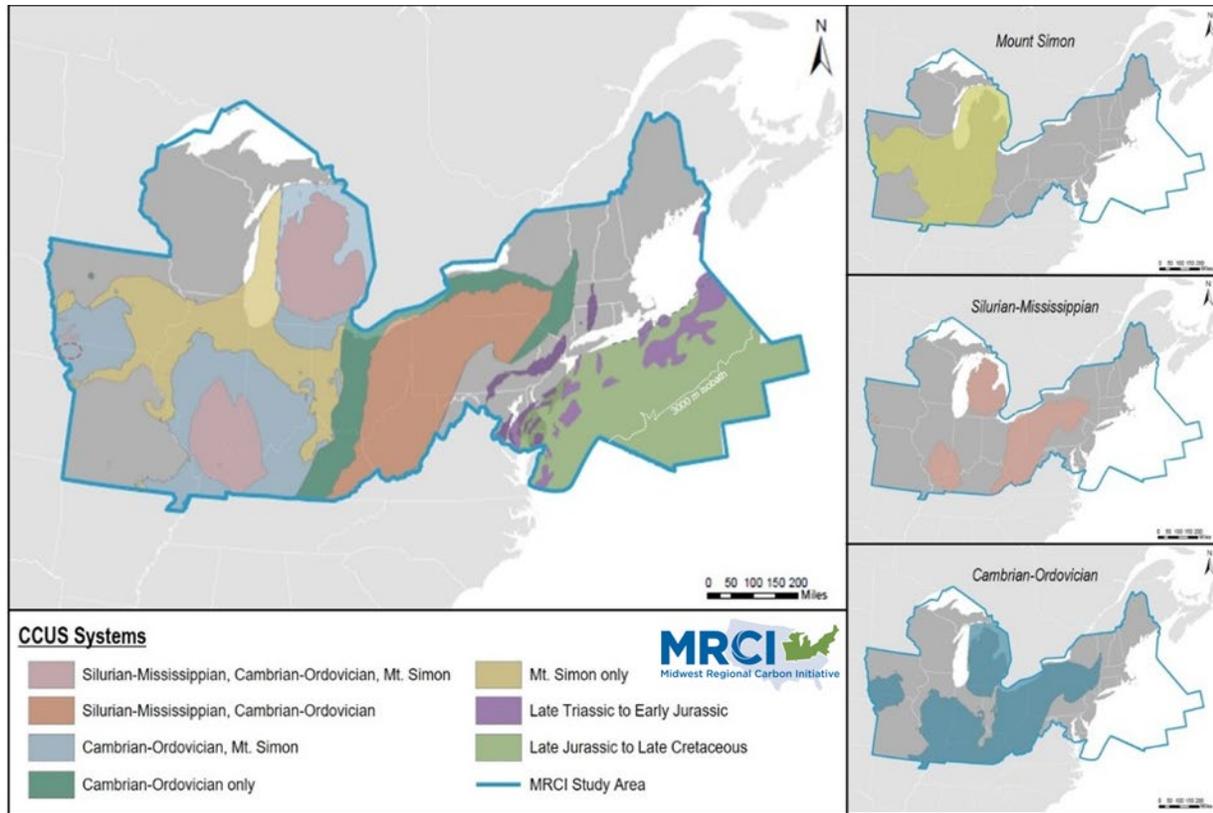
In order to segment and classify the geology within the MRCI region, CCUS systems were identified by geologic age. A CCUS system is defined as an assemblage of at least one reservoir and caprock (seal) layer. The CO<sub>2</sub> storage systems in the MRCI region are contained within the volume of rock above the basement rock surface (i.e., Precambrian-age west of the Appalachian Mountains and pre-Mesozoic-age east of the Appalachian Mountains) and below the CO<sub>2</sub> supercritical depth threshold (i.e., 2,600 ft depth). Within this volume exist the potential CO<sub>2</sub> storage reservoirs and seal layers. A total of five carbon systems were established:

- Cambrian Mount Simon
- Cambrian-Ordovician
- Silurian-Mississippian
- Late Triassic to Early Jurassic
- Late Jurassic to Late Cretaceous

The spatial extent of each carbon system is shown in Figure 2-1. In certain regions of Michigan and Illinois, a combination of the Cambrian Mount Simon, Cambrian-Ordovician, and Silurian-Mississippian are all considered viable for CO<sub>2</sub> storage, with each carbon system containing at least one storage layer and one caprock layer. In the Appalachian Basin, the primary storage targets are in the Cambrian-Ordovician and Silurian-Mississippian carbon systems. On the east coast, the targets are younger in age, within the Late Triassic to Early Jurassic (rift basins) and the Late Jurassic to Late Cretaceous saline reservoirs.

The inset maps in Figure 2-2 show the lateral extent of the individual Mount Simon, Cambrian-Ordovician, and Silurian-Mississippian carbon systems. The Cambrian-Ordovician is the most extensive carbon system in the MRCI study area, with the Mount Simon and Silurian-Mississippian systems being largely constrained by depositional limits and their depth relative to the 2,600 ft supercritical depth limit.

## 2.0 Addressing Key Technical Challenges (Task 2)



*Figure 2-1. Areal extent of the shallowest carbon storage system at depths greater than 2,600 ft in the MRCI region. In the basins, older carbon systems underlie the shallowest system shown in the figure. Inset maps show the extent of three of the individual carbon systems.*

Within the area containing viable storage opportunities (i.e., rock strata more than 2,600 ft deep) 48 subregions were identified on the basis of stratigraphy, where the geologic formations present in each subregion, from the surface to the basement, are shown in a stratigraphic chart. The 48 stratigraphic charts were grouped into the following eight sets by structural province:

- Forest City Basin and Western arches
- Illinois Basin
- Upper Mississippi embayment
- Central arches
- Michigan Basin
- West Central Appalachian Basin
- Central Appalachian Basin
- Northern Appalachian Basin

## 2.0 Addressing Key Technical Challenges (Task 2)

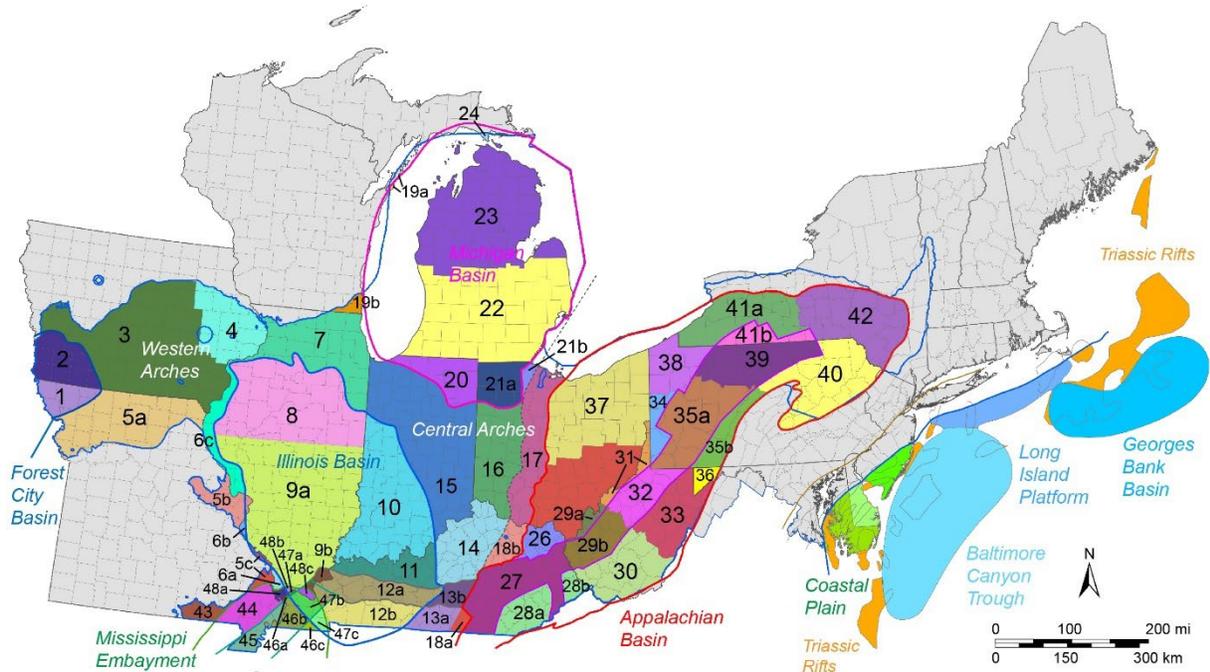


Figure 2-2. Map showing regions and subregions of the MRCI study area which have Paleozoic or younger strata at depths of more than 2,600 ft. Numbered subregions each have a corresponding stratigraphic column.

Example stratigraphic charts for subregions 1 through 6, which span the Forest City Basin and Western Arches regions, are shown in Figure 2-3. Within the stratigraphic chart, there are a few common and important characteristics. First, the red dashed line indicates the approximate depth of supercritical CO<sub>2</sub> storage. Stratigraphic units above the line are too shallow for supercritical CO<sub>2</sub> storage. The formations below the red dashed line are colored based on their potential for being a reservoir or caprock unit. Saline storage targets are colored in dark blue, local storage targets are colored in light purple, and storage reservoirs with salinities that are considered brackish are colored in light purple with diagonal red lines. Similarly, for confining units, a confining unit is shown with yellow, a confining unit with evaporite beds is shown with yellow and diagonal red lines, and a shale confining unit is shown with light brown. An organic shale, such as the Marcellus Shale in the Appalachian Basin, would be shown with green. At the base of each column, Precambrian sedimentary rocks are shown with dark brown fill while Precambrian igneous and metamorphic rocks are shown with pink fill.

These stratigraphic charts, in combination with definitions of carbon system locations, provide project developers with a basis for understanding which units are viable storage options in specific locations.

## 2.0 Addressing Key Technical Challenges (Task 2)

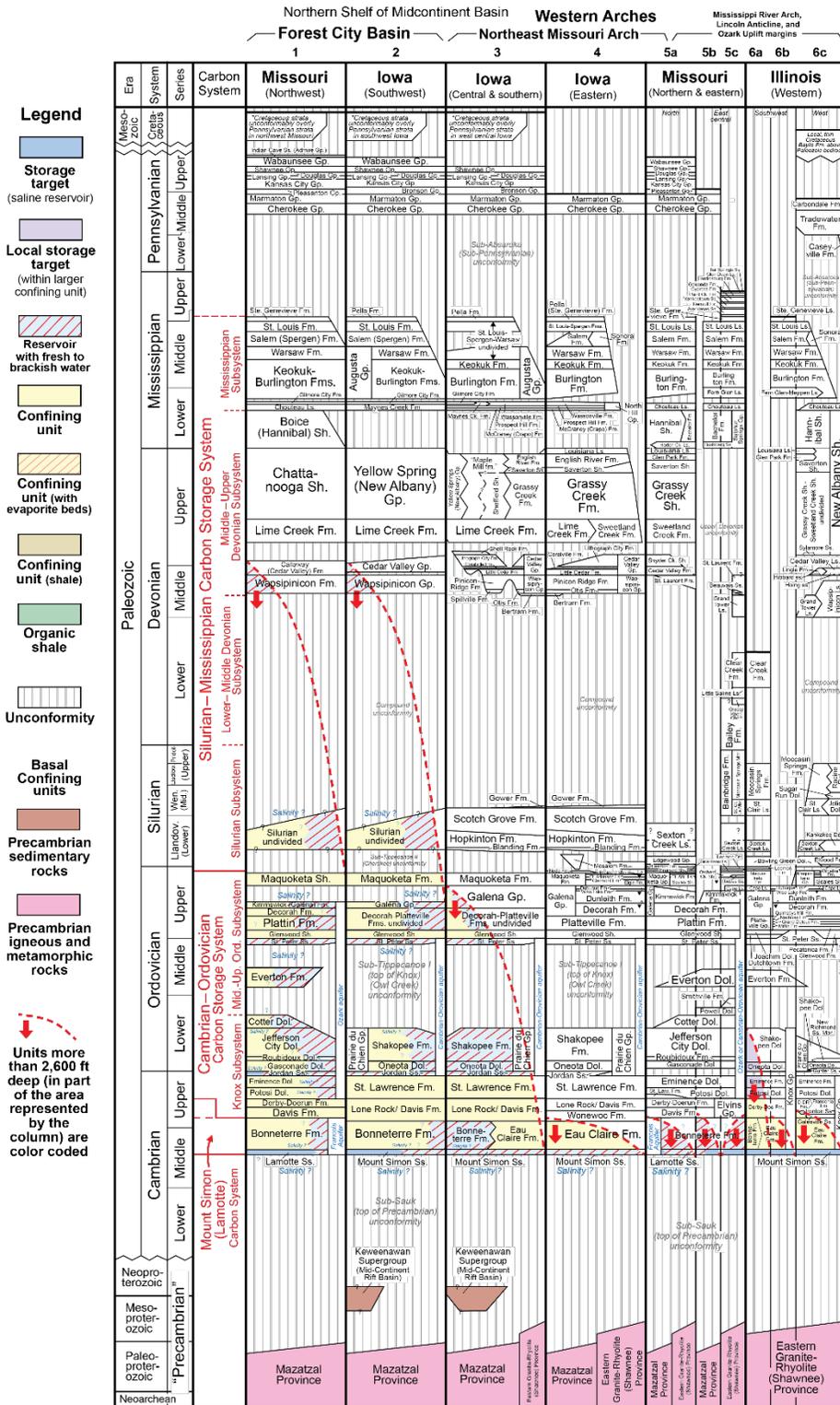


Figure 2-3. Stratigraphic chart for subregions 1 through 6, spanning the Forest City Basin and Western Arches regions within the MRCI.

## 2.0 Addressing Key Technical Challenges (Task 2)

The process of defining carbon storage systems and subregional geology helped better define the number of potentially viable storage formations within each structural province within the region. It is important to note that despite some regions having more potentially viable storage formations than others, a single storage formation in a certain region may have more storage capacity than multiple formations others. This is particularly true for the Cambrian Mount Simon carbon system, where its CO<sub>2</sub> storage capacity is greater than the combined storage capacity of multiple formations in several of the other carbon systems and provinces. Many of the formations that are deemed to have storage potential require further research to better understand depth, salinity, porosity, and permeability. Table 2-1 includes a count of potential storage reservoirs for each structural province in the MRCI based on carbon system. This includes local storage targets, regional saline storage targets and storage targets with potentially brackish reservoir water that is not well defined and requires further research. The corresponding formations represented by the numbers in this table are listed in the footnotes.

**Table 2-1. Number of potentially viable storage formations within each structural province by carbon system, based on the stratigraphic charts. The storage formations are listed in the footnotes.**

Structural Divisions	Carbon Storage Systems				
	CMS	C-O	S-M	LT-EJ	LJ-K
Western arches and Forest City basin	1 <sup>1</sup>	14 <sup>2</sup>	1 <sup>3</sup>	0	0
Illinois basin	1 <sup>1</sup>	7 <sup>4</sup>	1 <sup>5</sup>	0	0
Upper Mississippi embayment	1 <sup>1</sup>	7 <sup>6</sup>	1 <sup>7</sup>	0	0
Central arches	1 <sup>1</sup>	9 <sup>8</sup>	0	0	0
Michigan basin	1 <sup>1</sup>	10 <sup>9</sup>	10 <sup>10</sup>	0	0
West Central Appalachian basin	0	4 <sup>11</sup>	6 <sup>12</sup>	0	0
Central Appalachian basin	0	4 <sup>13</sup>	9 <sup>14</sup>	0	0
Northern Appalachian basin	0	7 <sup>15</sup>	12 <sup>16</sup>	0	0
Mid-Atlantic offshore and Coastal plain	0	0	0	1 <sup>17</sup>	5 <sup>18</sup>

Acronyms: CMS, Cambrian Mount Simon; C-O, Cambrian-Ordovician; S-M, Silurian-Mississippian; LT-EJ, Late Triassic-Early Jurassic; LJ-K, Late Jurassic-Cretaceous.

<sup>1</sup> Mount Simon-Lamotte Sandstone

<sup>2</sup> Potosi Dolomite, Eminence Dolomite, Jordan Sandstone, Gasconade Dolomite, Roubidoux Dolomite, Jefferson City Dolomite, Cotter Dolomite, Everton Formation, St. Peter Sandstone, Plattin Formation, Decorah Formation, Kimmswick Formation, Galena Group, Shakopee Formation

<sup>3</sup> Silurian undivided

<sup>4</sup> Potosi Dolomite, Eminence Formation, New Richmond Sandstone Member, Gunter Sandstone, Oneota Dolomite, Shakopee Dolomite, St. Peter Sandstone

<sup>5</sup> Moccasin Springs Formation

<sup>6</sup> Potosi Dolomite, Eminence Dolomite, Gunter Sandstone, Gasconade Dolomite, Roubidoux Formation, Jefferson City Dolomite, Shakopee Dolomite

<sup>7</sup> Moccasin Springs Formation

<sup>8</sup> Basal sand, Potosi-Davis Formations, Potosi Dolomite, Oneota Dolomite, Shakopee Formation, Kerbel Sandstone, Copper Ridge Dolomite, Rose Run Sandstone, Beekmantown Dolomite

<sup>9</sup> Potosi Dolomite, Knox Dolomite, Galesville Sandstone, Franconia Formation, Trempealeau Formation, Foster Formation, Prairie du Chien Group, St. Peter Sandstone, Black River Formation, Trenton Formation

<sup>10</sup> Lockport Formation, Bass Islands Group, Bois Blanc Formation, Sylvania Sandstone, Amherstburg Formation, Lucas Formation, Anderson Limestone, Dundee Limestone, Roger City Limestone, Traverse Group

<sup>11</sup> Basal sand, Copper Ridge Dolomite, Rose Run Sandstone, St. Peter Sandstone

<sup>12</sup> Clinton Sandstone, Tuscarora Sandstone, Keefer Sandstone, Newburg Sandstone, Wills Creek Formation, Oriskany Sandstone

<sup>13</sup> Copper Ridge Dolomite, Rose Run Sandstone, Gatesburg Formation, St. Peter Sandstone

<sup>14</sup> Tuscarora Sandstone, Grimsby Sandstone, Whirlpool Sandstone, Bass Islands Dolomite, Oriskany Sandstone, Venango Group, Catskill Formation, Pound Sandstone Member (Greenland Gap Group), Chadakoin Formation

<sup>15</sup> Basal sand, Copper Ridge dolomite, Rose Run sandstone, Gatesburg Formation, Galway Formation, Potsdam Sandstone, Black River Group

<sup>16</sup> Grimsby Sandstone, Oneida Conglomerate, Tuscarora Sandstone, Lockport Dolomite, Bass Islands Dolomite, Oriskany Sandstone, Bois Blanc Formation, Bradford Group, Elk Group, Lock Haven Formation, Catskill Formation, Glenerie Formation

<sup>17</sup> Rift basins

<sup>18</sup> Waste Gate (onshore), Mississauga (offshore), Potomac (onshore), Logan Canyon Sands (offshore), Mohawk/Mic-Mac (offshore)

### 2.1.2 Regional Geologic Cross Sections

In the previous MRCSP program, six regional cross-sections (A-A' to F-F') were constructed as educational charts to aid in visualization of subsurface geology relative to carbon storage across that region (Figure 2-4). The onshore sections (A-A' to E-E') were similarly formatted (Greb et al., 2019a-d; Lewis et al., 2019). Each included a cross section that utilized deep subsurface wells and correlated stratigraphic units from the surface to basement. Units were color-coded at depths of more than 2,600 ft to highlight the interval where natural pressure beneath the surface is commonly great enough to allow maximum storage capacity of CO<sub>2</sub>. This depth should also allow CO<sub>2</sub> to be miscible in oil for efficient use in potential enhanced oil recovery (EOR).

Units were color coded below 2,600 ft to help viewers quickly visualize the critical intervals for potential carbon storage, lateral changes in basin geology, and the areas and depths at which different units occurred in the subsurface. Colors were used to show a unit's potential as a (1) storage interval (regional saline reservoirs), (2) confining interval with local potential reservoirs, (3) confining interval, (4) organic-rich shale (important confining zone), and (5) a unit containing fresh- to brackish (rather than saline) water, similar to the color-coding for the previously described stratigraphic charts. Each cross-section chart includes a brief text summary of the geologic structures, key reservoirs, confining intervals, and references to pertinent carbon storage research in the area of the cross sections to help readers better understand the geology depicted relative to carbon storage. Each chart also includes inset maps showing the position of the cross sections relative to towns, regional structures, and oil and gas fields.

Three new cross sections (G-G', H-H', and I-I') were constructed for the MRCI project to complement the cross sections made for the previous MRCSP project. These new cross sections cover parts of the MRCI region that were not covered in the previous project. One of the sections, cross-section G-G', is located offshore and is discussed separately in Section 10 and Appendix A-1 of the Subtask 2.1 report (Battelle, 2024b). The two new onshore cross sections (H-H' and I-I') are for the Illinois Basin, Western arches region, and the eastern Forest City Basin. Cross-sections H-H' and I-I' are presented as large-format charts in Appendix A-1 of the Subtask 2.1 report (Battelle, 2024b). Cross-sections H-H' and I-I' use stratigraphic data from deep wells supplemented with data from shallower wells. Correlations from shallower wells and near-surface bedrock geology were used in some areas to determine bed dips of shallow units especially near faults and anticlines. In many cases, these shallower correlations were projected as inferred dips into the subsurface between the deep wells.

Cross-section H-H' is a north-south section through the Illinois Basin from south-central Wisconsin to western Tennessee. This cross section is based on 31 deep wells, and an additional 20 shallower wells. Part of the section is along a previous cross section by Treworgy et al. (1997) and the new section uses some of the subsurface correlations from that cross section. The H-H' cross section includes the Archer Daniels Midland No. 1 carbon capture and sequestration (CCS) injection well, which is injecting nearly a million tons of CO<sub>2</sub> annually into the Cambrian Mount Simon Sandstone (Greenberg, 2021). Cross-section H-H' highlights the changes in thickness of Paleozoic strata across the Illinois Basin from less than 1,000 ft on the Wisconsin Arch north of the basin to more than 20,000 ft above basement in the deepest part of the basin in western Kentucky. It also highlights the changing depths of key potential reservoirs and confining intervals, as well as structures (faults, arches, etc.) that influence the dip and depth of key units.

Cross-section I-I' is an east-west section across the western part of the MRCI region. It begins in the Forest City Basin on the Missouri-Nebraska border, crosses the Western arches region

## 2.0 Addressing Key Technical Challenges (Task 2)

through southern Iowa, and then crosses the Illinois Basin through Illinois and part of western Indiana. Cross-section I-I' is based on 22 deep wells, and an additional 19 shallower wells. It crosses the north-south cross-section H-H' at the Archer Daniels Midland No. 1 CCS injection well in the Illinois Basin. Section I-I' ends at the Texas Gas Transmission No. 1 Brown well in Indiana, which is the westernmost well in the previous D-D' cross-section. Cross-section I-I' highlights the changes in thickness and stratigraphic variability of Paleozoic strata between the basins on either side of the Western arches region. Precambrian basement is commonly less than 2,800 ft below the surface between the basins. The basement deepens to more than 4,000 ft westward into the Forest City Basin and to more than 8,500 ft eastward in the Illinois Basin. The section shows the changing depths of key potential reservoirs and confining intervals, as well as faults and structures that influence the dip and depth of key units in the Forest City and Illinois Basins. Several reservoirs which contain fresh water at shallow depths are saline reservoirs deeper in the basins. Cross-section I-I' is shown in Figure 2-5 for illustration and detailed view of all cross sections is in Appendix A-1 of the Subtask 2.1 report (Battelle, 2024b).

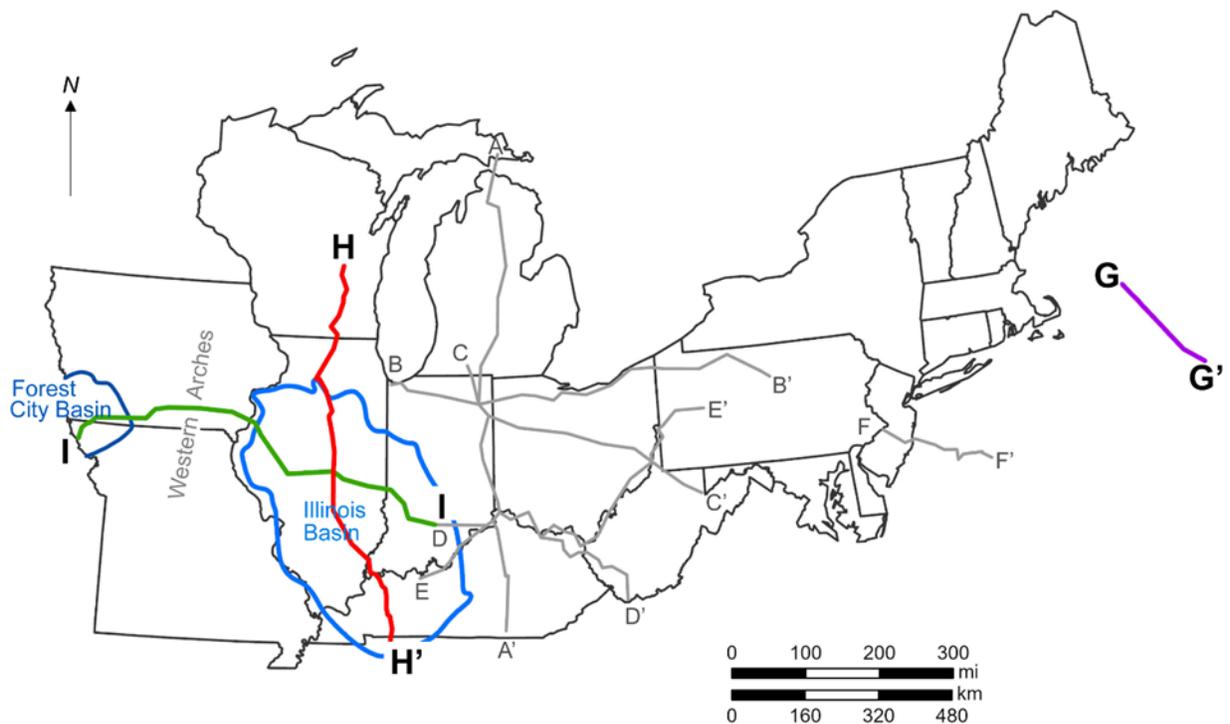


Figure 2-4. Location of new cross-section lines G-G', H-H', and I-I'. Cross-sections A-A' to F-F', which were completed for the previous MRCSP project, are also shown. Basin outlines are shown in blue for the Illinois Basin and the part of the Forest City Basin within the MRCI area.

## 2.0 Addressing Key Technical Challenges (Task 2)

### Subsurface geology for carbon storage in part of the Midwest Regional Carbon Initiative Region: from the Forest City Basin to the Illinois Basin

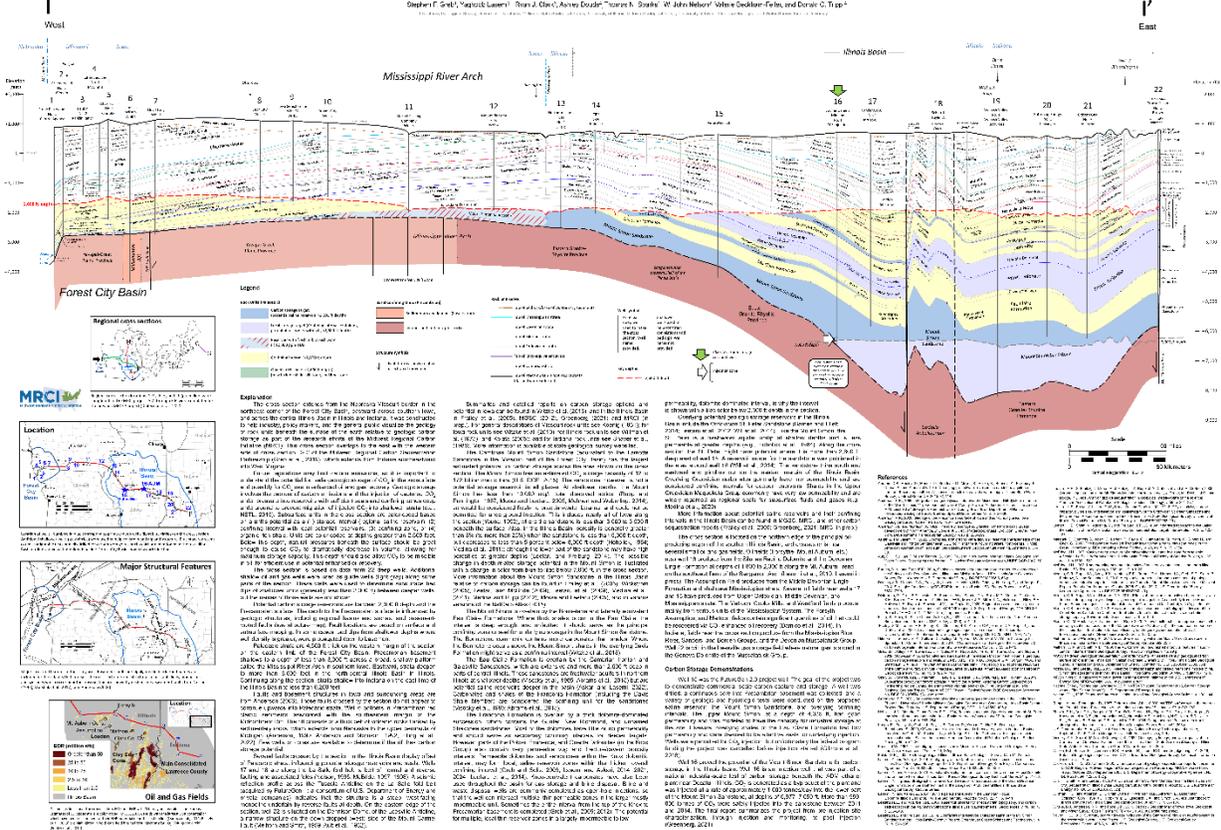


Figure 2-5. Subsurface geologic cross-section in the east-west direction from the Forest City Basin to the Illinois Basin.

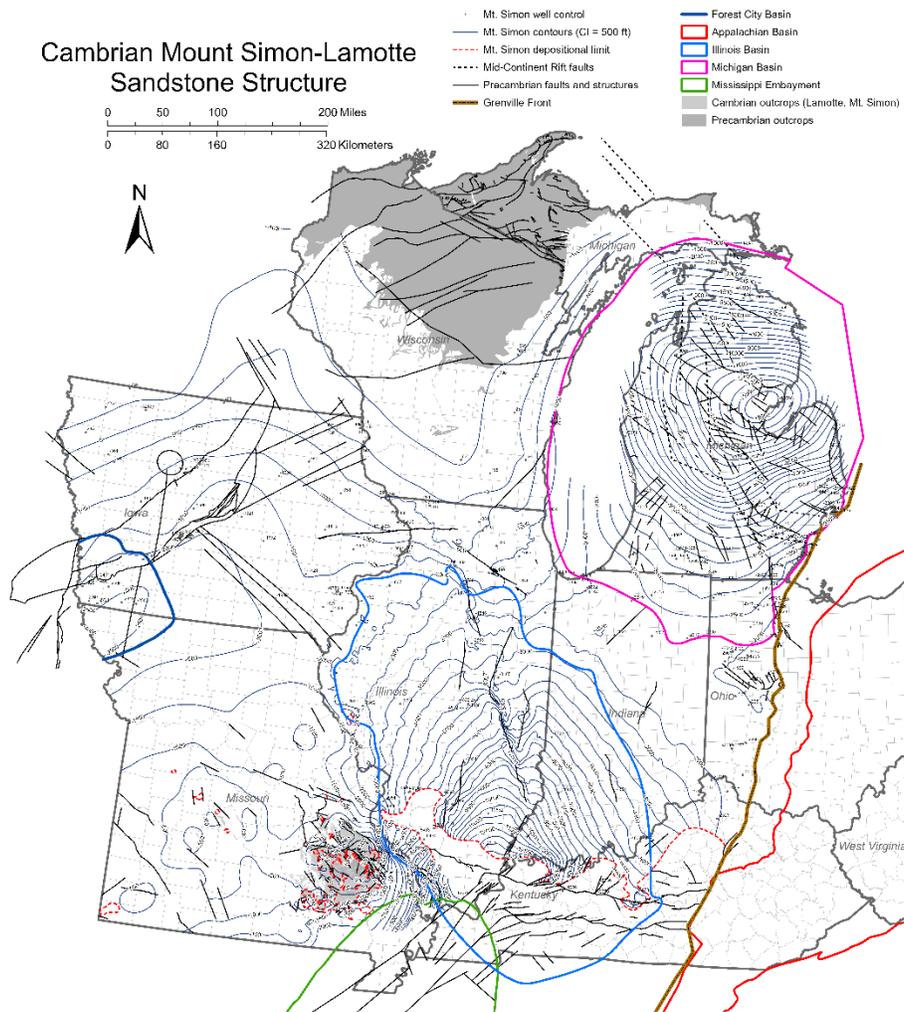
### 2.1.3 Regional Geologic Maps

Seven new regional maps were created for key storage targets, caprock units, and the basement rock within the MRCI region. The seven new maps include the following:

- Precambrian and Pre-Mesozoic basement structure contour map
- Mount Simon-Lamotte Sandstone structure contour map
- Mount Simon-Lamotte Sandstone isopach map
- Cambrian Eau Claire-Bonnerterre-Conasauga Formations (base of Knox Group) structure contour map
- Knox and Prairie du Chien Groups (Beekmantown, Everton, and Shakopee Dolomites) structure contour map
- Trenton/Lexington Limestone and Galena Group (Base of Maquoketa Formation) structure contour map
- Ordovician/Maquoketa/Queenston Shale structure contour map

## 2.0 Addressing Key Technical Challenges (Task 2)

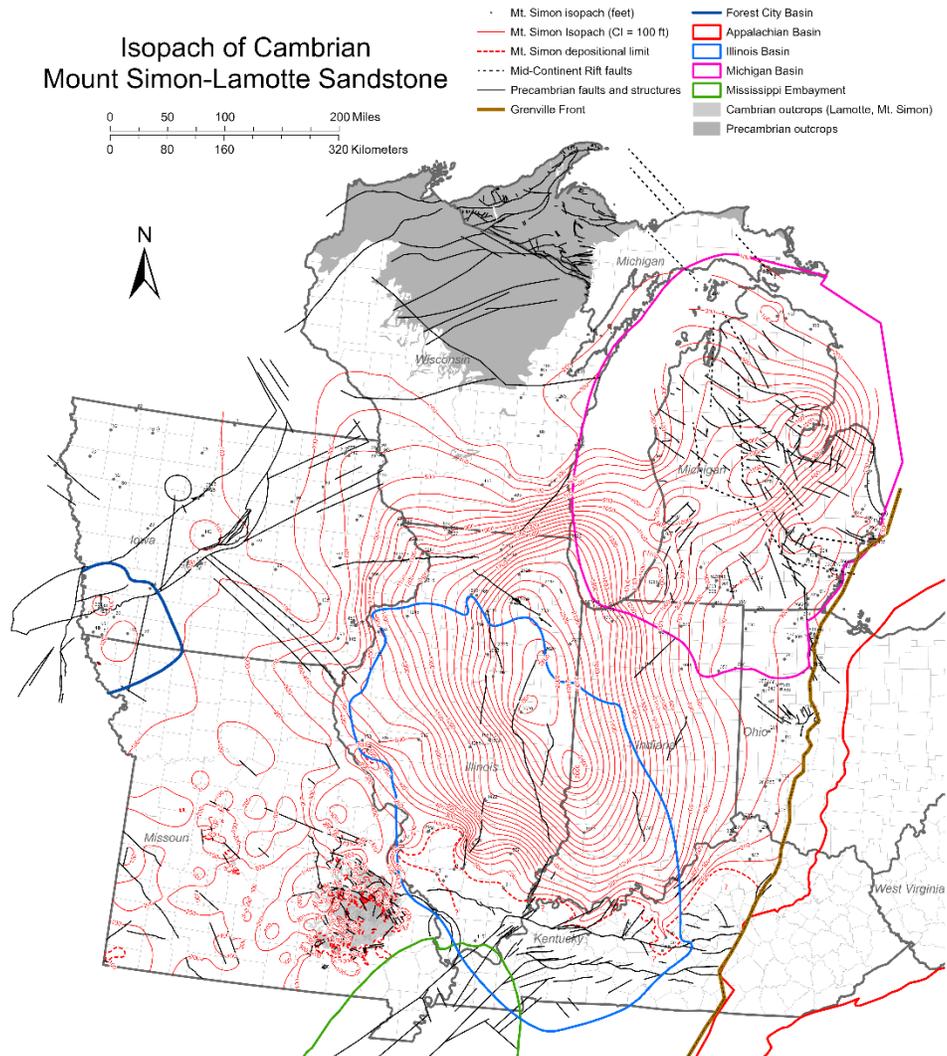
The first three maps listed above are shown here for illustration. All seven maps are included in Appendix A-2 of the Subtask 2.1 report (Battelle, 2024b). The regional maps were developed for units that are considered significant regional storage reservoirs, caprock units, or basement surface. For example, the Mount Simon-Lamotte Sandstone is widely considered a world-class reservoir for CO<sub>2</sub> storage, and thus, detailed structure contour and isopach maps were developed for this unit. The structure contour map for the Mount Simon-Lamotte Sandstone is shown in Figure 2-6. Within the map, the Precambrian faults are overlain on the structure contours. Other important features include the Mount Simon depositional limit and the Grenville Front, which represents the eastern boundary of the Mount Simon-Lamotte Sandstone.



*Figure 2-6. Structure map on top of the Mount Simon Sandstone and equivalent Lamotte Sandstone. Contour interval is 500 ft. Paleozoic and younger basins are outlined in color: Forest City Basin (dark blue), Illinois Basin (light blue), Upper Mississippi embayment (green), Michigan Basin (pink), and Appalachian Basin (red). The Grenville Front (brown) is used to approximate the eastern border of the Mount Simon Sandstone. Basal sandstones to the east of the Grenville Front are treated separately from Mt. Simon Sandstone. Gray areas are surface outcrops of Cambrian and older strata. Faults shown are basement faults. Surface and Paleozoic faults are not shown.*

## 2.0 Addressing Key Technical Challenges (Task 2)

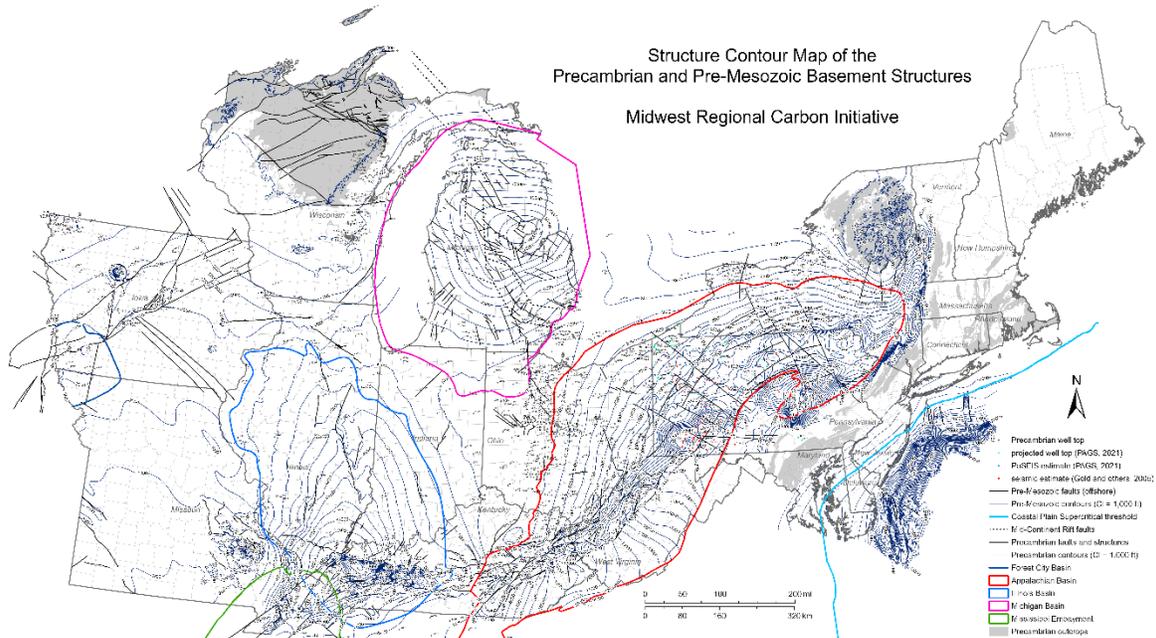
A corresponding isopach map was generated for the Mount Simon-Lamotte Sandstone which indicates where the thickest sections of the Mount Simon are present (Figure 2-7). These maps aim to provide a detailed view of the regional structure, faults, and thickness for rock units of interest for CO<sub>2</sub> storage.



*Figure 2-7. MRCI regional Mount Simon Sandstone isopach map. Contour interval is 100 ft. Paleozoic and younger basins are outlined in color: Forest City Basin (dark blue), Illinois Basin (light blue), Upper Mississippi embayment (green), Michigan Basin (pink), and Appalachian Basin (red). The Grenville Front (brown) is used to approximate the eastern border of the Mount Simon Sandstone. Basal sandstones to the east are treated separately. Gray areas are surface outcrops of Cambrian and older strata. Faults shown are basement faults. Surface and Paleozoic faults are not shown.*

## 2.0 Addressing Key Technical Challenges (Task 2)

The structure contour map for the Precambrian basement (west of the Appalachian Mountains) and Pre-Mesozoic basement (east of the Appalachian Mountains) was developed for the MRCI region and can be seen in Figure 2-8. This regional map utilized several sources where mapping was completed on a state-specific or basin-specific basis. More details regarding the data sources for the Precambrian and Pre-Mesozoic basement map can be found in the Subtask 2.1 report (Battelle, 2024b). Structure contours shown on the map represent 1,000-ft depth intervals. Basement faults are also shown on the map. Faults came from multiple sources, which in some cases were the same as the sources for structural contours, but in others were different or compiled from previous publications. Basement fault locations and lengths are sometimes identified on seismic data, but often are based on (1) extrapolation of known surface faults and structures, sometimes in combination with well data; (2) general or average line segments drawn through areas of complex faulting at the surface or near surface; (3) the margins of magnetic and gravity anomalies; and (4) other literature sources. The Precambrian/Pre-Mesozoic basement is not a storage target but nevertheless is an important unit because it defines the base of the CO<sub>2</sub> storage zone and/or understanding induced seismicity risks related to CO<sub>2</sub> injection.



**Figure 2-8. Structure map of the Proterozoic basement west of Appalachian Mountains and pre-Mesozoic basement east of Appalachian Mountains. Contour interval is 1,000 ft. The location of Paleozoic and younger basins above basement are outlined: Forest City Basin (dark blue), Illinois Basin (light blue), Upper Mississippi embayment (green), Michigan Basin (pink), Appalachian Basin (red), and Atlantic coastal plain and offshore (turquoise) basins. Gray areas are surface outcrops of Precambrian units. Faults shown are basement faults. Midcontinent rift margin faults in southern Michigan are approximated (dashed lines). Surface faults, Paleozoic faults, and Triassic rift basin faults are not shown.**

## 2.1.4 Stress

### 2.1.4.1 Preliminary Stress Data Compilation

As part of the MRCI project, stress data for the region were compiled. The objective for compiling the stress information was to provide data to facilitate assessing the stability of the basement rocks and to inform safe and effective implementation of CCUS in the study region. The data compilation effort was led by the Kentucky Geological Survey (KGS) and supported by Battelle and the Geoteam. Stress data were compiled in a database with a schema that was based on that of the World Stress Map (WSM) (Heidback et al., 2016; Heidback et al., 2018). However, the WSM data set had not been updated since 2016, so additional stress data were gathered and compiled from MRCI states, from peer-reviewed publications (Carlson et al., 2018; Carpenter et al., 2020; Snee and Zoback, 2020; and Yang et al., 2014), and seismological data centers.

The newly compiled data (160 points) are plotted on a map of the MRCI region in Figure 2-9; the stress data from the WSM are plotted separately on a map of the MRCI region in Figure 2-10. Most of the 160 new stress data points are from single-event earthquake focal mechanisms. The other types of stress data included are hydraulic fracturing, borehole breakouts over coring, focal mechanism formal inversions, and drilling-induced tensile fracturing.

Figures 2-11 and 2-12 provide additional pie charts that summarize the type of stress regime and the orientations of the maximum horizontal stress, respectively. In contrast with the WSM dataset, where most data (62 percent) lack stress-regime designations, only 32 percent of the MRCI compilation have unknown stress regimes. Consistent with stress observations made in the central and eastern US (e.g., Hurd and Zoback, 2012) and the WSM dataset, the SHmax azimuths in the MRCI compilation are generally oriented northeast-southwest (Figure 2-12).

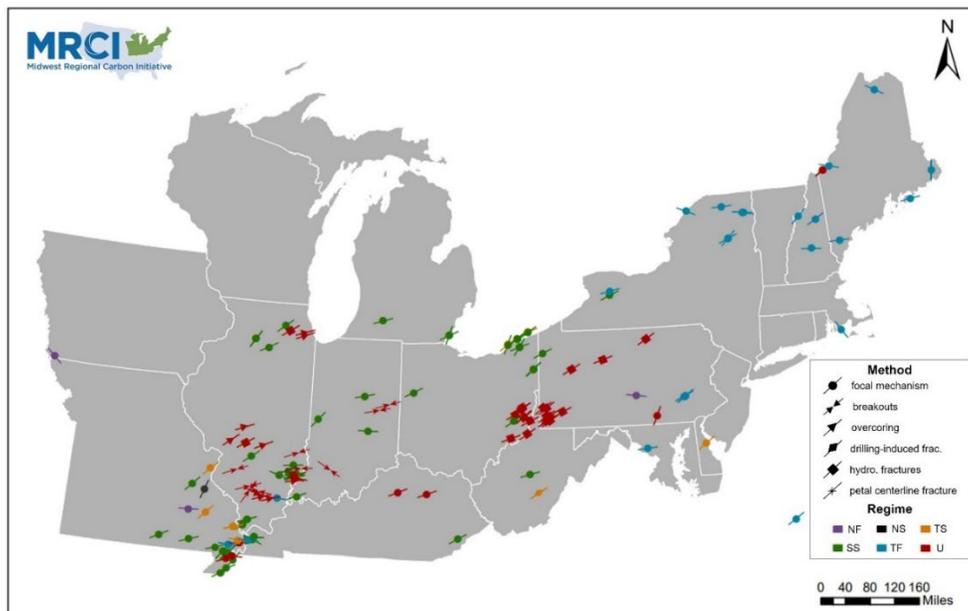


Figure 2-9. Stress data for the MRCI region (160 new data only).

2.0 Addressing Key Technical Challenges (Task 2)

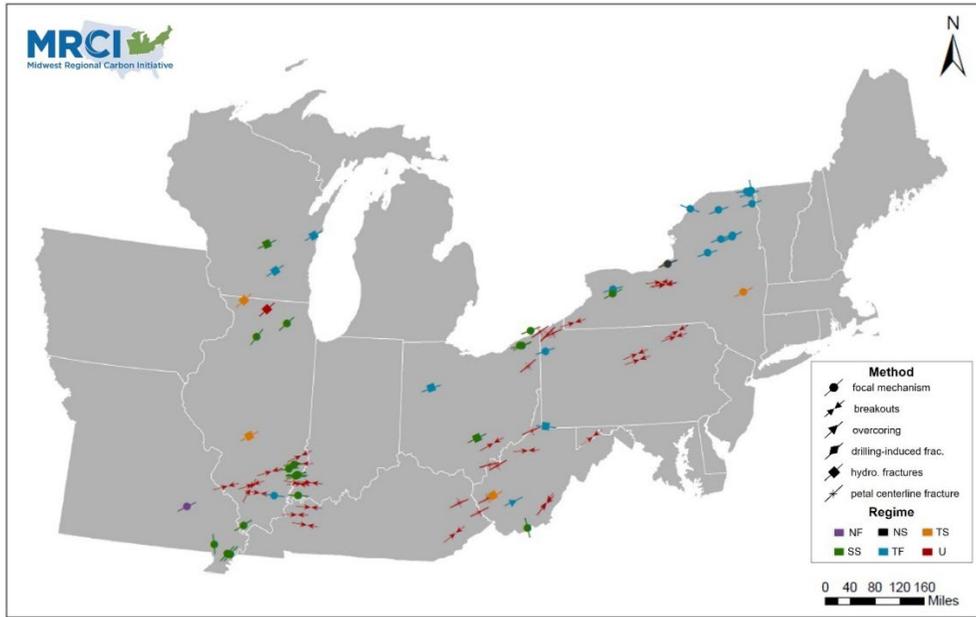


Figure 2-10. Stress data for the MRCI region (WSM data only).

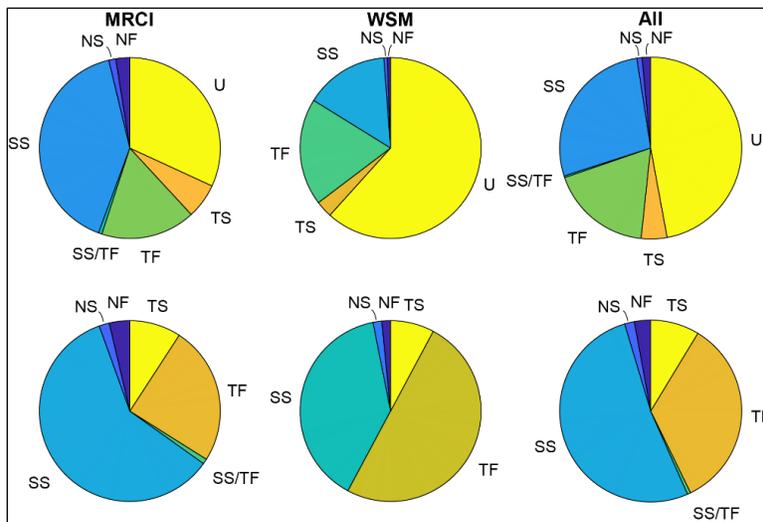


Figure 2-11. Distributions of stress regime attributes in the MRCI data compilation for new data (left column), WSM data (middle column), and the combination of the two (right column). TF, thrust faulting; TS, oblique thrust faulting; SS, strike-slip faulting; NS, oblique normal faulting; NF, normal faulting; U, no stress regime assignment. The distribution of stress regimes excluding “U” data are shown in the lower row.

## 2.0 Addressing Key Technical Challenges (Task 2)

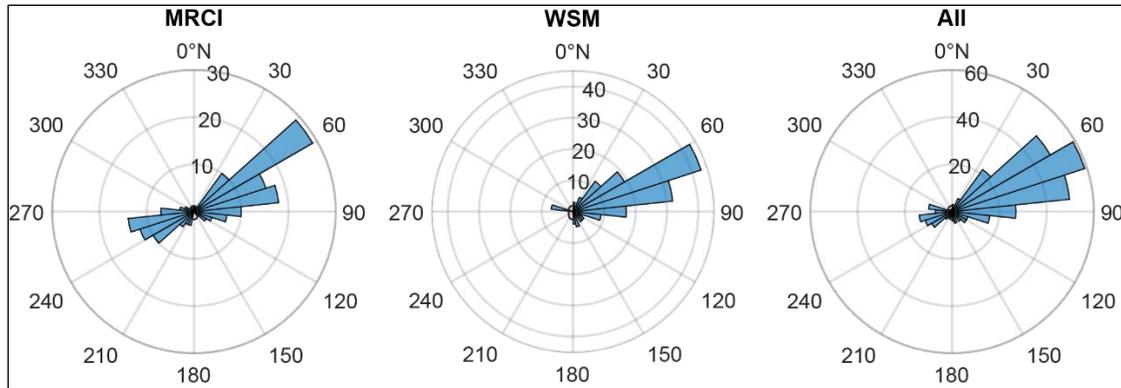


Figure 2-12. Distributions of SHmax azimuths in the MRCI compilation, in the WSM dataset, and for the composite dataset.

### 2.1.4.2 Supplemental Stress Data

Within the MRCI region, stress data are available from the WSM (Heidbach et al., 2016) and additional sources discussed in the previous section. Many of these data are clustered in southern Illinois, southeastern Missouri, West Virginia, New York, and New Hampshire, with others scattered across the region. However, there are areas of the MRCI region where stress data are sparse and additional data are needed to assess whether local stresses deviate from the regional characterization. To augment the preliminary stress data compilation, recently determined focal mechanisms were collected and new focal mechanisms were calculated. Then, the resulting enhanced data compilation was used to perform a series of stress inversions for discrete areas to characterize the state of stress across the MRCI region. Figure 2-13 shows all stress data acquired to date except for those in the WSM compilation which are omitted for clarity. An inverse analysis was performed for 10 subdomains across the MRCI study region (see Figure 2-14). In the absence of site-specific stress measurements, stress tensors for specific sites can be approximated from the regional scale inversion of focal mechanisms shown in Figure 2-14. It should be noted that the tensor results were calculated using small datasets that are spread across broad areas and as such may not reflect local stresses at a given site, which introduces modeling uncertainty.

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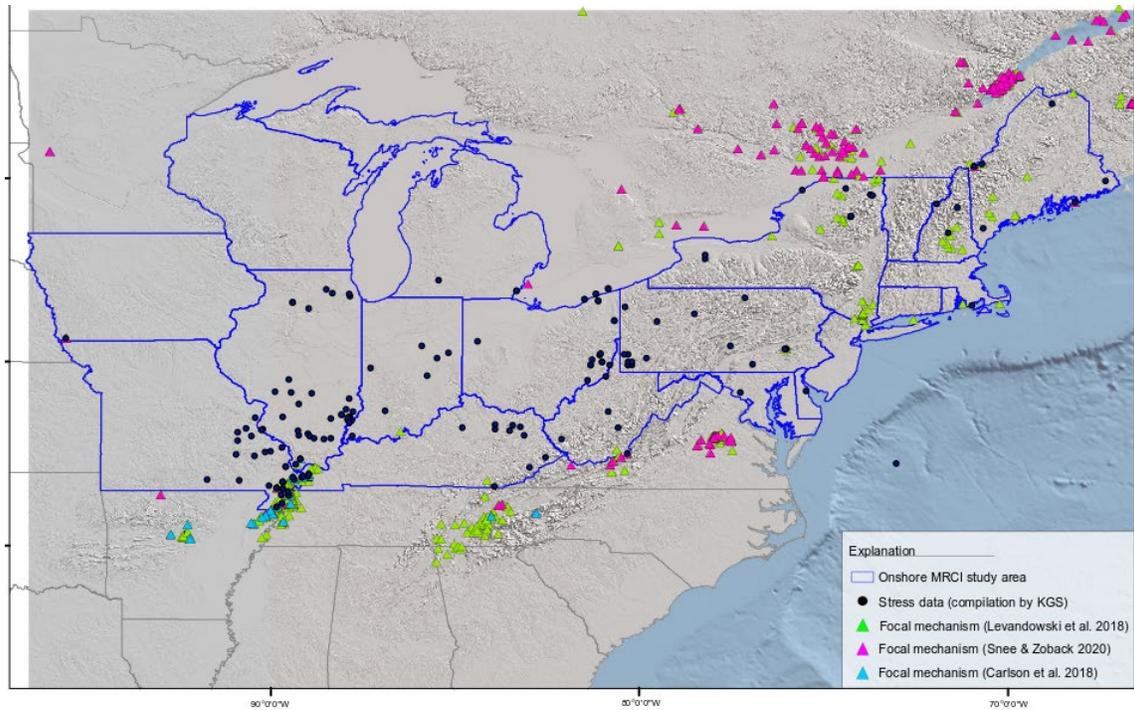


Figure 2-13. Stress data compiled for the MRCI region. Initially compiled data are plotted as black circles. Additional focal mechanism data compiled to better constrain the stress inversions are plotted as triangles. World Stress Map data not shown for clarity.

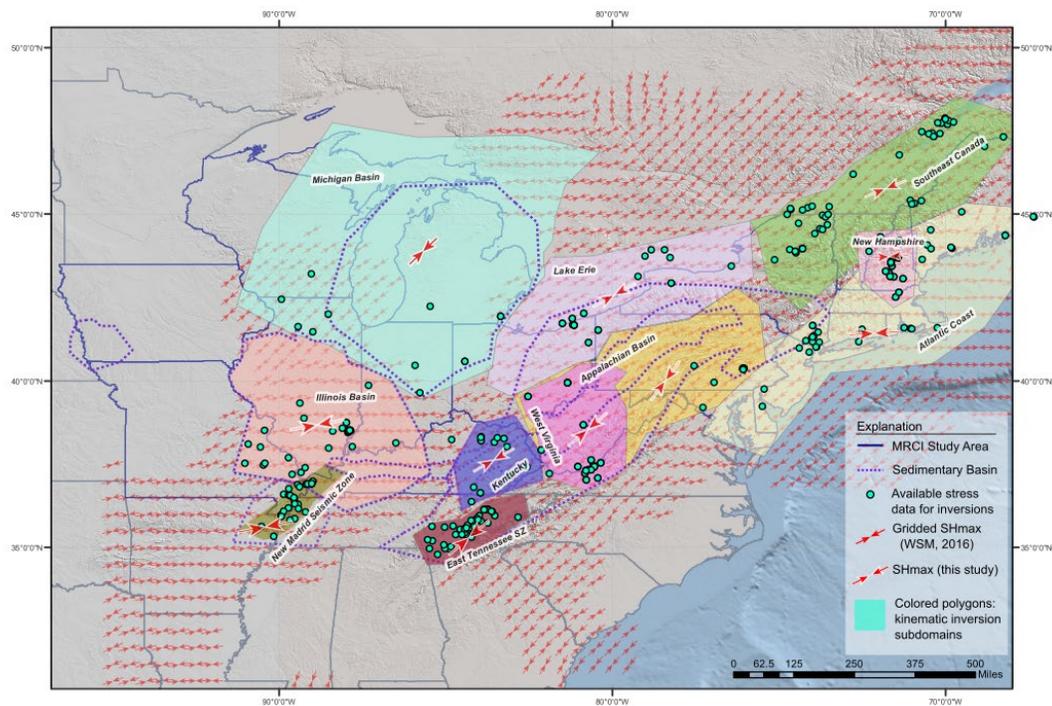


Figure 2-14. Ten Subdomains in which stress fields were determined (colored polygons) and the focal mechanisms used in the stress inversions. Gridded arrows indicating orientation of maximum horizontal principal stress provided by the World Stress Map (Heidbach et al., 2016). Results from the inverse analysis shown as single arrow pairs in each subdomain.

### 2.1.5 Historical Seismicity

Understanding location and magnitude of historical seismicity is important for predicting potential future seismic activity, both natural and induced, by other activities such as fluid injection into deep wells. The historical seismicity of the MRCI region was evaluated to identify earthquake locations, magnitude, and other relevant seismic source parameters. Past seismicity indicates the presence of critically stressed faults and current thinking is that most, if not all the central and eastern US (CEUS) is in a state of critical stress. All available lists of earthquakes were collected and compiled into an earthquake catalog for the MRCI region.

An historical seismicity catalog containing a list of earthquakes that occurred in the MRCI study area from 1568 through 2020 was compiled from various sources of earthquake data. The starting catalog, consisting of earthquakes from 1568 through 2019, was provided by Lettis Consultants International (LCI). Figure 2-15 shows the location and magnitude of historical earthquakes included in the MRCI earthquake catalog. These earthquake data were compiled from several sources, which are described in the Subtask 2.2 report (Battelle, 2024c).

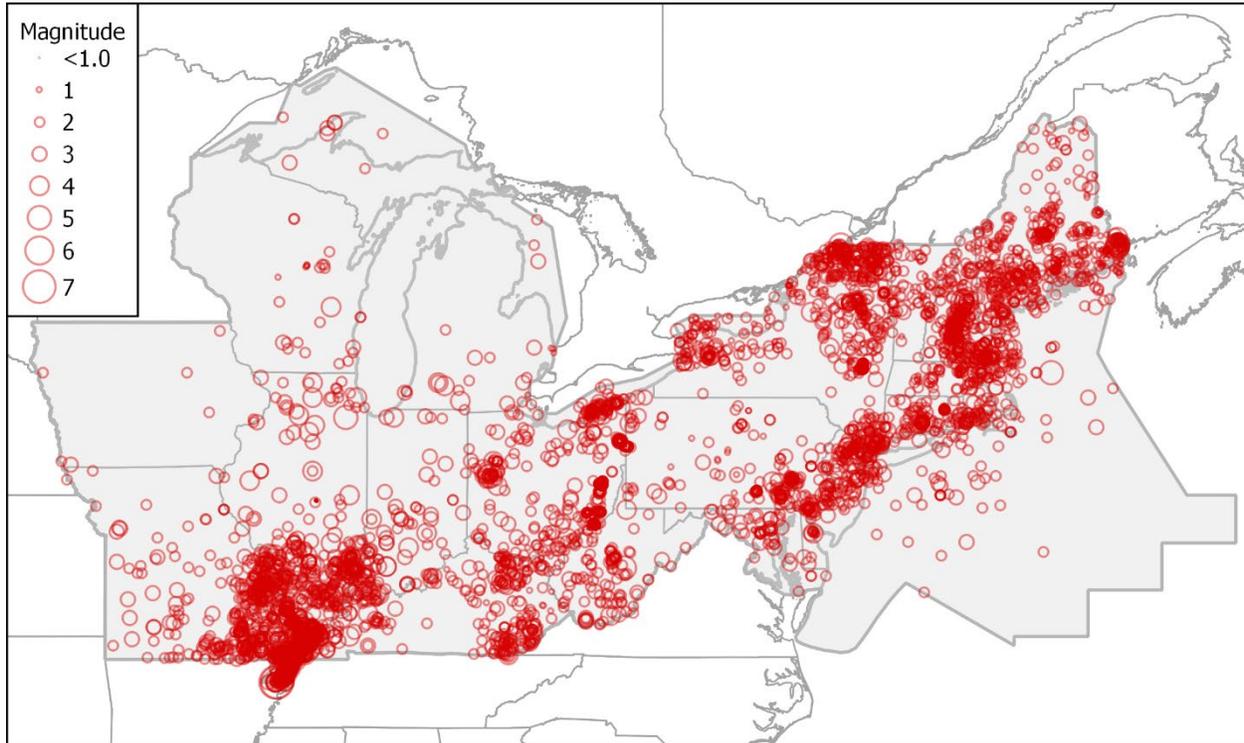


Figure 2-15. The MRCI Earthquake Catalog.

### 2.1.6 Map Database and Rock Property Data Inventory

#### 2.1.6.1 MRCI Interactive Map (Map) Database

The MRCI online interactive map (IMap) database is a compilation of over 800 geologic maps contained within a centralized online ArcGIS system. Most of the maps were developed in previous studies but some were newly developed in the MRCI project. As seen in Figure 2-16,

## 2.0 Addressing Key Technical Challenges (Task 2)

the IMap is organized into a set of eight tabs which are divided by carbon storage system. Users have the option to view all layers (for all carbon systems) at once or can view subsets of the maps grouped by basement, Cambrian Mount Simon, Cambrian-Ordovician, Silurian-Mississippian, Late Triassic-Early Jurassic, and Late Jurassic-Cretaceous Carbon Systems. The map layers available within the IMap primarily include structure and thickness for key storage formations, plus some property (porosity, CO<sub>2</sub> storage capacity) maps and unit outlines. While the majority of the maps are from previous projects such as MRCSP, state geological survey mapping projects, and other regional consortiums such as the Appalachian Storage Hub (ASH) project, there are some new maps included in the IMap, such as those described in Section 2.1.3 of this report. The map layers contained within the online ArcGIS system are listed in Appendix B of the Subtask 2.1 report (Battelle, 2024b). The online IMap developed in this project can be accessed at the following link:

<https://atlas2.wvgs.wvnet.edu/portal/apps/instant/portfolio/index.html?appid=f3e99f96205a4ca0a04d43eaeab901fc> [atlas2.wvgs.wvnet.edu]

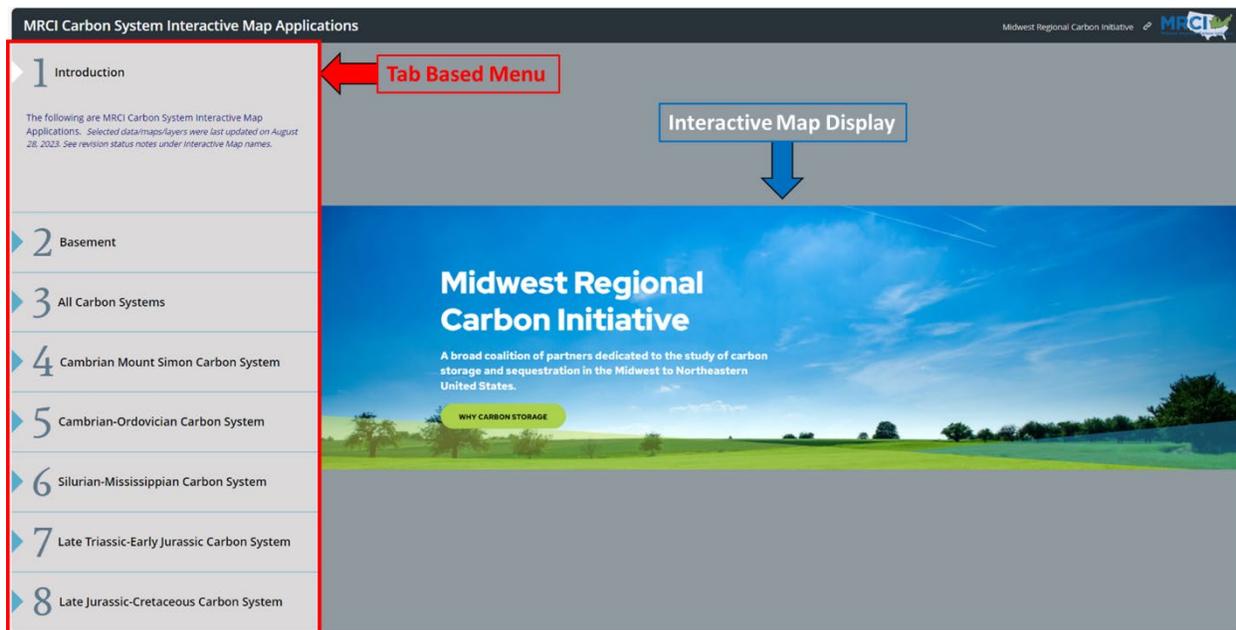


Figure 2-16. Image of the login home screen for the MRCI IMap website.

An example of the viewing pane for selected maps is seen in Figure 2-17. In this example, the Cambrian Mount Simon Carbon System is selected and both the isopach contour map and gridded isopach map for the Mount Simon Sandstone are toggled on. The base layers (i.e., state and county outlines) which are available across each of the carbon system tabs are shown in the red box in the figure, while carbon system specific maps (i.e., structure and thickness maps) are shown in the blue box. Each of the 813 maps which are available within the IMap can be toggled on and viewed in this map window. Each map within the IMap has associated metadata provided by state Geoteam member and Battelle. The data were divided according to carbon systems and remaining base map and well data. Many of the generated maps were a collaborative effort involving several states and were assigned to the state or organization that

## 2.0 Addressing Key Technical Challenges (Task 2)

had the initial primary responsibility for creating the map. Each metadata file is associated with the data file corresponding to each IMap layer and is saved within the larger ArcMap package where the layers are stored.

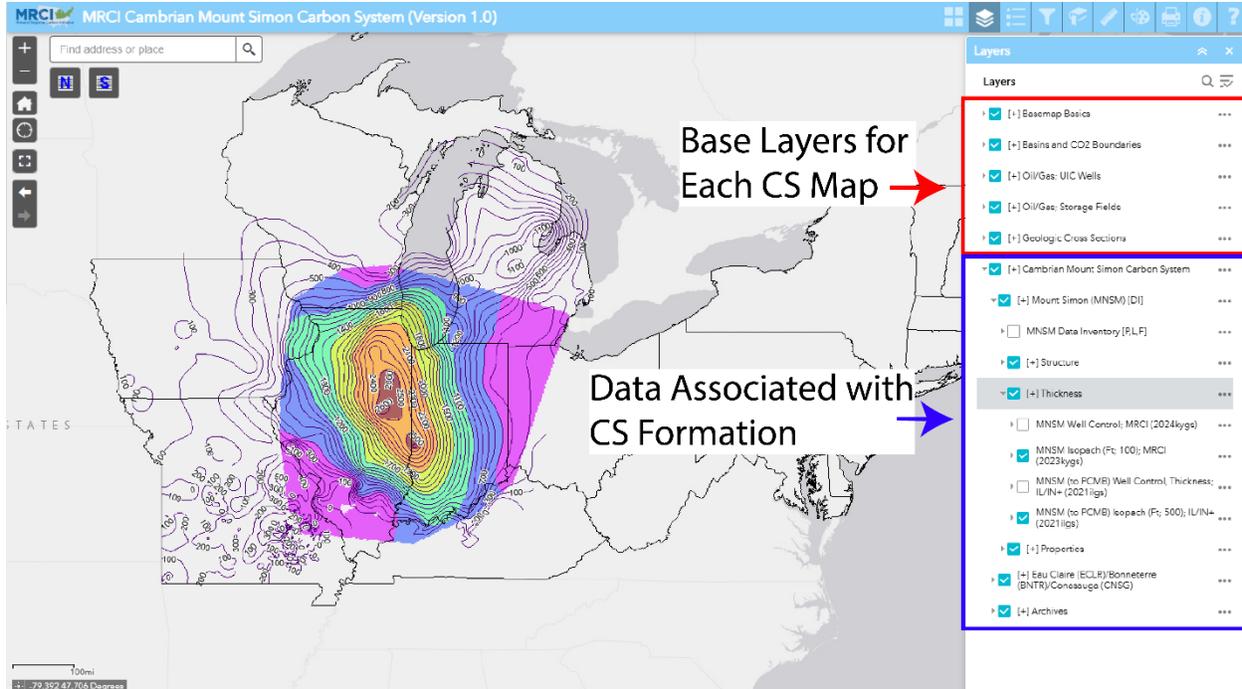


Figure 2-17. Example isopach (thickness) map for the Mount Simon Sandstone with displays for base layers and associated data for each formation within the carbon system shown in the input pane.

In addition to the map layers within each carbon system that are formation-specific, there are universal maps available within each carbon system. These include basemap basics (state and county outlines), basins and supercritical CO<sub>2</sub> boundaries, oil/gas and underground injection control (UIC) well locations, oil/gas and storage field locations, and geologic cross sections.

Within the basins and supercritical CO<sub>2</sub> boundaries folder, users can choose to turn on the subregion map (Figure 2-18). This displays the unique subregions within the MRCI area, with the option to click on a specific subregion. This leads to a pop-up which lists the name of the subregion and provides a link to the stratigraphic chart associated with the specific subregion.

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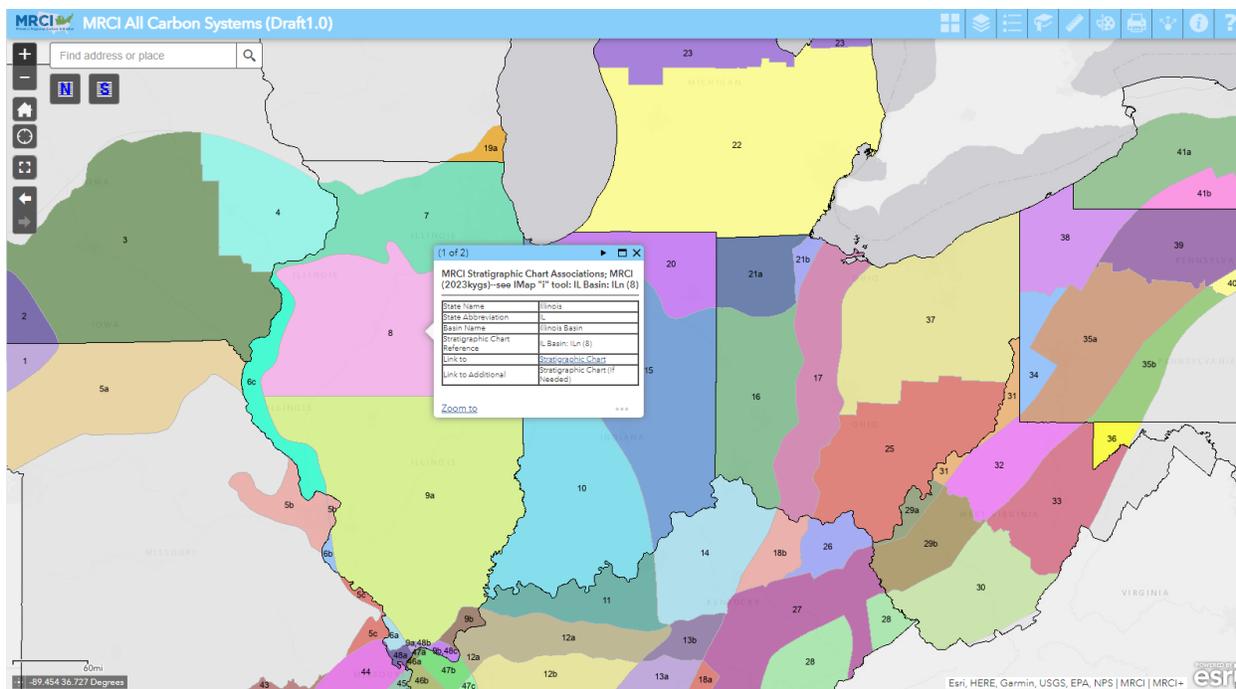


Figure 2-18. Stratigraphic chart pop-up window in the IMap which allows users to view each stratigraphic chart.

Additionally, users can view regional cross sections within the IMap. On the cross-section layer, users can select a cross section of interest (see Figure 2-4) which will provide a pop-up and link to the cross section selected. This feature is available for cross-sections A-A' through I-I'. Similar to the stratigraphic charts, the link will open a PDF containing the selected cross section.

### 2.1.7 Rock Property Data Inventory for Key Formations

A data inventory was compiled for the key storage targets within the MRCI region. This data inventory aimed to identify and compile existing rock property data (by formation and by well) for specific formations of interest. The formations inventoried were those which had existing structure and isopach maps and corresponding well control for those maps. Ultimately, this led to developing a data inventory for 29 storage formations within the MRCI region. These formations developed are identified in Figure 2-19.

The data inventory provides a resource for project developers to easily identify where rock property data are available for formations considered for CO<sub>2</sub> storage. In the IMap, each well that penetrates a specific formation contains a pop-up window containing key information indicating whether the well has well logs, the type of log(s), and the format of the logs (raster log, LAS log). In addition, the pop-up window indicates whether or not physical core and core-test data (i.e., porosity and permeability) are available. While these resources are typically accessible on each geological state survey website, the IMap database provides a centralized source of the data focused on CO<sub>2</sub> storage reservoirs and provides a graphical view of the location of the available data within selected storage targets. An example for the information available at the well level is shown in Figure 2-20.

Once users select the formation which contains data inventory that they are interested in viewing, there is a filter tool in the online ArcGIS mapping system which allows the user to filter

## 2.0 Addressing Key Technical Challenges (Task 2)

the wells by data type. The filter tool is also available, where users can select whether they want to only view wells with raster logs, LAS logs, physical core, and/or core data.

While the data itself are not available within the online ArcGIS system, it is available on each state's geological survey website. Appendix B of the Subtask 2.1 report (Battelle, 2024b) provides instructions from each state survey accessing the data that is shown on the IMap. The goal of the data inventory was to compile information regarding key regional storage formations into a single resource not bounded by state lines. Additionally, the Access database with the data inventory is available under MRCI submissions on EDX.



## 2.0 Addressing Key Technical Challenges (Task 2)

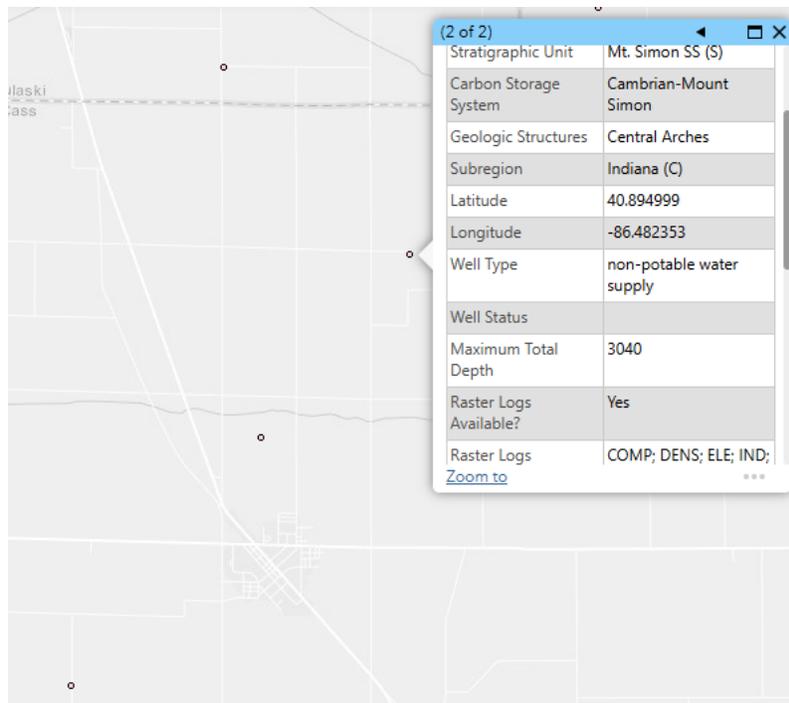


Figure 2-20. Pop-up window showing information available for each well within the IMap.

## 2.2 Injectivity Feasibility Assessment for Selected Carbon Storage Systems (Formations)

### 2.2.1 Objectives and Scope

According to the DOE Carbon Storage Atlas (<https://netl.doe.gov/carbon-management/carbon-storage/atlas-data>), the geology of the MRCI region has an estimated CO<sub>2</sub> storage capacity of 149 to 564 billion tonnes of CO<sub>2</sub> (this is the amount of CO<sub>2</sub> storage available in saline reservoirs in the MRSCP and MGSC areas, which includes most of but not the entire MRCI study area). However, the injectivity of most of the formations in the region, which is the key performance metric for CO<sub>2</sub> storage, has not been defined either through modeling or field injection tests. In this study, modeling was used to numerically evaluate the feasibility of achieving commercial-scale CO<sub>2</sub> storage in selected carbon storage systems (formations) in the region. Commercial scale was defined as an injection rate of at least 1 million tonnes per year with a reasonable number of injection wells and requiring a reasonable land area. Specifically, the modeling aimed to define the following parameters for each carbon storage system:

- the number of wells required to inject 1 million metric tonnes (MMt)/yr of CO<sub>2</sub> for a 30-year period;
- the injection well spacing (if more than one well is needed);
- the area of the CO<sub>2</sub> plume and the area with increased pressure due to CO<sub>2</sub> injection. These two criteria define the area of review (AoR) as defined by the United States Environmental Protection Agency (USEPA) Class VI (Geologic CO<sub>2</sub> Sequestration) regulation.

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The potential of the different modeled carbon storage systems was then compared based on these modeling results (i.e., fewer wells and smaller plume area is considered more favorable).

Eight sites were considered for modeling but ultimately six of these eight sites were subject to numerical modeling of CO<sub>2</sub> injection to determine their ability to accommodate a commercial-scale CO<sub>2</sub> injection project. The six different model locations include three carbon storage systems (Mount Simon, Cambrian-Ordovician, and Silurian-Mississippian) and a subset of rock types, petrophysical properties and subsurface conditions that are present throughout these carbon storage systems. The location of the model sites is shown in Figure 2-21 and Table 2-2 identifies the carbon system and geologic formation(s) considered for CO<sub>2</sub> storage at each site.

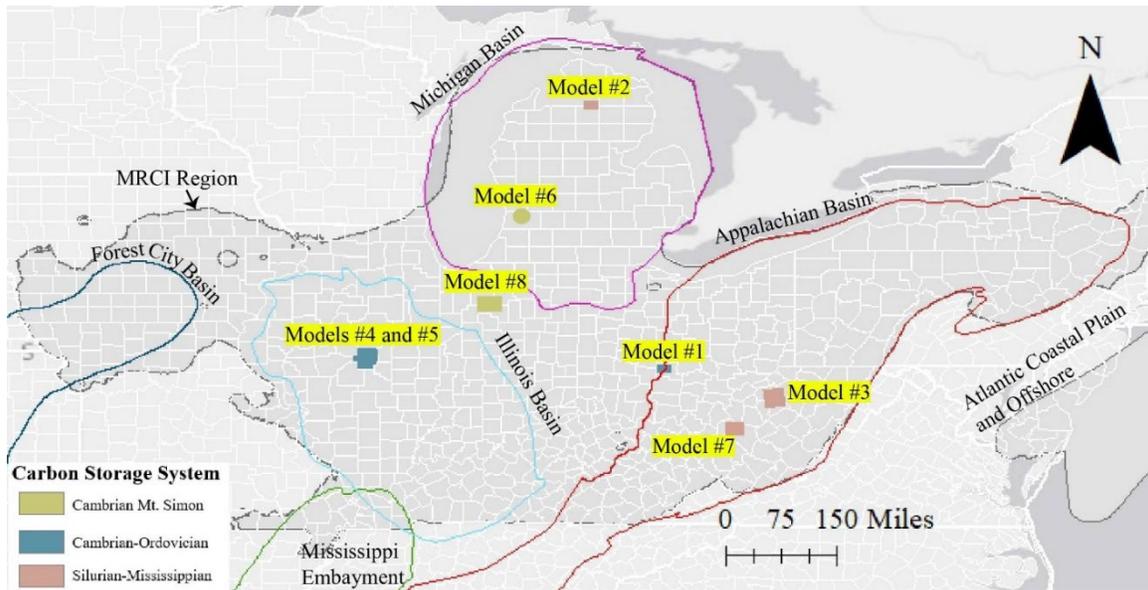


Figure 2-21. Model locations and the carbon storage system evaluated.

**Table 2-2. Location of model sites and geologic formations evaluated in the numerical models.**

Model #	Model Location	Carbon Storage System	Storage Formations of Interest	Dynamic Model	Previous Model Reference
#1	Pickaway County, Ohio	Cambrian-Ordovician	Maryville, Upper Conasauga	Yes	Battelle (2017)
#2	Antrim and Otsego Counties, Michigan	Cambrian-Ordovician	Bass Islands	Yes	Battelle (2018)
#3	Tri-State Area (Gilmer, Ritchie, Doddridge Counties, West Virginia)	Silurian-Mississippian	Oriskany	Yes	N/A [New model]
#4	Macon County, Illinois	Cambrian-Ordovician	Potosi	Yes <sup>a</sup>	Adushita et al., (2013 and 2014)
#5	Macon County, Illinois	Cambrian-Ordovician	St. Peter	Yes <sup>a</sup>	Will et al., (2014)
#6	Ottawa County, Michigan	Cambrian Mount Simon	Mount Simon	Yes	N/A [New model]
#7	Kanawha and Putnam Counties, West Virginia	Silurian-Mississippian	Oriskany, Newburg	No	N/A [New model]
#8	Cass, Fulton, Pulaski, and White Counties, Indiana	Cambrian Mount Simon	Mount Simon	No	N/A [New Model]

The Potosi model and the St. Peter model were developed and used in previous studies. The numerical models were not available to use in this study, so no new model simulations were run. The results included in this table were taken from the modeling reports.

In addition to the metrics mentioned above, the CO<sub>2</sub> injectivity index ( $J$ ) was calculated for the site (geologic formation) model from the modeling results and was used as an additional metric for expressing CO<sub>2</sub> storage site performance. The injectivity index is the ratio of CO<sub>2</sub> injection rate for every pound per square inch (psi) of pressure buildup at the injection well and is directly correlated to reservoir properties such as permeability and thickness (higher values of  $J$  indicate higher injectivity). It is an extremely reliable metric for rapid evaluation and comparison of reservoir quality and performance that has been adapted from traditional oil and gas industry application. Ravi Ganesh and Mishra (2014) determined that there exists a linear relationship between the injectivity index and the permeability-thickness product ( $kh$ ) of the reservoir from a comprehensive simulation and a field dataset (see Figure 2-24 later in this section). Valluri et al. (2020) updated the empirical correlation between  $J$  and  $kh$  to include lower and upper bounds of  $J = 0.03 \times kh$  and  $J = 0.23 \times kh$ , respectively, with the average trend represented by  $J = 0.08 \times kh$ . The CO<sub>2</sub> injection modeling was performed by building geological models using the publicly available static-earth modeling software PETREL (Schlumberger, 2022) and numerically evaluating CO<sub>2</sub> injection scenarios in the chosen sites of interest using the dynamic reservoir simulation code GEM (Computer Modeling Group, 2019). In addition, hub-scale feasibility was evaluated for Model/Site #6 to illustrate regional carbon storage potential in a high-quality injection target. A generalized modeling workflow is shown in Figure 2-22.

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Figure 2-22. Simplified modeling workflow.

### 2.2.2 Results of CO<sub>2</sub> Injection Modeling

Table 2-3 summarizes and compares key performance metrics (number of injection wells, CO<sub>2</sub> plume area, diameter of pressure-based AoR) for each of the modeled sites. The formations with the highest injectivity are the Mount Simon Sandstone (Model #6), the St. Peter Sandstone (Model #4) and the Potosi Dolomite (Model #5). Furthermore, all three of these systems are capable of accommodating a hub-scale facility, defined in this study as an injection rate  $\geq 3$  MMT/yr for 30 years. Two model sites (#1, #3) evaluated in this study can support commercial-scale injection rate (1 MMT/year for 30 yrs) but only if multiple injection wells are used. Model #1 is located in the Appalachian Basin, Cambrian-Ordovician Carbon Storage System (Maryville and Upper Conasauga Formations) and Model #3 is located in the Appalachian Basin, Silurian-Mississippian Carbon Storage System (Oriskany Sandstone). For model site #2 (Ottawa County, Michigan, Silurian-Mississippian Carbon Storage System, Bass Islands Dolomite), the modeling shows that the Bass Island Dolomite alone would require multiple injection wells to achieve commercial-scale injectivity; however, in the model area in northern Michigan, the Bass Islands Dolomite is co-located with the (deeper) Niagaran carbonate reefs and the (deeper) St. Peter Sandstone, and together these three systems could provide commercial-scale storage. The AoR (i.e., land area required to accommodate the injection wells, CO<sub>2</sub> plumes and over-pressured area resulting from CO<sub>2</sub> injection) ranged from approximately 30 square miles (equivalent to a circular area with a radius of 3.1 miles) for the Potosi and St. Peter model sites to 275 square miles (equivalent to a circular area with a radius of 9.75 miles) for the Oriskany model site. The Maryville model site has an AoR of approximately 75 square miles (equivalent

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to a circular area with a radius of 4.9 miles). Figure 2-23 is a graphic comparison of these performance metrics for all the model sites except Model #2.

**Table 2-3. Summary of model performance for commercial-scale CO<sub>2</sub> injection.**

Model #	Cumulative CO <sub>2</sub> injected in 30 years, MMT	Number of injection wells	Permeability-thickness product, mD.ft	Injectivity, Tonnes/yr/psi	Pressure-based AoR Diam, mi).	Max CO <sub>2</sub> Plume Area (mi <sup>2</sup> )/Diam (mi)
1 (commercial scale <sup>a</sup> )	30	3	17602	641	14.6	30.2 (7.0)
2 <sup>b</sup>	0.4 to 4.65	Multi-well scenarios not modeled			NA	NA
3 (commercial scale)	32	8	823	68	18.7	83.1 (10.8)
4 (hub scale <sup>c</sup> )	96	1	367650	21333	19	178.1 (16.8)
5 (hub scale <sup>c</sup> )	96	1	173880	7767	6	26.6 (5.8)
6 (commercial scale)	30	1	27648	2381	0.7	10.6 (4.2)
6 (hub scale)	117	1	27648	2381	10.1	30.2 (6.2)
6 (hub scale)	120	2	27648	3410	10.3	50.7 (9.1)

- a. commercial-scale injection is defined as 1 MMT/yr for 30 yrs
- b. Commercial-scale injection not achieved in the Bass Islands Dolomite
- c. Hub-scale injection is defined as ≥3 MMT/yr for 30 yrs

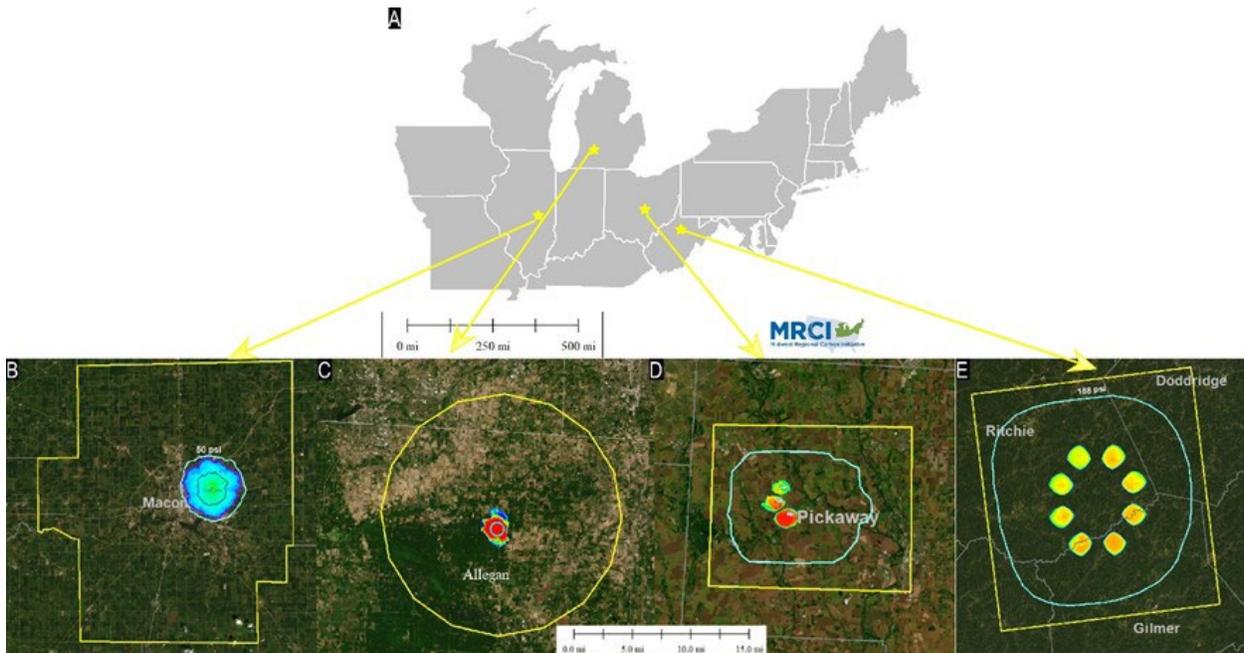


Figure 2-23. Comparison of commercial-scale injection at chosen CS systems with the CO<sub>2</sub> plumes at the end of injection and the estimated AoR. Models 5 (Panel B), 6 (Panel C), 1 (Panel D), and 3 (Panel E) are shown here. Model 2 is not included in this comparison as it does not achieve commercial-scale injection as modeled. Model 4 results are not shown because the injection well location is the same as Model 5.

Calculated *J* values for the commercial-scale injection scenarios are plotted in Figure 2-24. The *J* values for the models evaluated are found to honor the empirical correlation of Valluri et al.

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(2020) (i.e., the  $J$  values plot within the lower and upper bounds of  $J = 0.03 \times kh$  and  $J = 0.23 \times kh$ , respectively) with the exception of model #2 (Bass Islands Dolomite). These results indicate that the Ritchie/Gilmer County, West Virginia (Oriskany Sandstone) model has the lowest injectivity and the Macon County, Illinois (Potosi Dolomite) model has the highest injectivity, with the other model sites having injectivities between these two.

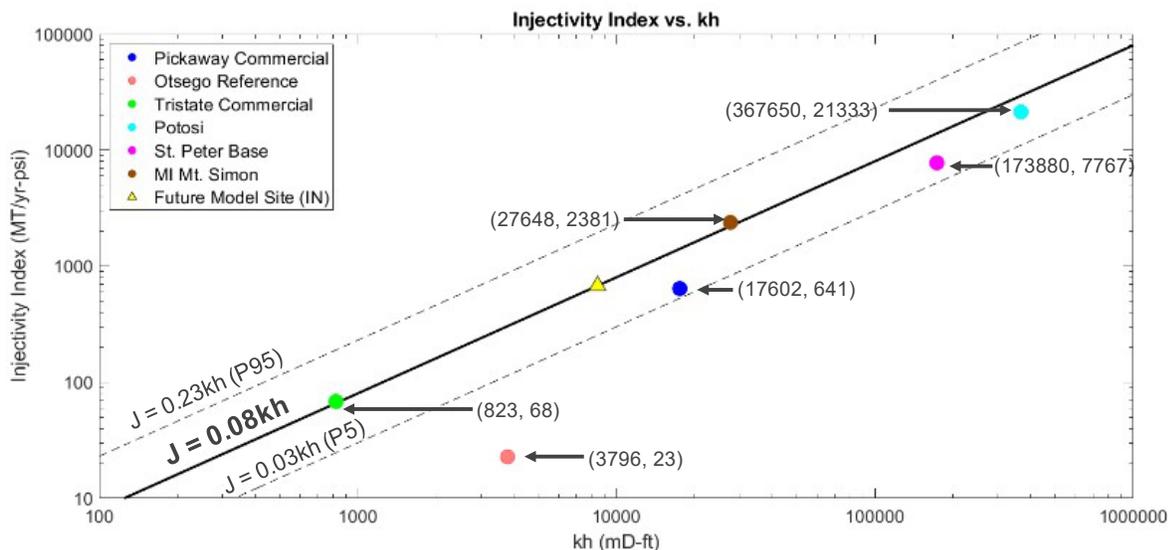


Figure 2-24. Comparison of injectivity index for the model sites (reference-case scenarios) compared to the correlations of Ravi Ganesh and Mishra (2014) (solid line) and Valluri et al. (2020) (dashed lines).

## 2.3 Risk Assessment for Selected Carbon Storage Systems

### 2.3.1 CO<sub>2</sub> Leakage Risks

In addition to possessing suitable injectivity, the geology at a commercial-scale CO<sub>2</sub> storage facility must also provide acceptable containment of the injected CO<sub>2</sub> against leaks. Subtask 2.5 focused on assessing leakage risks for potential commercial-scale storage complexes in selected carbon storage systems. Specifically, leakage risk analysis was conducted for four sites which were subject to dynamic reservoir (injectivity) modeling (see Section 2.2) to evaluate the potential magnitude and impacts of CO<sub>2</sub> and brine leakage through two pathways: 1) leakage of CO<sub>2</sub> and brine through/along leaky cemented wellbores that penetrate the injection zone; and 2) upward migration of CO<sub>2</sub> and brine through an unfractured caprock. The first leakage pathway (wellbore leakage) was evaluated using the DOE NRAP Open-IAM software and the second leakage pathway (caprock leakage) was evaluated using the GEM model that was constructed for each site to evaluate its injectivity (see Section 2.2). The results of the leaky wellbore analysis include plots showing estimated rate and cumulative mass of brine and CO<sub>2</sub> leaked into a shallow underground source of drinking water (USDW) aquifer at the sites and the volume of the USDW aquifer that is impacted above specified threshold values for pH and total dissolved solids (TDS). A summary of the leakage risk modeling scenarios that were performed is provided in Table 2-4. Both leakage pathways (i.e., leaky wellbore and unfractured caprock leakage) were modeled for the Maryville (Pickaway County, Ohio) model site (Model #1), the

## 2.0 Addressing Key Technical Challenges (Task 2)

Bass Islands (Otsego and Antrim Counties, Michigan) model site (Model #2); and the Oriskany (Ritchie/Gilmer Counties, West Virginia) model site (Model #3). In addition, leakage via an unfractured caprock was also evaluated for the Ottawa County, Michigan site (Model #6).

A conceptual model of the leaky wellbore pathway for the Pickaway County, OH (Model #1) site is shown in Figure 2-25. The results of the caprock leakage analysis include estimates of the leakage rate and cumulative mass of brine and CO<sub>2</sub> flux across the caprock and the volume of impacted groundwater in the shallow USDW aquifer. For the sites evaluated, the rate and cumulative mass of CO<sub>2</sub> and brine that leaked to the shallow USDW aquifer via the leaky wellbore pathway during 40 years (30-yr active injection period and 10-yr post injection period) ranged from 0 to 47 metric tons for CO<sub>2</sub> and 0 to 26 metric tons for brine. These small CO<sub>2</sub> leakage rates for the leaky wellbore pathway produced minor impacts to the shallow aquifer (i.e., a small dissolved-phase CO<sub>2</sub> plume with concentrations above the specified mass fraction of 0.001 [ $\sim$ 1,000 mg/L] threshold concentration). Brine leakage via the leaky wellbore pathway did not produce concentrations of TDS in the shallow aquifer above the specified threshold mass fraction value of 0.01 ( $\sim$ 10,000 mg/L) at any of the sites that were evaluated. Example model results for the Pickaway model are shown in Figures 2-26 (CO<sub>2</sub> leakage rate and cumulative mass), 2-27 (brine leakage rate and cumulative mass), and 2-28 (volume of shallow aquifer with CO<sub>2</sub> and TDS concentrations above threshold values). The leaky caprock analysis indicates that there would be no CO<sub>2</sub> flux and only minor brine flux across the caprock during the 40-year injection scenarios. For each of the three sites evaluated, no CO<sub>2</sub> reached the top of the caprock. This is due to the low permeability of the caprock (0.001 mD to 0.9 mD).

In summary, the impacts to USDW aquifers from CO<sub>2</sub> and brine that leaks from the storage reservoir via leaky wellbores and upward flow across an unfractured caprock are likely to be minimal.

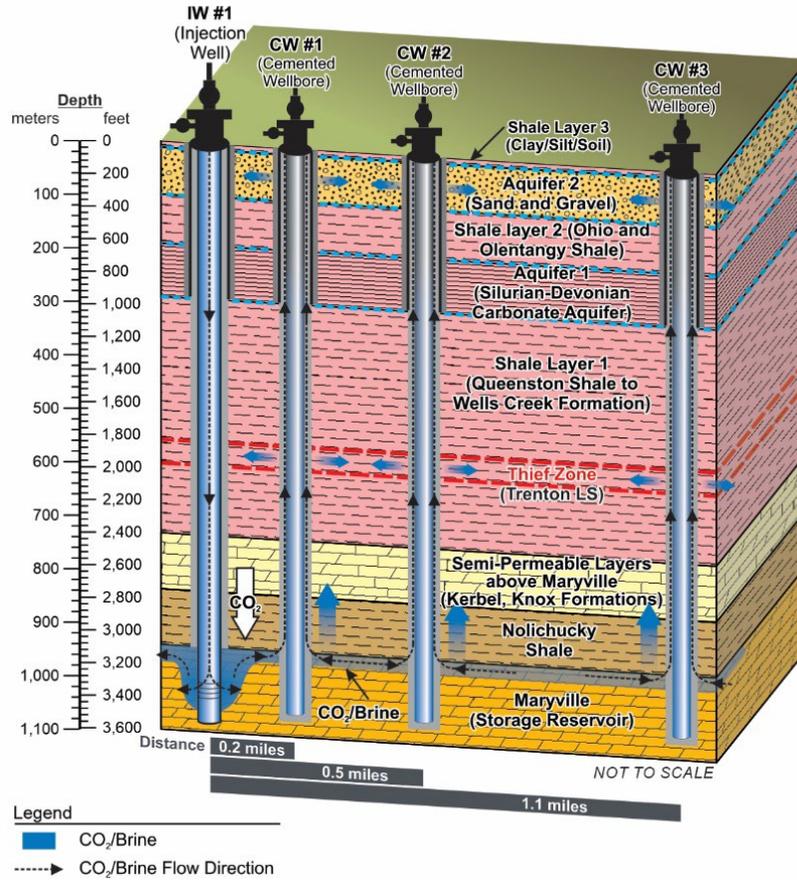
**Table 2-4. Dynamic reservoir (Injectivity) modeling scenarios and leakage risk assessment scenarios.**

MRCI Model Site	Scenario	No. of injection wells	Dynamic Reservoir (Injectivity) Modeling Scenarios	Wellbore Leakage	Unfractured Caprock Leakage
Model #1 (Pickaway Co. OH)	Reference	1	X		
	Commercial scenario	3	X	X	X
	Stacked injection (Multiple Injection zones)	1	X		
Model #2 (Otsego/Antrim Co., MI)	Reference	1	X	X	X
	Rel perm variant	1	X		
Model #3 (Ritchie/Gilmer Co., WV)	Reference Heterogeneous	1	X		X
	0.5-mile lateral horizontal well #1	1	X		
	1.0-mile lateral horizontal well #1	1	X		X
	1.5-mile lateral horizontal well #1	1	X		
	1.0-mile lateral horizontal well #2	1	X		
	Reference Homogeneous	1	X		
	Commercial	8	X	X	X

2.0 Addressing Key Technical Challenges (Task 2)

**Table 2-4 (continued). Dynamic reservoir (Injectivity) modeling scenarios and leakage risk assessment scenarios.**

MRCI Model Site	Scenario	No. of injection wells	Dynamic Reservoir (Injectivity) Modeling Scenarios	Wellbore Leakage	Unfractured Caprock Leakage
	Homogeneous				
Model #6 (Ottawa Co., MI)	Commercial scenario	1	X		
	Hub-Scale Scenario	2	X		X



*Figure 2-25. Conceptual model of leaky cemented wellbore pathway for the Pickaway County, OH (Model #1) Site.*

## 2.0 Addressing Key Technical Challenges (Task 2)

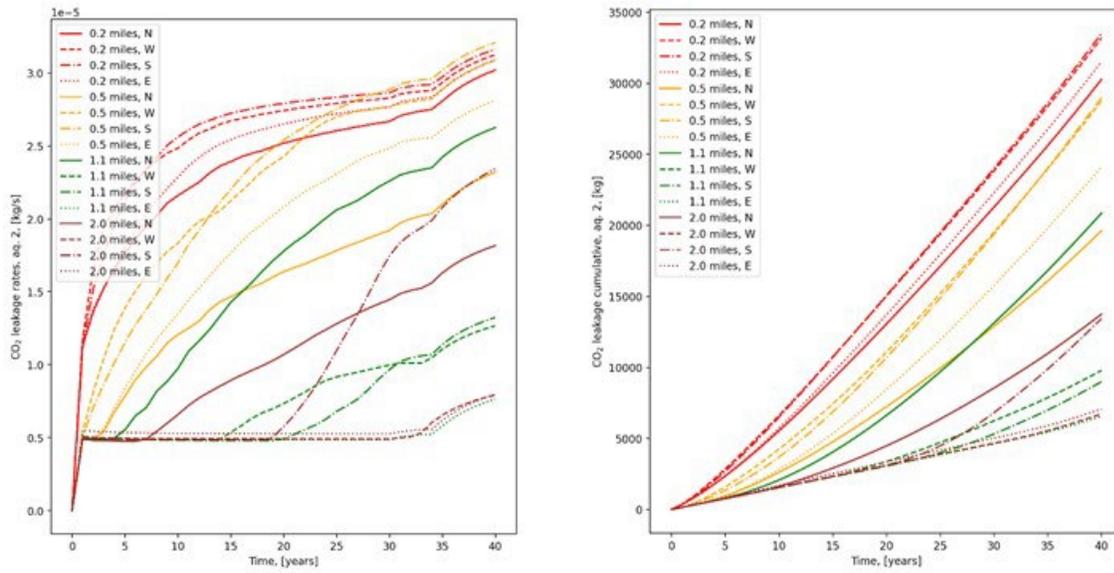


Figure 2-26. CO<sub>2</sub> leakage rates (left) and cumulative mass flux to the shallow aquifer at multiple hypothetical leaky cemented wells at the Pickaway County, OH (Model #1) Site (note that each curve represents a different well location relative to the injection well).

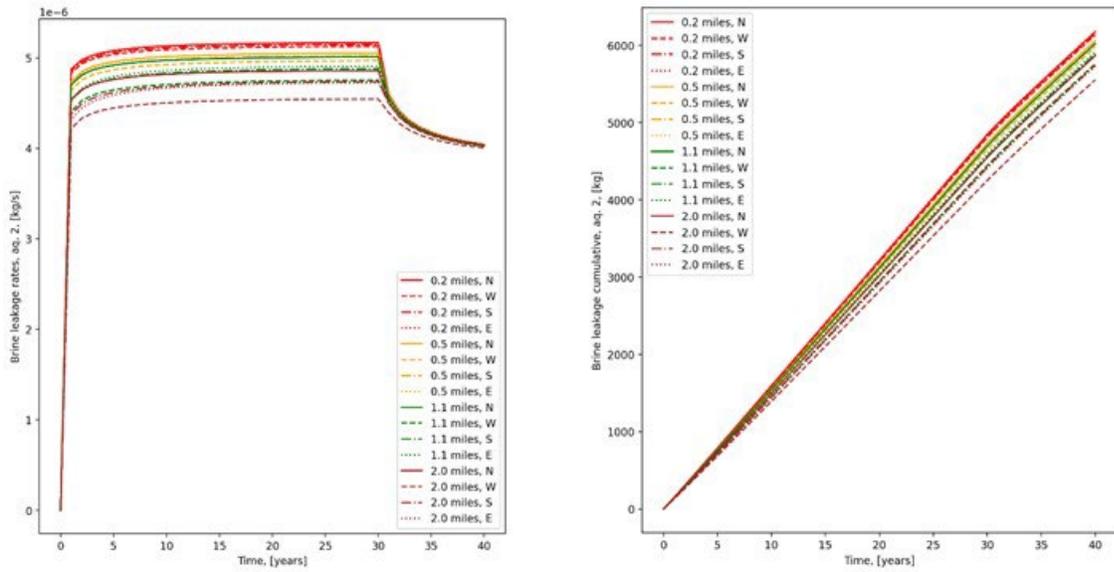


Figure 2-27. Brine leakage rates (left) and cumulative mass flux to the shallow aquifer at multiple hypothetical leaky cemented wells at the Pickaway County, OH (Model #1) Site (note that each curve represents a different well location relative to the injection well).

## 2.0 Addressing Key Technical Challenges (Task 2)

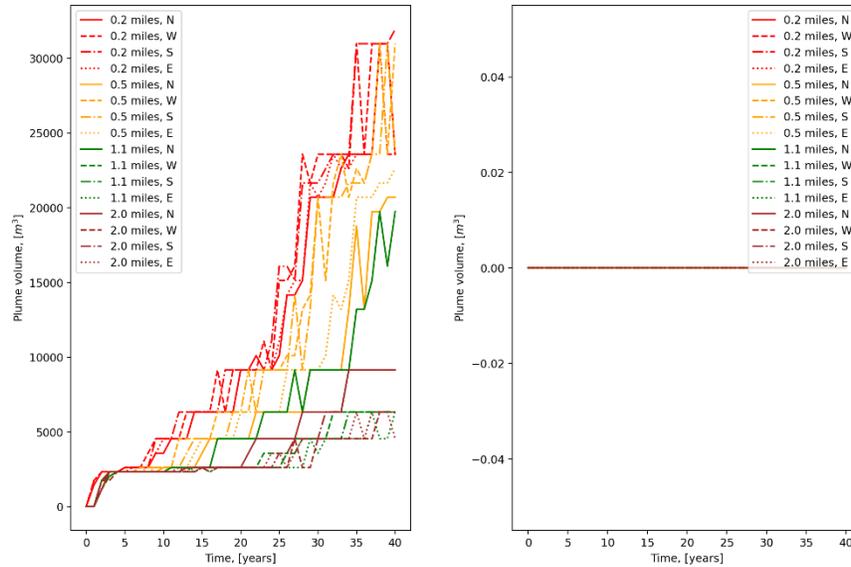


Figure 2-28. Dissolved CO<sub>2</sub> plume volumes (left) and total dissolved salts (right) plume volumes at multiple hypothetical leaky cemented wells in the shallow aquifer at the Pickaway County, OH (Model #1) Site. (note that each curve represents a different well location relative to the injection well). For the total dissolved solids plot (right), all wells produced zero plume volume in the shallow aquifer.

### 2.3.2 Induced Seismicity Risk

In addition to the two leakage pathways mentioned above, the risk of induced seismicity due to fault reactivation was evaluated for the Ritchie/Gilmere County, West Virginia Site (Model #3) and the Ottawa County, Michigan site (Model #6). Mapped faults are present at both model sites; therefore, there is a potential for fault reactivation if CO<sub>2</sub> injection causes pressure at the faults to increase to critical levels. Results of the analysis for the Michigan model are summarized here; results for Model site #3 are provided in the Subtask 2.4/2.5 report (Battelle, 2024e).

At the Michigan site, the storage reservoir (Mount Simon) directly overlies the Precambrian basement, and two faults transect the site. In order to understand the risk of induced seismicity, pressure buildup along each of the fault planes was analyzed to determine if fault slip via shear reactivation could occur under these conditions. Since the region had minimal fault characterization information, two simulations were run considering end-member fault configurations, including one scenario that assumes the faults are sealing (non-transmissive) and a second scenario that assumes the faults are transmissive. The dynamic modeling analysis indicates that pressure at the fault closest to an injection well will increase by approximately 1300 psi for the non-transmissive fault scenario and approximately 550 psi for the transmissive fault scenario (Figure 2-29).

LCI performed fault slip potential modeling to better understand the seismogenic potential of mapped faults with respect to the known or inferred stress states using three model solutions to interpret potential fault activity: slip tendency (Ts), dilation tendency (Td), and fracture susceptibility (S<sub>F</sub>). The fracture susceptibility is the key parameter used to assess potential for fault slip.

## 2.0 Addressing Key Technical Challenges (Task 2)

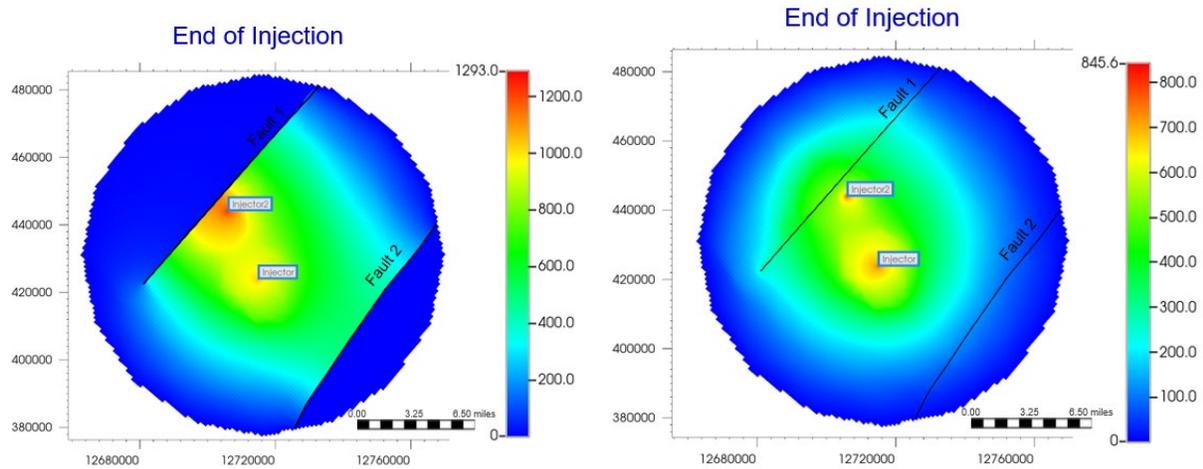


Figure 2-29. Map views (axes are in ft) of the pressure increase in the Mount Simon at the end of the injection period for the non-transmissive fault scenario (left) and at for the transmissive fault scenario (right).

Critical threshold pressures that could trigger fault slip were determined with the software Fault Slip Potential (FSP) developed by Stanford University Center for Induced and Triggered Seismicity and FracTend developed by Aberdeen University (Stephens et al., 2017). Critical values of  $S_F$  that will result in fault slip are summarized in Table 2-5 along with input assumptions (fault strike, fault dip, coefficient of friction, and in-situ stress [ $S_v$ ,  $SH_{max}$ ,  $Sh_{min}$ ]). The modeled  $S_F$  values (increase in reservoir pressures in the storage reservoir) range from -1972 to -1044 psi (for low coefficient of friction), from 1725 to 2538 psi (for moderate coefficient of friction), and from 2436 to 2600 psi (for high coefficient of friction). Low friction ( $\mu = 0.2$ ) models produce negative  $S_F$  values, suggesting faults with this characteristic would likely be creeping faults under current conditions (i.e., an increase in reservoir pressure is not required to cause slip). As shown in Figure 2-29, modeled reservoir pressures at the faults are not high enough to trigger fault reactivation (slip) (except for the low coefficient of friction scenario, which is an unlikely condition). Based on these results, neither the commercial-scale injection scenario (one injection well and injection rate of 1 MMt/yr for 30 yrs) or the hub-scale injection scenario (two injection wells and injection rates of 2 MMt/yr per well for 30 yrs) would be expected to trigger seismicity at the Ottawa County, Michigan site. It should be noted that predicted  $S_F$  values have high uncertainty due to model input parameters that are undefined, requiring assumptions to be made.

**Table 2-5. Fracture susceptibility input assumptions and results for the Ottawa County, Michigan Mount Simon model.**

INPUT VARIABLES			STANDARD DEVIATION			FRACTURE SUSCEPTIBILITY ( $S_F$ )	
Strike	Dip	Coefficient of Static Friction ( $\mu$ )	Std Dev [ $S_v$ ]	Std Dev [ $SH_{max}$ ]	Std Dev [ $Sh_{min}$ ]	Modal $S_F$ (MPa)	Modal $S_F$ (PSI)
004	60	0.2	0.1	0.1	0.1	-13.6	-1972
	75					-12.7	-1841.5
	90					-7.2	-1044
004	60	0.6	0.1	0.1	0.1	11.9	1725.5
	75					12.9	1870.5
	90					17.5	2537.5
004	60	0.8	0.1	0.1	0.1	16.8	2436
	75					17.4	2523
	90					18	2610

### 2.4 Developing Industrial Partnerships

Under the objective of regional data collection and helping accelerate deployment, MRCI provided support to industrial stakeholders in their project planning, characterization, and analysis related to CO<sub>2</sub> storage. In exchange for the support provided by Battelle and the MRCI team, the MRCI project acquired valuable technical data and information that otherwise would not have been available. The data and information shared by the industrial collaborations were added to the regional CCS framework development and were incorporated into the overall datasets, while addressing any proprietary data requirements. Three examples of collaborative partnerships with industry that have provided valuable geologic characterization data that are beneficial to the MRCI program are briefly described below.

**Example 1:** The owners of a UIC Class II permitted saltwater disposal (SWD) facility in eastern Ohio provided historical operational data (injection rate and injection pressure) to Battelle for the purpose of determining if the data could be used to determine reservoir properties for the injection zone. The facility includes two Class II injection wells that are used to inject oil-field brine into multiple stacked geologic formations within the Cambrian-Ordovician Carbon Storage system of eastern Ohio. Battelle conducted a review of the operational data for the period of record (July 2020 through May 2021) and selected representative injection events for analysis. The operational data were analyzed using reservoir engineering methods such as pressure transient analysis and history matching (modeling) and determined key reservoir properties (e.g., permeability-thickness product) for the injection formation(s). Because both Class II wells inject into multiple formations, the estimated properties are reflective of the combined properties and thickness of the individual formations intersected by each well. The reservoir properties gleaned from this analysis provide valuable empirical data that can be used to design CO<sub>2</sub> storage facilities in the Cambrian-Ordovician Carbon Storage system of eastern Ohio.

**Example 2:** Core Energy is actively conducting large-scale CO<sub>2</sub> EOR in several Niagaran-age carbonate pinnacle reef reservoirs in northern Michigan. Core Energy's operation, which consists of multiple reefs in various stages of enhanced recovery (all reefs have undergone primary production and now are in secondary or tertiary production) was the host site for the MRCSP Program from 2006 through 2020. During the MRCSP Program, Battelle conducted extensive reservoir modeling and monitoring for multiple reefs, including the Chester 16 reef. At the time, the Chester 16 reef had gone through primary production and Core Energy was planning to implement secondary (CO<sub>2</sub>) EOR in the reef. A detailed three-dimensional (3D) dynamic reservoir model was developed by Battelle to evaluate alternate CO<sub>2</sub> injection and production strategies and predict the extent of the injected CO<sub>2</sub> and pressure changes. During the subsequent MRCI program, CORE Energy initiated CO<sub>2</sub>-EOR using an injection/production approach that was evaluated using Battelle's model. Since commencing CO<sub>2</sub>-EOR, production from the Chester 16 reef has significantly exceeded predictions. Core Energy has shared the data and information from the Chester 16 EOR operation with Battelle to update and calibrate the reservoir model to match actual field results (i.e., production rates and pressures). This exercise provides valuable insights and lessons learned about fluid (CO<sub>2</sub>, oil, water) behavior in the carbonate reefs that can be incorporated into future modeling studies involving CO<sub>2</sub> injection/storage in other reefs.

**Example 3:** Marquis Energy LLC is developing a commercial-scale geologic CO<sub>2</sub> storage facility at its ethanol plant in Hennepin, Illinois. Battelle's commercial carbon services group was hired by Marquis to obtain the UIC Class VI permit for the project, which entailed drilling a test well and conducting geologic field characterization and testing, modeling, and preparing the permit

## 2.0 Addressing Key Technical Challenges (Task 2)

application. Site characterization activities included acquiring two-dimensional (2D) and 3D seismic surveys, drilling and coring, logging and testing a characterization well, and preparing a UIC Class VI (CO<sub>2</sub> injection well) permit application on behalf of Marquis for CO<sub>2</sub> injection into the Cambrian Mount Simon Formation. A dynamic 3D reservoir model was developed to assimilate the characterization data and simulate and predict CO<sub>2</sub> and pressure distribution resulting CO<sub>2</sub> injection into the Mount Simon Formation. Marquis shared the geologic characterization data, modeling results, and permitting lessons learned with the MRCI program so that other operators that are interested in developing a CO<sub>2</sub> storage facility in the Mount Simon Formation in the MRCI area can benefit. The MRCI team incorporated elements of the new data into existing regional (thickness and structure) maps for key CO<sub>2</sub> storage reservoirs, such as the Mount Simon Formation. Similarly, rock property data from geophysical logs and core tests from the Marquis site were incorporated into the properties database developed under Task 2 of the MRCI project (see Section 2.1). These data were also used to derive representative regional rock property values for the Mount Simon Formation.

## 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

### 3.1 Task Summary

One of the objectives of the MRCI was to facilitate data collection, sharing, and analysis to support development of CCS in the region. This effort leveraged previous research and field data sets for industry, regulators, stakeholders, and DOE-NETL carbon management programs. During the initial stages of Task 3, an inventory was prepared of existing data and analyses across the MRCI. Data from previous efforts under the MGSC, MRCSP, state research initiatives on carbon storage, and other DOE-funded efforts, including data submitted to the DOE Energy Data Exchange (EDX), were reviewed for the inventory. This information was shared with industry, regulators, researchers, and stakeholders to aid in advancing safe and effective CCS projects.

The data inventory was completed to compile a useful list of items pertaining to CCS research in the MRCI region. Figure 3-1 summarizes the progression of CCS from concept to regional characterization, field tests, and industrial-scale projects in the MRCI region. Field datasets from existing injection tests, well drilling, risk assessments, models, monitoring, and geotechnical testing were identified under the inventory. In total, this included more than 1,000 research papers, field datasets, presentations, and DOE reports (Figure 3-2). The data inventory was organized into an indexed database and web-based portal listing key research by state, topic, project, and metadata. Over the past 20+ years, research on CO<sub>2</sub> storage in the MRCI region has advanced from initial proof-of-concept studies to industrial-scale demonstrations injecting millions of tons of CO<sub>2</sub>. The field tests and characterization sites have been completed in major sedimentary basins and geologic provinces in the MRCI (Figure 3-3).

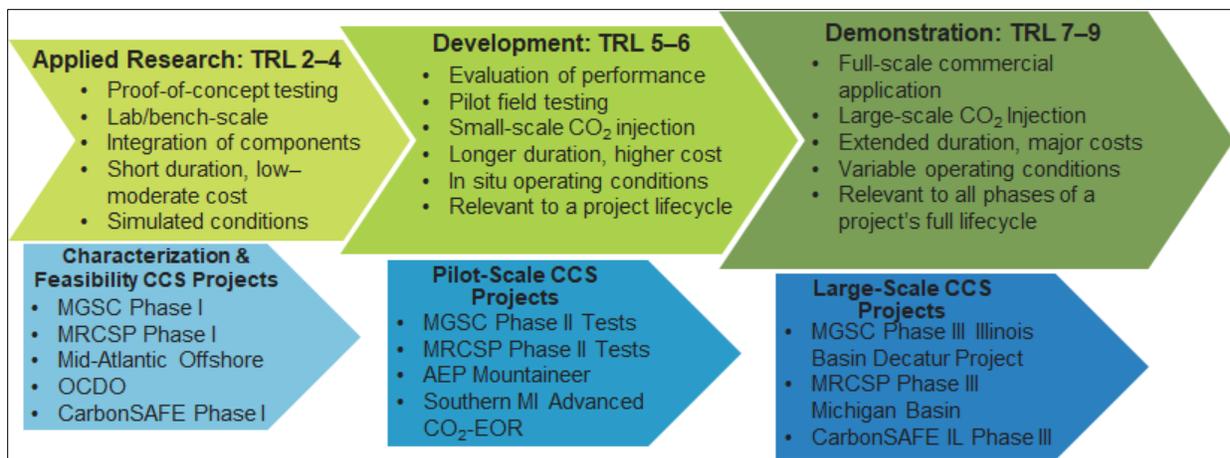


Figure 3-1. Summary of the CCS technology development and projects in the MRCI.

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

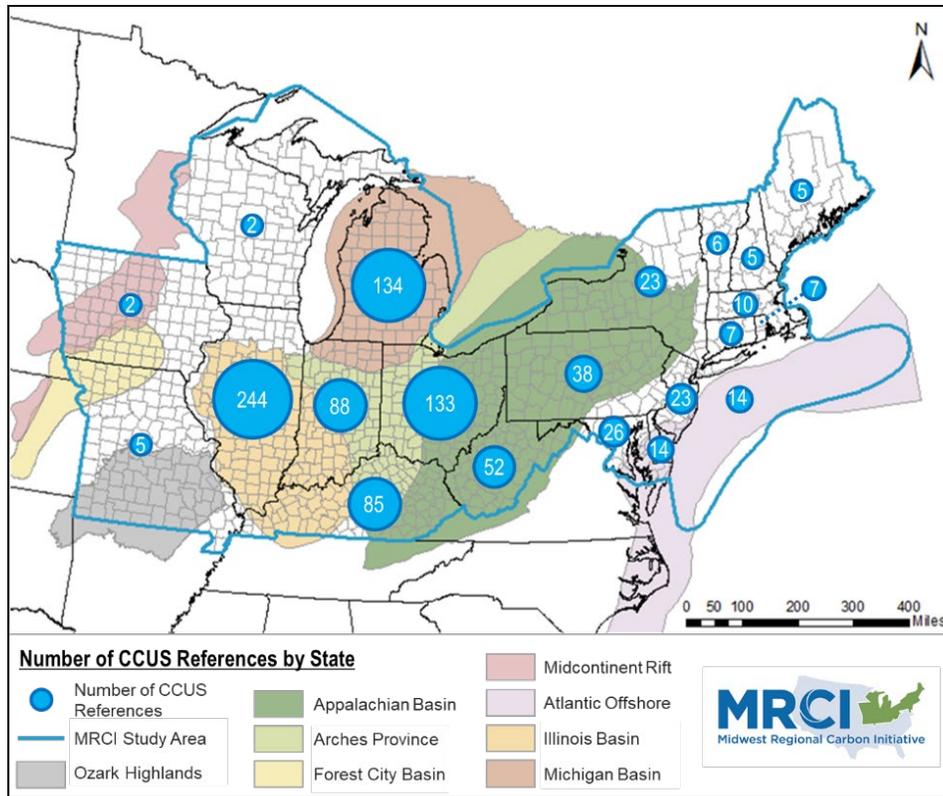


Figure 3-2. Map showing the number of references in each state within the MRCI region.

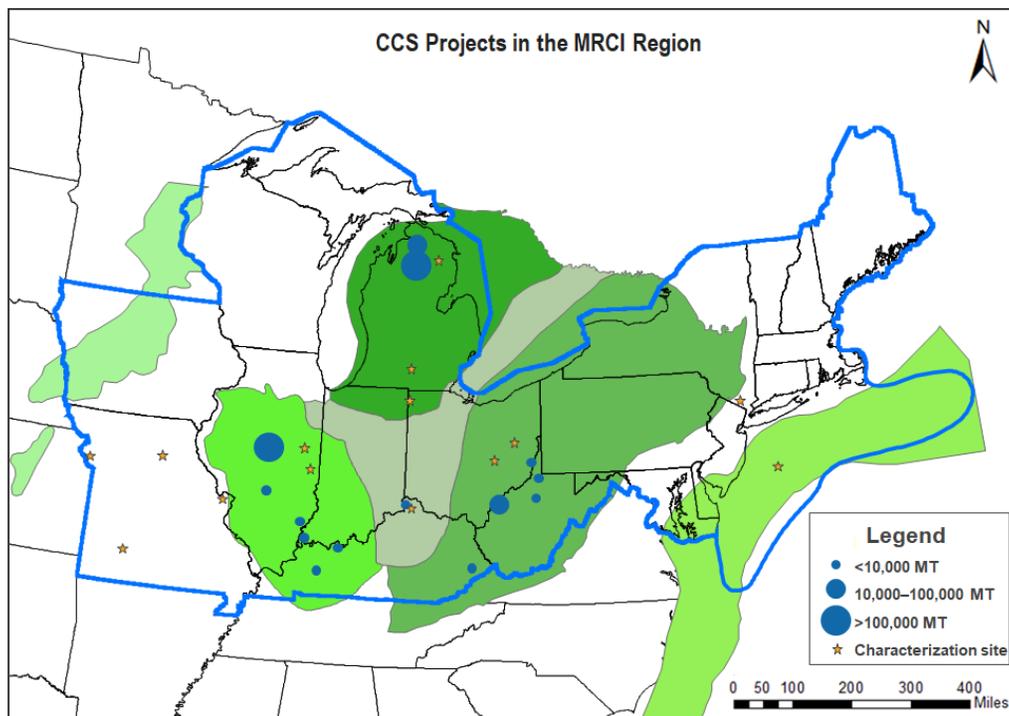


Figure 3-3. Locations of small- and large-scale CCS injection sites in the MRCI region and metric tons (MT) of CO<sub>2</sub> injected. Characterization sites are also shown.

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

As more CO<sub>2</sub> storage projects were advanced in the MRCI, several key topics were also identified for analysis based on existing datasets under Task 3. These topics were determined through review of CO<sub>2</sub> development in the MRCI and feedback from industry, regulatory, and research stakeholders in the region. Table 3-1 summarizes the accomplishments of MRCI Task 3. Selected results are provided in the text below. Machine learning and data analytics were also used to evaluate items related to CCS applications. Data sharing and engagement with NETL and National Laboratories was also completed under Task 3.

**Table 3-1. Summary of Topics for MRCI Data Inventory, Sharing, and Analysis.**

SubTask	Results
3.1 Inventory Available Data & Analyses	<ul style="list-style-type: none"> <li>● Inventory pre-existing datasets, research, reports</li> <li>● Organize and update previous research and data into sharable database</li> </ul>
3.2 Facilitate Data Collection, Sharing	<ul style="list-style-type: none"> <li>● Data sharing, survey industrial CCUS progress, engage regulatory agencies</li> <li>● Provide data/info for industry CCS development</li> </ul>
3.3 Additional Analyses	<ul style="list-style-type: none"> <li>● Legacy Seismic Data Procurement, Organization, and Evaluation</li> <li>● Class I &amp; II Underground Injection Control Well Injectivity Analysis</li> <li>● Central MRCI Ethanol Plant CCS Screening Study</li> <li>● Greenhouse Gas Emissions Life Cycle Analysis for MRCI Sources</li> <li>● AGI database compilation and web portal for key research/datasets</li> <li>● Natural Gas Power Plant CCS Screening</li> <li>● Appalachian Basin Carbonate Storage Characterization</li> <li>● Minimum Miscibility Pressure testing Oil Samples in MRCI CO<sub>2</sub>-EOR fields</li> <li>● ACT ENSURE collaboration for micro-seismicity</li> </ul>
3.4 Engage NRAP/NETL	<ul style="list-style-type: none"> <li>● NRAP Class VI Rules and Tools support</li> <li>● Wabash R. NRAP Open-IAM &amp; SOSAT tool application</li> <li>● Task 2 risk modeling with NETL and LANL</li> <li>● NRAP workgroups, identify field datasets, review collaboration activities</li> </ul>
3.5 Engage Nat. Labs	<ul style="list-style-type: none"> <li>● NRAP workgroups, identify field datasets, review collaboration activities</li> <li>● Survey/engage other Nat. Labs CCUS projects in MRCI</li> </ul>
3.6 Advise Machine Learning for CCUS	<ul style="list-style-type: none"> <li>● BHP/BHT Prediction from Wellhead Data Using Machine Learning</li> <li>● Carbonate Characterization using 2D/3D Images to Predict Reservoir Props</li> </ul>
3.7 Participate in SMART Initiative	<ul style="list-style-type: none"> <li>● Predictive Analysis of Press and Temp in Carbonate Reservoirs</li> <li>● Machine Learning Based Near-Realtime Leakage Detection for Caprock</li> <li>● Integrity Monitoring using DAS (Distributed Accoustic System) data from CCS Operations</li> </ul>

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

Regional characterization, stratigraphic test wells, legacy seismic data sets, field CO<sub>2</sub> injection tests, monitoring data, geologic maps, and infrastructure evaluations provided a foundation for establishing CO<sub>2</sub> storage projects in the MRCI region. Selected accomplishments under the data sharing, collection, and analysis task are summarized as follows.

**CCS Screening Study for Ethanol Plants in the Central MRCI Region** - A screening study was completed for 27 ethanol plants in the central MRCI for CO<sub>2</sub> storage feasibility based on geological, social, economic, and geographic factors. Results showed that 13 of the 27 ethanol plants had fair to favorable factors for CO<sub>2</sub> storage near the plant locations (Table 3-2). Six sites were marginal, two sites had low potential for CO<sub>2</sub> storage, and six of the plants were small with unlikely economics to support CO<sub>2</sub> storage costs. CO<sub>2</sub> injectivity and faults/seismic setting were the major geological factors for low to marginal sites. Results were communicated to industry at MRCI meetings. Many of the current CO<sub>2</sub> storage projects under development in the MRCI are located at ethanol plants which have benefited from previous CCS research in the region.

**Table 3-2. Summary of central MRCI ethanol plant CCS feasibility screening.**

Plant	Formation	Caprock	Seismic/ Faults	Injectivity	Source/Sink	Economics	Surface Factors	Ranking
Poet Biorefining-Marion	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable	Favorable
The Andersons Albion Ethanol, LLC	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable
Valero Renewable Fuels-Linden	Favorable	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable
The Andersons Marathon Ethanol, LLC	Fair	Marginal	Favorable	Marginal	Favorable	Marginal	Marginal	Marginal
Valero Renewable Fuels-Bloomington	Marginal	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Fair
Valero Renewable Fuels-Bluffton	Favorable	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable
Cardinal Ethanol, LLC	Fair	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Fair
Valero Renewable Fuels-Mount Vernon	Favorable	Favorable	Low	Marginal	Marginal	Favorable	Favorable	Marginal
Poet Biorefining-Cloverdale	Favorable	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable
Green Plains-Mt. Vernon	Favorable	Favorable	Low	Marginal	Marginal	Favorable	Favorable	Marginal
Poet Biorefining-Alexandria	Favorable	Marginal	Low	Favorable	Favorable	Favorable	Favorable	Fair
Poet Biorefining-North Manchester	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable	Favorable	Favorable
Poet Biorefining-Portland	Favorable	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable
Poet Biorefining-Leipsic	Fair	Marginal	Low	Favorable	Favorable	Favorable	Favorable	Fair
Poet Biorefining-Fostoria	Low	Marginal	Marginal	Marginal	Favorable	Favorable	Favorable	Low
Poet Biorefining-Shelbyville	Favorable	Favorable	Favorable	Marginal	Favorable	Favorable	Favorable	Favorable
Poet Biorefining-Caro	Marginal	Favorable	Marginal	Low	Favorable	Marginal	Favorable	Marginal
Guardian Lima, LLC	Marginal	Marginal	Marginal	Fair	Fair	Marginal	Marginal	Marginal
South Bend Ethanol, LLC	Marginal	Marginal	Fair	Favorable	Marginal	Marginal	Marginal	Marginal
Central Indiana Ethanol, LLC	Favorable	Favorable	Favorable	Marginal	Favorable	Marginal	Favorable	Fair
Valero Renewable Fuels-Riga	Low	Marginal	Marginal	Marginal	Marginal	Marginal	Favorable	Low
Carbon Green BioEnergy, LLC	NA	NA	NA	NA	NA	Low	NA	NA
Iroquois Bio-Energy Company, LLC	NA	NA	NA	NA	NA	Low	NA	NA
Marysville Ethanol, LLC	NA	NA	NA	NA	NA	Low	NA	NA
Three Rivers Energy, LLC	NA	NA	NA	NA	NA	Low	NA	NA
MGPI of Indiana	NA	NA	NA	NA	NA	Low	NA	NA
Grain Proc. Corp.-Washington wet mill	NA	NA	NA	NA	NA	Low	NA	NA

**Greenhouse Gas Emissions Life Cycle Analysis for Industrial CO<sub>2</sub> Sources** – A greenhouse gas emissions life cycle analysis (LCA) was completed for ethanol plants, natural gas power plants, and (proposed) direct air capture facilities in the MRCI. The objective of the topical analysis was to evaluate potential greenhouse gases generated for CCUS facilities in the Midwest-northeast US, account for CO<sub>2</sub> equivalent emissions for carbon capture, transport, and storage operations in relation to volume of CO<sub>2</sub> stored underground, and integrate MRCI specific factors on CO<sub>2</sub> sources, geology, and geographic location. The end product of the analysis was greenhouse gas life cycle guidance for developing CCUS in the MRCI region in terms of maximizing net CO<sub>2</sub> storage effectiveness. A greenhouse gas life cycle model was applied for capture, compression, transport, and injection scenarios for ethanol plants (108 in MRCI), natural gas power plants (192 in MRCI), direct air capture (0 in MRCI), CO<sub>2</sub>-EOR (1 in MRCI), hydrogen plants (16 in MRCI), petroleum refinery (21 in MRCI), cement plants (32 in MRCI), and fertilizer/ammonia plants (7 in MRCI). Key inputs included source emissions quantity, energy for capture, compression requirements, pipeline transport distances, geologic

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

setting for CO<sub>2</sub> storage, and fugitive emissions. Results reflect net CO<sub>2</sub> stored versus emissions generated from capture, compression, transport, and injection (Table 3-3). Sources that have a high purity CO<sub>2</sub> stream and/or integrate capture and compression like ethanol plants, hydrogen plants, fertilizer/ammonia plants, and cement plants have highest net storage potential of 80-90% (CO<sub>2</sub> stored minus CO<sub>2</sub> equivalent emission generated via CCS operations). CO<sub>2</sub> EOR operations and natural gas power plants had lower net storage potential at 60-75%. Greenhouse gas emissions life cycle analysis helps depict the net benefits of carbon capture and storage. Results reflect net CO<sub>2</sub> stored versus emissions generated from capture, compression, transport, injection, and economies of scale. There are many opportunities for CCS in the MRCI region. CCS LCA emissions are likely to change over time as operations are optimized to reduce emissions.

**Table 3-3. Summary of Greenhouse Gas Life Cycle Analysis Results for Key CO<sub>2</sub> Source in the MRCI Region.**

GHG LCA Net CO <sub>2</sub> Storage																									
Input Flows		Ethanol Plant with CS				Natural Gas Power Plant				Direct Air Capture				Hydrogen Plant		Petroleum Refinery		Cement Plant		Fertilizer/Ammonia Plant		CO <sub>2</sub> -EOR		CO <sub>2</sub> -EOR (with storage)	
Category	Quantity	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O
CO <sub>2</sub> captured	1,000,000	1,000,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO <sub>2</sub> stored	800,000	800,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO <sub>2</sub> emissions	200,000	200,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Net CO <sub>2</sub> storage	600,000	600,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Legacy Seismic Data Collection, Analysis, and Archiving –** The project team collected legacy 2D and 3D seismic survey data to support CCS projects in the region (Figure 3-4). The legacy data were acquired or “salvaged” from oil and gas companies that were no longer interested in the area for exploration, retiring, or unable to maintain the physical data media. These legacy seismic data were organized, summarized, and digitized to support CCS in the MRCI region.

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

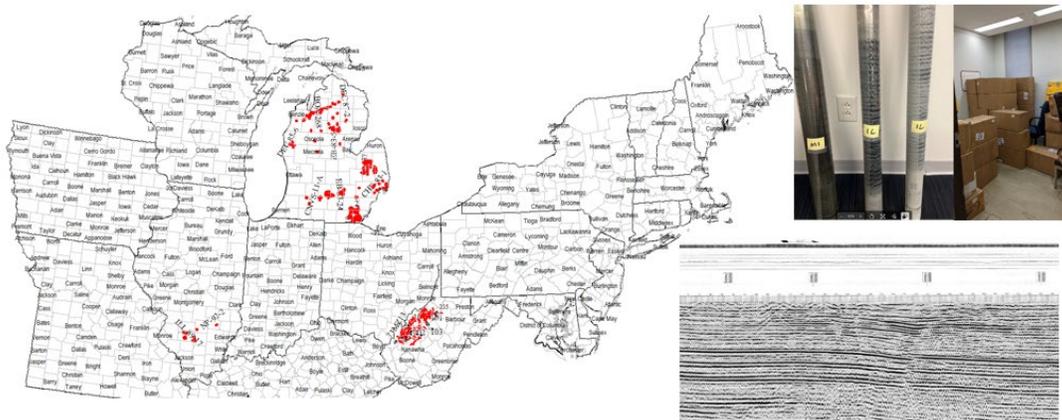


Figure 3-4. Legacy seismic data collected for the MRCI region.

The legacy seismic data collected under MRCI included the following items:

- 2,016 linear miles of 2D seismic data (1043 individual surveys)
- 43 square miles of 3D seismic data (2 surveys)
- 57 boxes containing CDs, cassettes, reels, field data, and paper seismic records
- Six oil and gas operating companies with data from Illinois, Michigan, and Appalachian Basins.

The seismic data were cataloged in terms of acquisition parameters, vintage, quality, location, and resolution. Seismic data were described and organized in relation to sedimentary basins, geologic structures, faults, and provinces. The seismic data were utilized to assess several sites for CO<sub>2</sub> storage feasibility under MRCI Task 2. Results indicated that many areas of the main sedimentary basins in the MRCI have few local geologic structures and major faults. There are some faults in areas but these faults are more prevalent in Silurian-Ordovician age rocks. The legacy seismic is useful for CCS developers to screen potential injection sites, plan additional seismic surveys for CCS sites, and understand the nature of deep rock formations in the region.

**Class I & II Underground Injection Control Well Injectivity Analysis** – Class I & II UIC well injectivity analysis was completed to evaluate injection rates, pressures, and long-term performance in brine disposal and wastewater disposal wells in the MRCI region. Brine disposal well operational data were analyzed for Class I and II UIC wells in Ohio, Michigan, and Pennsylvania using simple methods to determine injectivity and attempt to examine injectivity behavior with injection formations. This analysis involved the compilation of injection performance data in terms of fluid injection volumes and corresponding tubing pressures from brine disposal wells in Ohio and Pennsylvania. Results showed high injectivity in the Mount Simon Sandstone formation in southern Michigan (9.4 barrel/day/psi). Injectivity in Ohio wells was more variable with higher injectivity in the Clinton-Medina and Knox rock formations. Pennsylvania wells had limited operations data, but indicated low injectivity.

**Machine Learning Prediction for CO<sub>2</sub> Bottomhole Pressure and Temperature** – Machine learning methods were used to predict bottomhole pressure (BHP) and temperature (BHT) for CO<sub>2</sub> injection to aid in CO<sub>2</sub> storage operations in the region. A systematic machine learning workflow was applied for data-driven models using (a) exploratory data analysis to visually understand patterns, trends and outliers in the multivariate datasets, (b) statistical imputation to

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

fill in missing values (if any), (c) unsupervised learning to identify natural groupings (statistically homogeneous subsets) across the space of independent variables (predictors), and (d) supervised learning to fit predictive models between known predictors and responses (dependent variables). The data used for this task were collected as part of the monitoring program for the MRCSP Phase III project and included the well head and bottomhole attributes for three CO<sub>2</sub> injection wells located in the Dover-33, Charlton-19, and Bagley Townships of Otsego County in northern Michigan, respectively. The study found that machine learning methods can train a variety of models to obtain good performance in predicting test observations from the same well(s) as the training data. However, these models are limited in ability to make predictions for observations in new wells (i.e., wells not represented in the training set).

**Characterization of Secondary Porosity for MRCI Carbonate Rock Formations –** Secondary porosity in carbonate rock formations was characterized based on rock core computer tomography images, helping to better define these important CO<sub>2</sub> storage intervals in the MRCI region. The work provided datasets to help identify and characterize other carbonate rock formations in the MRCI region, which have been increasingly important for CO<sub>2</sub> storage in the Illinois Basin, Appalachian Basin, and Michigan Basin.

**MRCI CCS Key Topic Web Database –** The American Geological Institute (AGI) ported the MRCI database compilation to an indexed web portal for key research/datasets for the MRCI website. The web portal links the database to a state map, key topics, and projects related to CCS in the MRCI (Figure 3-5). This data sharing instrument aided developers, regulators, and stakeholders to leverage previous research in the MRCI when evaluating CO<sub>2</sub> storage development plans.

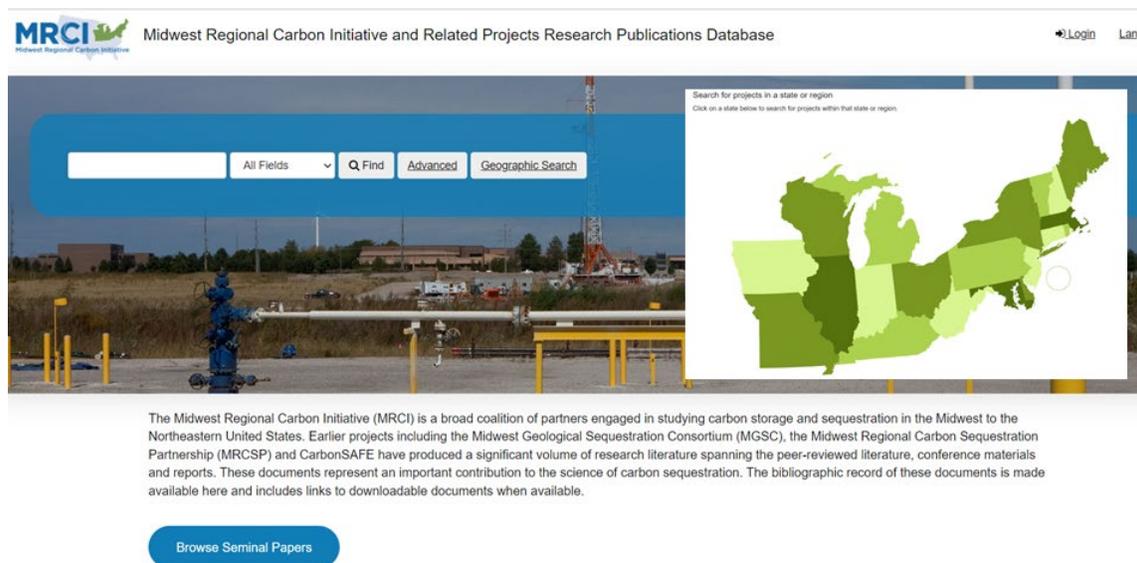


Figure 3-5. Searchable database for MRCI website.

**CCS Screening for Natural Gas Power Plants in MRCI –** A natural gas power plant CCS screening was performed for plants in the MRCI to understand the potential for CCS at larger natural gas power plants. The study identified 781 natural gas plants with 200,000 MW generating capacity in the MRCI. 59/781 natural gas plants meet proposed USEPA rules (>300 MW and 50% capacity factor). Screening results for engineering specifications, geologic setting,

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

and surface factors for CCS development indicated 15 fair/favorable plants, eight marginal plants, and 36 unfavorable plants (Figure 3-6). Favorable plants were located in deeper portions of sedimentary basins near undeveloped lands. Many marginal and unfavorable plants are located along the east coast and eastern Appalachian Basin.

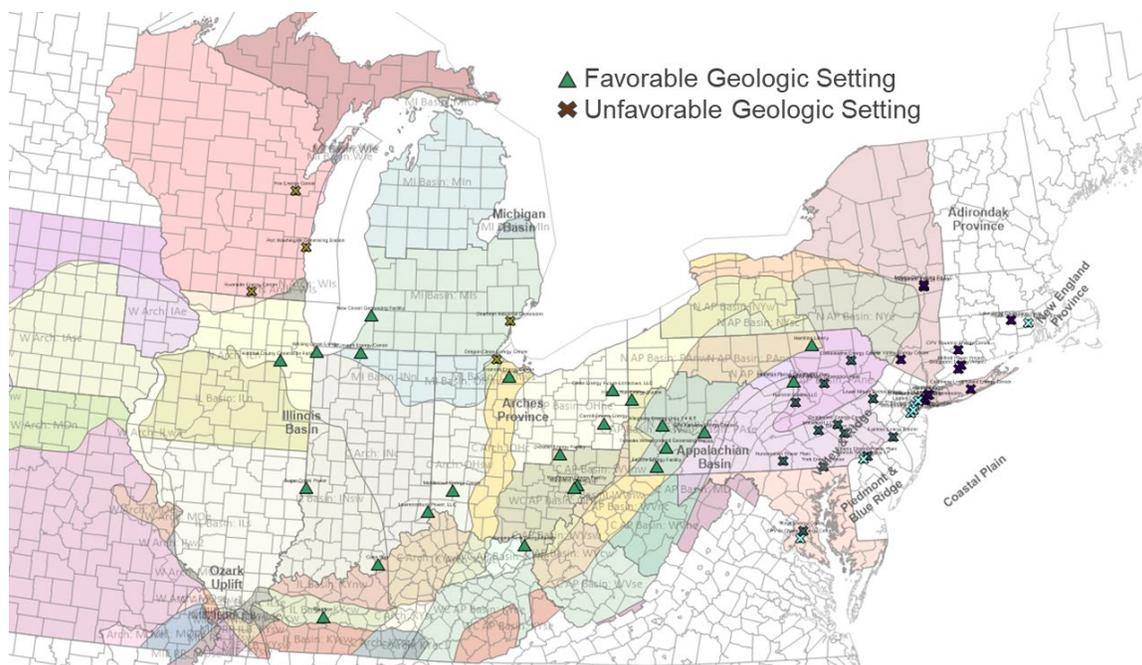


Figure 3-6. Map of natural gas power plant geological screening for CO<sub>2</sub> storage.

**Appalachian Basin Carbonate Storage Characterization** – A study was completed to depict carbonate CO<sub>2</sub> storage systems in the Appalachian Basin. The analysis examined hydrothermal dolomite trends in relation to lineaments and faults in the basin. Results of the study outlined several areas in the Appalachian Basin for consideration of CO<sub>2</sub> storage. These carbonate zones are likely to be key storage targets in the Appalachian Basin, since there are few thick, highly porous sandstones in the basin.

**Minimum Miscibility Pressure (MMP) Testing** – Testing of six oil samples from MRCI CO<sub>2</sub>-EOR fields was conducted by the ISGS to examine the potential for associated CO<sub>2</sub> storage with EOR in the Illinois Basin. Oil samples were tested with a slim tube testing apparatus to measure MMP. Results showed suitable MMPs for several reservoirs in the Illinois Basin that would have potential for CO<sub>2</sub> EOR along with associated CO<sub>2</sub> storage.

**ACT ENSURE Collaboration for Micro-Seismic Monitoring** – The MRCI project team contributed to the international ACT ENSURE research program to improve methods for monitoring micro-seismicity at CO<sub>2</sub> storage facilities. The work included sharing field micro-seismicity monitoring datasets with the ENSURE researchers to develop more effective micro-seismic monitoring methods to prevent induced seismicity associated with CO<sub>2</sub> storage.

**MRCI Collaboration with U.S. DOE-NETL National Risk Assessment Partnership** – The MRCI project collaborated with the U.S. DOE-NETL NRAP initiative and national laboratories to validate and test NRAP tools with MRCI field datasets. Most of this work was related to the NRAP Open-IAM model, State of Stress Assessment Tool, and CCS Cost Storage models.

### 3.0 Facilitating Data Collection, Sharing, and Analysis (Task 3)

NRAP tools were tested with data from the CarbonSAFE Illinois Macon County project, Wabash CarbonSAFE, Illinois Storage Corridor, and MRCSP data. The MRCI project team also contributed to NRAP work on Class VI UIC Rules/Risk Assessment Tools, workshops on risk-based decision making, and reusing existing wells for carbon storage.

Overall, the MRCI Task 3 work was effective in supporting CCS development in the region. Previous field tests, research, and datasets were especially important to developers concerned about the general feasibility of CCS for their projects. Existing datasets were also used to address key CCS challenges emerging in the region and support DOE-NETL carbon management programs. Through the MRCI, data have been shared with industry, academia, non-governmental organizations, and regulators to site, operate, and monitor CCS projects. Previous research was provided to parties interested in developing CO<sub>2</sub> storage projects in Illinois, Kentucky, Indiana, Iowa, Ohio, Maryland, Michigan, New York, Pennsylvania, and West Virginia. In addition, many key research papers, case studies, and datasets from the MRCI are referenced in U.S. EPA Class VI guidance documents, U.S. DOE-NETL guidance for CCS, and other state regulations for CO<sub>2</sub> storage. Data from CO<sub>2</sub> injection field projects and test wells in the Appalachian Basin, Arches Province, Illinois Basin, and Michigan Basin were especially useful to parties interested in developing CCS. These projects provide practical examples of CO<sub>2</sub> injection operations, permitting, site characterization, monitoring, and stakeholder outreach. The field tests were a large reason why there are currently 10 to 20 CCS projects in progress in the MRCI (Figure 3-7).

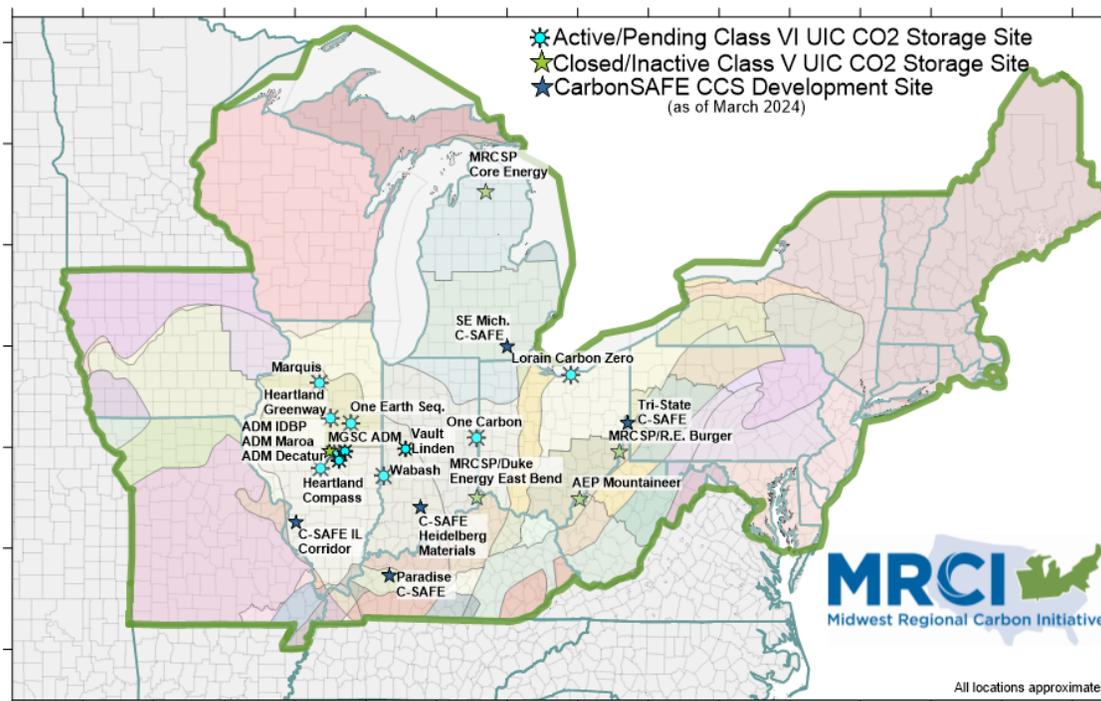


Figure 3-7. Map showing CCUS project in MRCI region as of winter 2023.

## 4.0 Evaluating Regional Infrastructure (Task 4)

### 4.1 Infrastructure Assessment

The purpose of the Infrastructure Assessment task was to evaluate current infrastructure and future needs to accelerate CCS deployment. Underpinning the task is a rethinking infrastructure for CCS. Instead of focusing exclusively on the required physical equipment that enables CCS, research also included the policy, economics, and people that make CCS work. To achieve this, four subtasks were created:

- *Infrastructure Readiness*: Strategizing the buildout of capture, transport, and storage infrastructure in the Midwest, Northeast, and Mid-Atlantic Offshore.
- *Site Readiness*: Determining the CCS readiness of each state in the MRCI region in the categories of subsurface readiness; infrastructure readiness; regulations, permitting, and incentives; and social dynamics.
- *Jobs, Economics, and Social Characteristics*: Quantifying the economic potential, job opportunities, and training opportunities for CCS as well as the social characteristics of the region with a focus on energy and environmental justice issues.
- *Policy and Regulations*: Providing an updated accounting of the CCS-relevant policy and regulations in the MRCI region.

### 4.2 Infrastructure Readiness

The infrastructure readiness assessment was intended to investigate the possible buildout of CCS in the MRCI area. This section provides a summary of the main accomplishments of the infrastructure readiness subtask:

- *Source Assessment*: Includes an assessment of the sectors emitting CO<sub>2</sub>, the industries emitting CO<sub>2</sub>, the impact of the expansion of the 45Q tax credits and assigning sources to specific regions for further analysis.
- *Source/Sink/Transport Assessment/Development Scenarios*: The source/sink/transport assessment includes modeling realistic CO<sub>2</sub> transport scenarios using a hub, distributed, or local approach. The Michigan Hub scenario developed by the MRCI team is presented to demonstrate the process.
- *Investigating Impacts to High Consequence Areas (HCAs)/Sensitive Areas*: The impact of hypothetical pipelines on HCAs and sensitive areas was investigated for the Michigan Basin hypothetical modeled pipeline route.
- *Pipeline Routing Philosophy*: The pipeline routing philosophy was developed to evaluate the possible impacts of routing pipelines through sensitive areas and HCAs.
- *Offshore Development Issues*: Issues that are unique to the development of the Mid-Atlantic Offshore were investigated.
- *Infrastructure Security*: The team developed an infrastructure security approach to assess the protectiveness of infrastructure related to CCS, especially the infrastructure that is close to other critical infrastructure. The process involves a threat assessment, vulnerability assessment, consequences assessment, and protectiveness assessment.

**Source Assessment:** The source assessment was intended to show the facility type and emissions from existing sources (U.S. EPA, 2023), point and non-point sources emissions by sector (Energy Information Administration [EIA], 2023), and changes in electric power

#### 4.0 Evaluating Regional Infrastructure (Task 4)

nameplate capacity across the MRCI region. Several topline trends can be extracted by the 2022 CO<sub>2</sub> emissions data, the most recent data available at the time of this analysis:

- Around 70% of the emissions in the MRCI study area are from electric power sources with 30% of emissions from industrial sources.
- The CO<sub>2</sub> emissions from individual states vary; however, at least half of all CO<sub>2</sub> emissions are from electric power sources in all states except Iowa and Illinois.
- The states with the largest amount of CO<sub>2</sub> emissions include Indiana (111.7 MMt), Ohio (100.3 MMt), and Pennsylvania (97.2 MMt). Together these states accounted for 37% of all CO<sub>2</sub> emissions reported in the Greenhouse Gas Reporting Program (GHGRP) from states in the MRCI study area (U.S. EPA, 2023).
- Although states in the western part of the MRCI study area emit comparatively less CO<sub>2</sub> than Indiana, Ohio, and Pennsylvania, states like Iowa, Missouri, Illinois, and Wisconsin have a relatively high proportion of purer streams of CO<sub>2</sub>.
- States in the eastern part of the MRCI study area also emit comparatively less CO<sub>2</sub> than Indiana, Ohio, and Pennsylvania; however, states like New Jersey, New York, and those in New England and the Maryland area have some of the most ambitious climate goals. Achieving these goals will likely require a combined mitigation approach that includes measures like power plant fuel switching, increased energy efficiency, and additional technologies like CCS or emerging technologies.

One of the biggest developments for CCS during the execution of the MRCI project was the expansion of the 45Q tax credits to include smaller sources. Industrial facilities that can capture at least 12,500 tonnes of CO<sub>2</sub> per year (down from 100,000 tonnes) and electric power facilities that can capture at least 18,750 tonnes of CO<sub>2</sub> per year (down from 500,000 tonnes) are now eligible for the tax credit now valued at \$85 per tonne for saline storage (up from \$50 per tonne) and \$60 per tonne for utilization (up from \$35 per tonne). This expansion means that an additional 1,167 facilities emitting a combined 84.1 MMt CO<sub>2</sub> in 2022 (U.S. EPA, 2023) are now eligible for 45Q tax credits (Figure 4-1).

In addition, sources were aggregated using natural and political boundaries to demarcate source regions in the first step of pipeline routing and source-sink matching. A map of the boundaries used to develop the source regions and the resulting source regions is shown in Figure 4-2. The resulting source regions (in order from descending emissions) are the Arches to Illinois (313.0 MMt), Appalachian Basin (201.0 MMt), Atlantic Coast (119.6 MMt), Corn Belt (109.6 MMt), Michigan Basin (86.1 MMt), and Green Mountains Area (4.3 MMt) (Table 4-1).

#### 4.0 Evaluating Regional Infrastructure (Task 4)

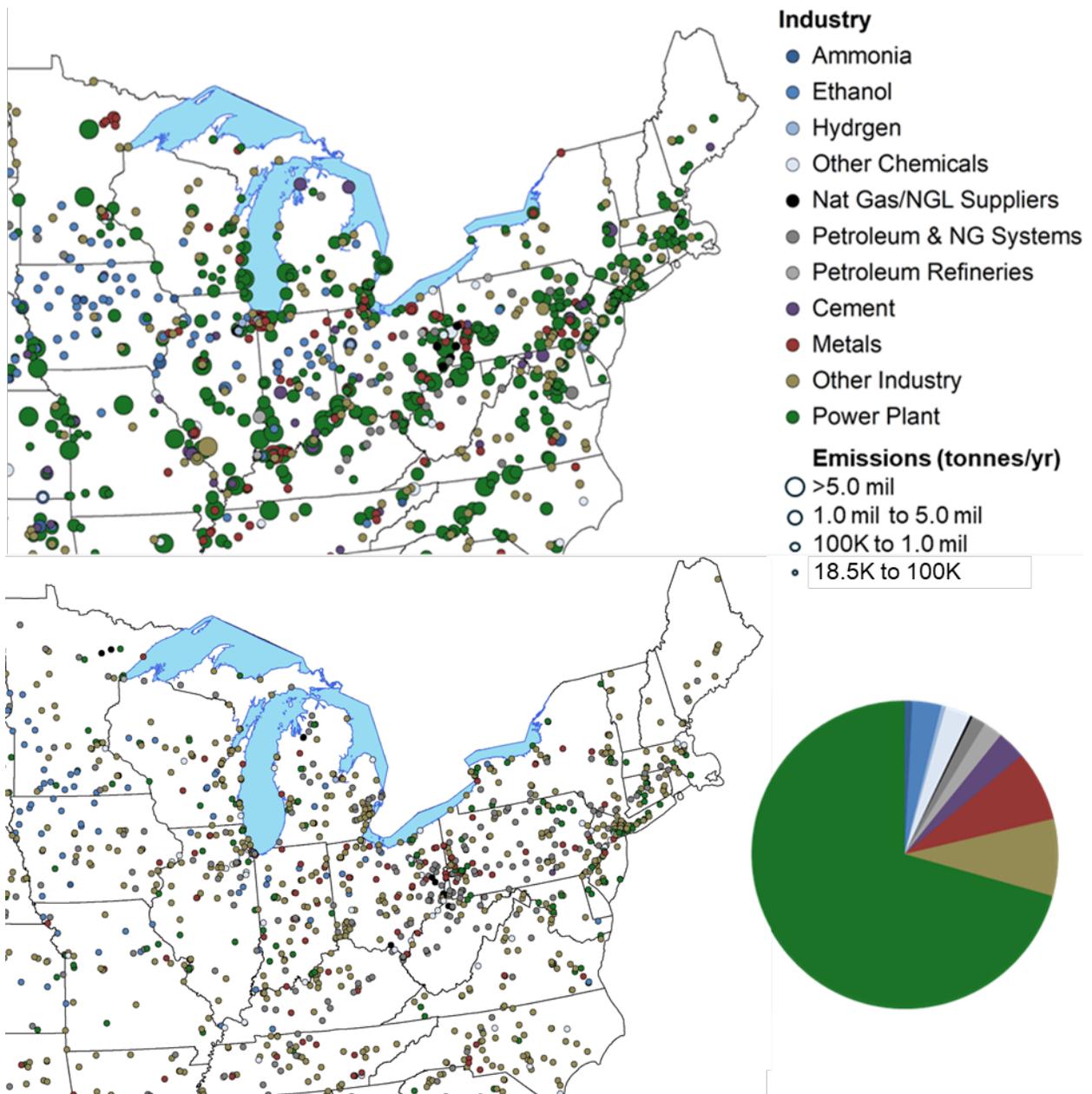


Figure 4-1. Sources in the MRCI area, by industrial sector, that emitted more than 100,000 tonnes in 2022 (top) and around source emitting 18,500 to 100,000 tonnes (bottom) in 2022 (U.S. EPA, 2023).

#### 4.0 Evaluating Regional Infrastructure (Task 4)

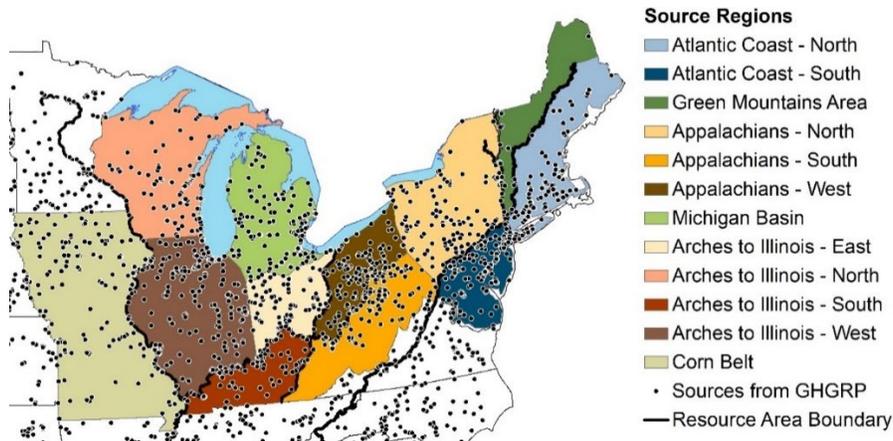


Figure 4-2. Source regions with 45Q-eligible sources. Natural and political boundaries used to develop source areas are also identified.

**Tale 4-1. CO<sub>2</sub> emissions (in MMT) and number of facilities, by industry, for each source region. This table includes sources that are newly eligible for the 45Q tax credit in addition to those that were eligible prior to its expansion (Data are from U.S. EPA, 2023).**

Industry	Atlantic Coast		Green Mountains Area		Appalachians	
	Emissions	No. Facilities	Emissions	No. Facilities	Emissions	No. Facilities
Ammonia	0.0	0	0.0	0	0.0	0
Cement	5.0	8	0.2	1	2.7	4
Chemicals	4.1	17	0.0	0	4.2	22
Ethanol <sup>3</sup>	0.0	0	0.0	0	0.3	4
Hydrogen	0.5	2	0.0	0	0.2	2
Metals	0.8	8	0.0	0	13.0	59
Natural Gas/Natural Gas Liquids (NGLs) Supply	0.0	0	0.0	0	1.7	14
Petroleum & Natural Gas Systems	2.2	22	0.0	1	5.9	113
Petroleum Refineries	4.9	2	0.0	0	2.9	3
Other Industry	12.9	147	0.5	11	10.5	98
Power Plants	89.3	153	3.5	4	159.5	98
<b>All</b>	<b>119.6</b>	<b>359</b>	<b>4.3</b>	<b>17</b>	<b>201.0</b>	<b>417</b>
Industry	Michigan Basin		Arches to Illinois Basin		Corn Belt	
	Emissions	No. Facilities	Emissions	No. Facilities	Emissions	No. Facilities
Ammonia	0.0	0	2.0	2	4.8	4
Cement	3.5	3	5.5	8	8.3	7
Chemicals	0.4	8	13.3	36	0.8	6
Ethanol <sup>3</sup>	1.2	13	11.9	54	12.2	61
Hydrogen	0.8	3	2.4	7	0.0	0
Metals	4.5	22	42.4	63	1.1	10
Natural Gas/NGLs Supply	0.0	1	0.3	1	0.0	0
Petroleum & Natural Gas Systems	1.3	19	2.5	46	0.4	12
Petroleum Refineries	3.2	3	5.9	5	0.0	0
Other Industry	7.6	82	28.3	182	7.7	50
Power Plants	63.5	41	198.6	123	74.3	41
<b>All</b>	<b>86.1</b>	<b>195</b>	<b>313.0</b>	<b>527</b>	<b>109.6</b>	<b>191</b>

**Source/Sink-Transport Assessment/ Development Scenarios:** The MRCI project area has a diversity of sources and sinks. Strategies to match sources, sinks and route pipelines to connect them were developed as part of this project. This work covers the source/sink and transport assessment for the expanded MRCI area. This report presents the final results of the process described in Battelle (2022). Battelle plans to use the processes described in this document for future DOE-sponsored and commercial efforts. Scenarios fit into one of three project types (Figure 4-3): Limited local (CO<sub>2</sub> from a single source or small group of sources injected into a single underlying or nearby sink area), Hub (CO<sub>2</sub> from several sources feeding into a central trunkline delivered to a large sink or wellfield for storage), and Distributed (CO<sub>2</sub> from several sources feeding into a central trunkline, along which several smaller scale projects are in discrete areas).

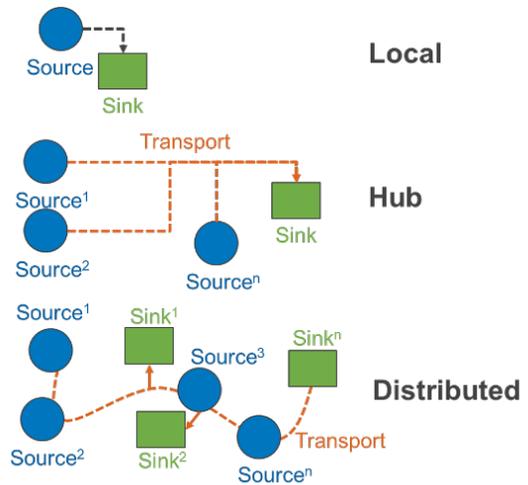


Figure 4-3. Graphical representation of infrastructure development scenarios.

Six modeling scenarios were developed as part of the project (Table 4-2). Each scenario served as the basis for further analyses as discussed in the description of the project. Results from the Michigan Hub Scenario are presented in this document. Results from the other scenarios are presented in Battelle (2024g).

Table 4-2. Modeled Source/Sink-Transport Scenarios.

Scenario	Model Used	Description
Local – Central Ohio	SimCCS (Open source)	A scenario covering a storage area in the Cambro-Ordovician Storage Complex in Central Ohio that varies that size and distribution of sources considered in three separate realizations. The scenario included a high-level economics analysis and an analysis of sensitive areas.
Distributed – Appalachian	SimCCS <sup>PRO</sup>	-Scenarios in the Tri-State area of Eastern Ohio, Western Pennsylvania, and West Virginia connecting distributed storage areas that correspond with areas modeled by MRCI and other DOE-sponsored projects. Two realizations were generated for this scenario. <i>Realization 1</i> connects actual sources throughout the region. <i>Realization 2</i> connects realistic but hypothetical natural gas processing facilities, natural gas power plants, and hypothetical hydrogen facilities.
Hub – Indiana	SimCCS (Open source)	A scenario connecting realistic but hypothetical industrial and electric power sources with three storage areas in Northern, Central, and Southern Indiana.
Hub – Michigan Basin	SimCCS (Open source)	A scenario that connects actual sources in the southern half of the Lower Peninsula of Michigan with two hypothetical wellfields in southeastern and southwestern Michigan. The scenario was used to demonstrate the intersection of project infrastructure with HCAs and critical

#### 4.0 Evaluating Regional Infrastructure (Task 4)

**Table 4-2 (continued). Modeled Source/Sink-Transport Scenarios.**

Scenario	Model Used	Description
		infrastructure and Stakeholder Analysis and Characterization.
<b>Regional –Industrial Midwest</b>	SimCCS (Open source)	A scenario that considers sources that emit at least 0.1 MMt/yr in the Industrial Midwestern State of Ohio, Indiana, Illinois, and Kentucky was run to determine the phased approach of large-scale regional pipelines. These results were used to determine the economics of the phased approach.
<b>Regional – MRCI-wide</b>	SimCCS (Open source)	A scenario that considers the sources that emit at least 0.1 MMt/yr in the entire MRCI region was run to determine the phased approach of large-scale regional pipelines. These results were used to determine the economics of the phased approach and the impact of consider Environmental Justice (EJ) communities.

**Intersection of HCAs and Critical Infrastructure in Michigan:** The Michigan Saline hub scenario was developed to simulate the connection of larger industrial and electric power sources in the southern half of the Lower Peninsula of Michigan to hypothetical storage wellfields in southeastern and southwestern Michigan. The scenario consisted of candidate pipelines, split into different segments with a distinct size, location, and flow rate (Figure 4-4). The Northwest Network connects 11 sources from Saginaw Bay toward Grand Rapids and Lake Michigan and turns southward to eastern Van Buren County in southwestern Michigan. The Southeast Network connects 18 sources extending from north of Detroit and the Capital Region through the Detroit Metro Area and south to Monroe.

The intersections of the hypothetical pipeline routes generated by the Michigan Hub scenario along with sensitive areas are outlined in Table 4-3, split into four categories: population, water, critical infrastructure, and environment. Maps showing population and critical infrastructure receptors are shown in Figures 4-5 and 4-6. In the Northwest Network, 68 of 467 km (15%) intersects highly populated areas (HPAs). Intersections occur mainly near Kalamazoo (NB1 and NB2), Grand Rapids (NT3 and NB4), Holland (NB3/3a) and Bay City (NT7 and NB7). In general, these intersections are either limited or with relatively short and smaller branches. The exceptions are the B3/3a branch of the hypothetical pipeline, which moves 7.4 million tonnes of CO<sub>2</sub> per year in 8.8 km of a 20-inch pipeline near the HPA of Holland and the NT3 hypothetical trunk line, which moves 7.0 MMt/year in 11.2 km of a 20-inch pipeline near the HPA of Grand Rapids. In addition, 10.6 km of 467 km (2%) of the hypothetical Northwest Network intersect other populated areas (OPAs). Generally, these intersections are along short distances of the segments impacted. The pipeline also intersects OPAs along 10.6 km of the 467 km pipeline (2%) mainly along smaller branches.

In the Southeast Network, 173 of 511 km (34%) intersects HPAs. Intersections occur mainly near Lansing (ST1 and SB1), Jackson (ST2 and ST3), Detroit (ST3, ST9, and SB3) and Detroit (ST6/6a, ST7 CLD, and SB4). Like the Northwest Network, these intersections are either limited or with relatively short and smaller branches. The exceptions are T6, which moves 5.3 MMT/year in 36.8 km of a 16-inch pipeline near the HPA of Holland and T5, which moves 6.1 MMT/year in 34.3 km of a 16-inch pipeline near the HPA of Detroit and its suburbs. In addition, 11.3 km of 511 km (2%) of the Southeast Network intersect OPAs. Generally, these intersections are along short distances of the segments impacted. The pipeline also intersects Other OPAs along 11.3 km of the 511 km pipeline (2%) mainly along smaller branches.

#### 4.0 Evaluating Regional Infrastructure (Task 4)

A map of the water receptors is shown in Figure 4-6, including surface water receptors (e.g., surface water intakes), groundwater receptors (e.g., wellhead protection areas [WHPAs] and commercial groundwater intakes), and water treatment plants. In general, the pipeline avoids areas within 1 km of surface water intakes and water treatment plants. ST3, which runs from Jackson westward, impacts a water treatment plant near Ann Arbor. SB3 (near Ann Arbor) and SB4, ST7, and ST8 (near Detroit) are near surface water intakes. Commercial groundwater intakes and WHPAs are more common across the area and are harder to avoid and five of 15 of the Northern Network sections and 11 of 16 of the Southern Network sections are near at least one intake. The overall impact may be less than these results suggest, however. Results show that only 17.8 of out of the 467 km (4%) Northern Network and 53 km out of the 511 km Southern Network (10%) intersect a WHPA.



Figure 4-4. Simulated pipeline routes to Central Processing locations. From here, the CO<sub>2</sub> will be routed to storage locations in southwestern (Northwest Network) and southeastern (Southeast Network) Michigan. The segments were labeled as trunklines (T), which are relatively large diameter with high flowrates, or branches (B), which are smaller diameter and shorter lines with generally lower flowrates. A cluster of branches in the City of Detroit are considered together (CLD). Details on each of the trunkline sections and branches are shown in the full Infrastructure Assessment report (Battelle, 2024g). The black numbers indicate the source according to the codes in Table 4-3.

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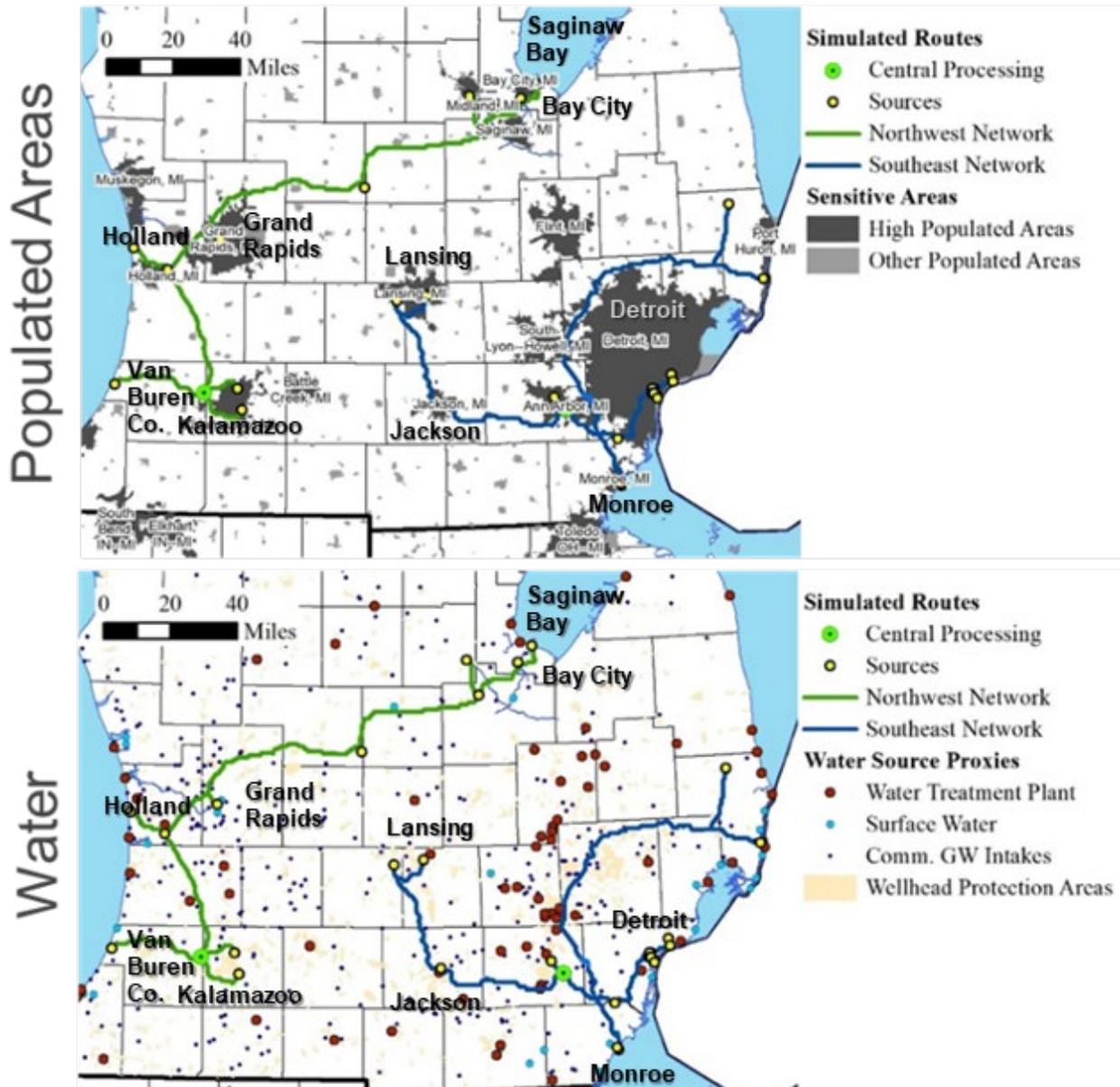


Figure 4-5. Maps of populated areas (PHMSA, 2018, 2017) (top); water receptors (EGLE, 2022; USGS, 2022) (bottom). The pipeline segments impacting each of these features are shown in Table 4-3.

A map of critical infrastructure receptors is shown in Figure 4-6, including hospitals, schools, and emergency responders as well as pipelines, transmission lines, roads, and rail lines. In general, where pipelines are routed through cities, intersections with schools and hospitals are unavoidable. This will result in potential safety and monitoring issues near these sensitive areas. Emergency responders are also found along the potential pipelines in these areas, meaning that, with proper outreach, these professionals could be employed in maintaining the safety and security of the pipeline.

4.0 Evaluating Regional Infrastructure (Task 4)

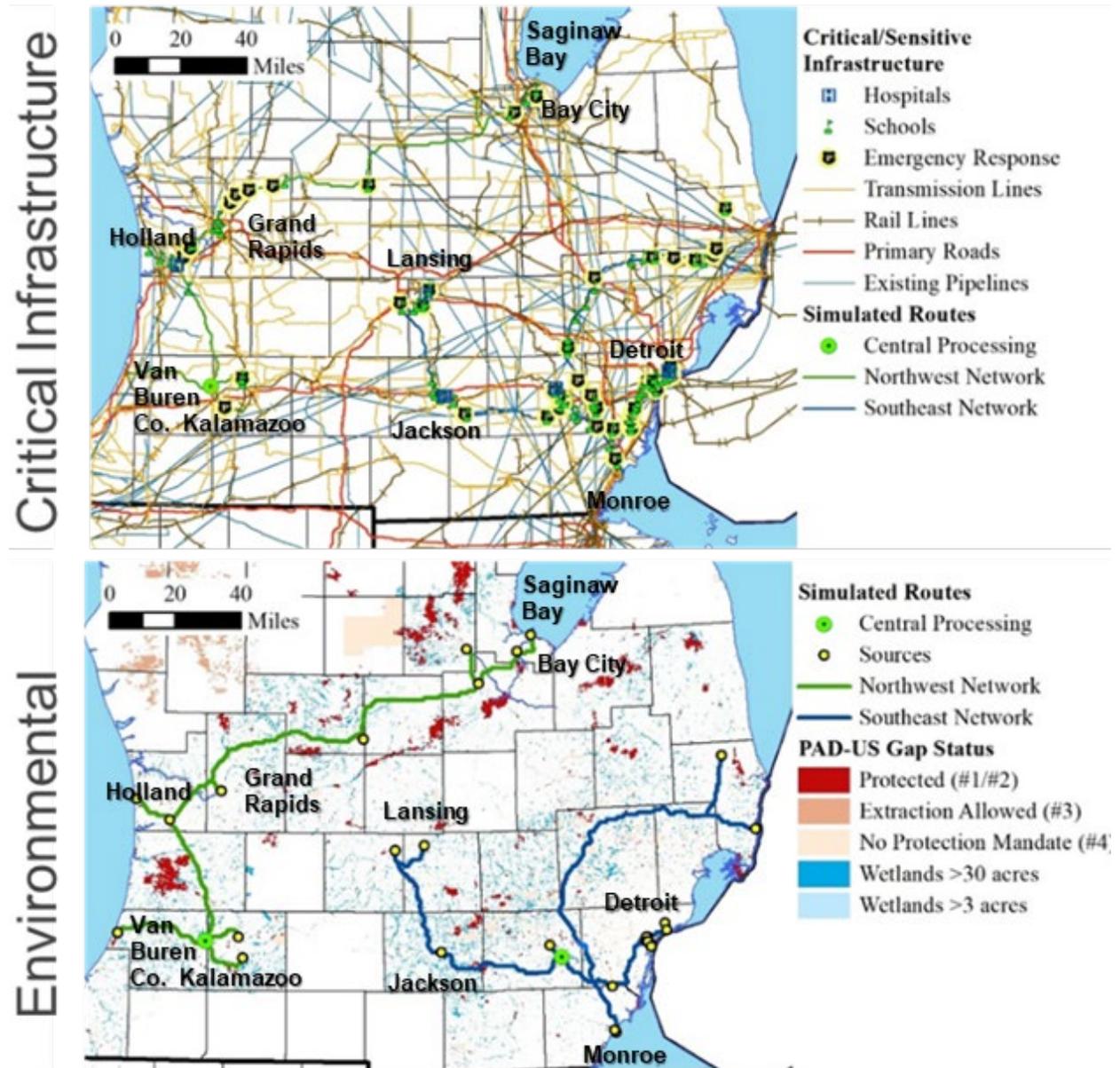


Figure 4-6. Map of critical infrastructure (USGS, 2017; EIA, 2022; Federal Railroad Administration [FRA], 1995; U.S. Census Bureau, 2017; EIA, 2020) (top); and environmental receptors (bottom) (USGS, 2016, USFWS, 2017). The pipeline segments impacting each of these features are shown in Table 4-3.

#### 4.0 Evaluating Regional Infrastructure (Task 4)

**Table 4-3. Pipeline segments and intersections to sensitive areas.**

Segment	Length (km)	Dia. (in)	Flow (MMT)	Population		Critical Infrastructure			Water					Environment			
				HPA	OPA	HOS	SCH	EMY	WTP	SWI	GW	CNW	WHPA	PAD1+2	PAD3	WL3	WL30
NB1	28.9	4	0.1	14.8	1.6	0	0	1	0	0	1	0	1.0	1.7	0	3.0	2.8
NB2	21.1	4	0.1	5.4	0	0	4	2	0	0	0	0	2.0	0.04	0	0.4	0.3
NB3	22.7	20	7.4	8.8	0	1	6	0	0	0	2	0	0.7	0.2	0	1.4	0.5
NB3a	0.8	12	1.9	0.8	0	1	1	0	0	0	0	0	0	0	0	0.01	0
NB4	7.1	4	0.2	5.6	1.5	0	6	0	0	0	0	0	0	0	0	0.2	0.1
NB5	2.5	8	0.7	0	0.5	0	2	2	0	0	0	0	0	0	0	0.2	0
NB6	19.9	16	3.8	0	2.8	0	0	0	0	0	0	0	0	0.8	0	2.4	1.9
NB7	1.1	4	0.1	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0
NT1	51.5	12	3	0	1.6	0	0	0	0	0	0	0	2.3	0	0	6.8	2.0
NT2	68.0	24	16.3	1.9	0	1	3	0	0	0	0	0	3.9	1.4	500	3.4	2.1
NT3	29.8	20	7	11.2	0	1	8	2	0	0	1	0	2.5	0.02	0	1.3	0.6
NT4	92.8	20	6.8	8.9	1.0	0	5	5	0	0	3	0	4.1	0.6	0	8.8	1.7
NT5	74.8	16	6.1	0	0.8	0	0	0	0	0	0	0	1.3	0.3	0	6.4	2.6
NT6	28.7	12	2.2	2.5	0.8	0	2	1	0	0	1	0	0	1.3	0	2.2	0.6
NT7	17.3	12	2.1	7.0	0	0	4	2	0	0	2	Yes	0	0	0	1.0	0.4
<b>Total</b>	<b>467.0</b>	<b>4-24</b>	<b>0.1-16.3</b>	<b>68.0</b>	<b>10.6</b>	<b>4</b>	<b>41</b>	<b>15</b>	<b>0</b>	<b>0</b>	<b>10</b>	<b>Yes (1)</b>	<b>17.8</b>	<b>6.4</b>	<b>0.5</b>	<b>37.5</b>	<b>15.6</b>
SB1	21.4	6	0.3	15.0	1.8	1	3	11	0	0	1	0	8.0	0.1	0	1.7	0.3
SB2	31.9	8	0.6	0	0	0	4	1	0	0	0	0	0.8	0	0	0.8	0.1
SB3	7.1	6	0.2	7.1	0	2	5	16	0	1	1	0	0.4	0.4	0	0.2	0
SB4	4.2	8	0.6	4.2	0	0	5	15	0	2	0	0	0	0	0	0	0
SB5	1.4	4	0.1	1.4	0	0	0	0	0	0	0	0	0.2	0	0	0	0
SB6	0.8	4	0.1	0.7	0.2	6	0	0	0	0	0	Yes	0	0	0	0.3	0.2
SCLD	8.9	6-12	0.2-2.7	8.9	0	0	8	17	0	0	5	0	0	0	0	0.1	0.1
ST1	7.0	8	0.8	5.7	0.4	0	2	1	0	0	1	0	2.5	0	0	0.1	0.1
ST2	57.6	8	1.1	14.8	0	2	4	13	0	0	2	0	7.9	0.6	0	4.9	2.3
ST3	75.5	12	2.0	20.4	4.7	0	11	20	2	0	2	0	10.2	5.6	0	9.2	4.1
ST4	26.8	16	5.5	0	0	0	0	0	0	0	1	0	0	0	0	2.2	1.5
ST5	155.7	16	6.1	34.3	2.5	0	17	25	0	0	5	0	22.6	0.6	0	16.3	7.8
ST5a	10.2	16	5.3	2.5	0	0	3	1	0	0	0	0	0	0.2	0	1.3	1.3
ST6	36.8	16	5.1	36.8	0	0	7	19	0	0	2	0	0	1.1	0	1.5	1.3
ST6a	1.4	16	4.3	1.4	0	0	0	3	0	0	1	0	0	0	0	0	0
ST7	11.6	8	0.7	11.5	0.02	0	10	42	0	2	1	0	0	0	0	0	0
ST8	30.3	24	14.2	4.7	1.7	0	4	2	0	1	0	Yes	0	0.8	0	2.8	2.2
ST9	22.0	30	25.6	3.5	0	0	2	13	0	0	0	0	0.6	0	0	1.6	0.3
<b>Total</b>	<b>510.6</b>	<b>4-30</b>	<b>0.1-25.6</b>	<b>173.1</b>	<b>11.3</b>	<b>11</b>	<b>85</b>	<b>199</b>	<b>2</b>	<b>6</b>	<b>22</b>	<b>Yes (2)</b>	<b>53.0</b>	<b>9.6</b>	<b>0</b>	<b>43.1</b>	<b>21.5</b>

Notes: 1. Population: Values for HPA and OPA (PHMSA, 2017; 2018) are the length of pipeline segment that intersects the feature (in meters)

2. Water: Values for WTP, GWI, and SWI (USGS, 2022) are the number of features within 1 km of the pipeline segment. Values for Commercially Navigable Waters (CNW) are "Yes" if the segment intersects a CNW (PHMSA, 2019). Values for WHPA are the length of pipeline segment that intersects the feature (meters) (Michigan Dept. of Environmental, Great Lakes, and Energy [EGLE], 2022);

3. Environmental: Values for PAD1+2, PAD3 (USGS, 2016), WL3, and WL30 (USFWS, 2017) are the length of pipeline segment that intersects the feature (meters).

4. Length, diameter, and flow diagrams are filled to show the values for each segment.

5. The population and environmental indicators are highlighted to show the percentage of the length of each segment that intersects the indicator: 0%, 1% - 10%, 10% - 20%, 20% - 30%, 30% - 40%, and >40%. The critical infrastructure and water indicators are highlighted to show where the segment intersects the indicator of interest.

**Pipeline Development Philosophy:** The team developed a pipeline routing philosophy. While natural gas pipelines have prescribed design factors for some HCAs<sup>19</sup>, these specific factors are not provided for hazardous liquid pipelines, the category that includes CO<sub>2</sub> pipelines. As a

<sup>19</sup> For natural gas pipelines, design factors are dependent on the location class, which is "determined by counting the number of dwellings within 660 feet of the pipeline for 1 mile (for Classes 1-3) or by determining that four-story buildings are prevalent along the pipeline (Class 4)." (PHMSA, 2013). Design factors are dependent on these classes (0.72 for Class 1, 0.60 for Class 2, 0.50 for Class 3, and 0.40 for Class 4) and thus location. Hazardous liquid pipelines HCAs do not have prescribed location classes like natural gas pipelines. Instead, per §195.5, the design factor is not to exceed 0.8. The PHMSA regulations do state that a design factor of 0.72 is typically used in most areas. Two exceptions are noted in §195.106: "Pipe, including risers, on a platform located offshore or on a platform in inland navigable waters", (design factor = 0.6) and for pipe subjected to cold temperatures and subsequently heated to high temperatures as defined by the rule (design factor = 0.54).

#### 4.0 Evaluating Regional Infrastructure (Task 4)

result, it was necessary for the MRCI program to develop a pipeline routing philosophy to ensure the protection of sensitive areas for pipeline designs. This philosophy was intended to determine the relative impact of pipelines going through these areas<sup>20</sup>. The purpose would be to demonstrate that the costs to build and operate pipelines through these areas are higher because of increased design requirements (§195.100 – 134), operation and maintenance (§195.450), and integrity management (§195.452 – 454). Three protective designations are used to control these changes in costs: (1) lowest susceptibility (base cost); (2) moderate susceptibility (2.0x base cost); and (3) high susceptibility (3.0x base cost).

The following will be considered to have High susceptibility:

- Any pipeline routed through HCAs, including HPAs, OPAs, commercially navigable waters (CNWs), and unusually sensitive areas (USAs) (Drinking Water and Environmental)
- Any pipeline routed within 1 km of a vulnerable population, as determined by the presence of schools/daycares, hospitals, elder care facilities, etc.
- Any pipeline routed through any of the following specific environmentally sensitive areas that do not otherwise meet the definition of an HCA:
  - National, State, or Local Parks, Monuments, Wilderness areas or other designations that are (1) in the Protected Area Dataset of the United States (PAD-US) and (2) Have a Gap Status of 1 or 2.
  - National or State Scenic Rivers (as determined by PAD-US)
  - Critical habitats for endangered species
- Pipelines greater than 18-inch nominal diameter that are routed through any of the following additional areas considered sensitive:
  - Wetlands (as determined by the National Land Cover Database [NLCD])
  - Areas of the National Registry of Historic Places (NRHP)
- Pipelines that may contain ammonia, H<sub>2</sub>S, or another highly toxic product above trace concentrations.

The following conditions will result in Moderate susceptibility:

- Any pipeline routed through any of the following specific environmentally sensitive areas that do not meet the definition of an HCA or other area defined to have High susceptibility:
  - National, State, or Local Parks, Monuments, Wilderness areas or other designations that are (1) in the PAD-US and (2) Have a Gap Status of 3.
- Other waterbodies not considered USAs or considered CNWs or otherwise designated to have High susceptibility.
- Pipelines less than 18-inch nominal diameter that are routed through any of the following additional areas considered sensitive:
  - Wetlands (as determined by the NLCD)
  - Areas of the NRHP
- Pipelines co-located with critical infrastructure (power lines, roads, rail, dams, existing pipelines, airports, existing industry, etc.) not otherwise designated to have high susceptibility.

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<sup>20</sup> Although this process was not demonstrated as part of the MRCI project, Battelle will consider implementing it in future DOE-sponsored projects.

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All other pipelines are designated as low susceptibility. The MRCI team did not have the budget to implement this process; however, Battelle plans to refine and implement this process as part of future DOE-sponsored efforts. A summary of sensitive areas for the infrastructure assessment, including the potential consequences of building pipelines in these areas and potential mitigation options, are shown in Table 4-4.

**Table 4-4. Shapefiles of environmentally and culturally sensitive areas that will help inform the MRCI infrastructure assessment. Adapted from Battelle (2019).**

Description	Consequences	Potential Mitigation Options	Protective Protocol	Buffer	Shape Type
<b>Category: HCAs (Population and Drinking Water) and other Highly Sensitive Areas</b>					
<i>Rationale: Protect Human Health/Public Safety</i>					
HCA – High population area	-Pipeline leaks could cause a suffocation hazard to nearby populace. -Urban areas contain significant obstacles that would prevent the siting of a pipeline.	-Avoid urbanized areas, preferring areas free of population centers and occupied structures. -When passing through urbanized areas, follow Location Class standards in place for natural gas pipelines. -Construct pipeline so that operating pressures through urbanized areas is sufficiently low for safe operations.	High	No	Polygon
HCA – Other populated area	-Pipelines routed through urban areas could exacerbate public opposition to project. -High population areas and OPAs are considered HCAs for hazardous liquid pipelines (§195.450).		High	No	Polygon
HCA – CWS/NTNCWS	-Underground pipeline leak could acidify important groundwater resources.		High	No	Point or Polygon
HCA – SWPA for Class I/IIA	-Drinking water resources, represented by wellhead protection areas, source water protection areas (SWPA), and sole source aquifer recharge areas are considered HCAs for hazardous liquid pipelines (49CFR§195.6).	Avoid areas where water is used for beneficial use, particularly for human consumption or food preparation.	High	No	Point or Polygon
HCA – Sole source karstic aquifer recharge area			High	No	Point or Polygon
Schools / Day Cares	-Pipeline leaks could cause a suffocation hazard to nearby students. -Pipeline construction near schools could lead to public opposition to project.	Avoid known school locations	High	1 km	Point
Hospitals / Elder Care Facilities	Pipeline leaks could cause a suffocation hazard to nearby populace. Pipeline construction near hospitals could lead to public opposition to project.	Avoid known hospital locations	High	1 km	Point
<b>Category: Critical Infrastructure/Mineral Extraction</b>					

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**Table 4-4 (continued). Shapefiles of environmentally and culturally sensitive areas that will help inform the MRCI infrastructure assessment. Adapted from Battelle (2019).**

Description	Consequences	Potential Mitigation Options	Protective Protocol	Buffer	Shape Type
<i>Rationale: Protect existing critical infrastructure</i>					
HCA – CNW	Commercially navigable waters are considered HCAs for hazardous liquid pipelines (49CFR§195.450).	Avoid commercially navigable waters, where possible	High	No	Line
Airports	-Pipeline construction/operation could affect sensitive areas and structures. -Pipeline leaks could cause a suffocation hazard to those in airport structures.	Operational buffer of 1-km recommended.	Moderate	1 km	Point
Dams	Pipeline construction and operation could affect sensitive operations.	Operations limited to the point location itself. No buffer needed.	Moderate	1 km	Point
Military Installation		Coordinate with military/Department of Defense	Moderate	No	Polygon
Emergency Services	Areas are critical infrastructure.	Coordinate with local, state, or federal authorities	Moderate	1 km	Point
Roads	Pipeline operations could impact or be impacted by the operation of this infrastructure. Will require coordination with relevant authorities.	Coordinate with state Departments of Transportation (DOT) and/or local authorities	Moderate	800 m	Line
Rail		Coordinate with DOT	Moderate	800 m	Line
Existing Pipelines		Coordinate with state or federal DOT / authorities	Moderate	800 m	Line
Power Lines		Coordinate with DOT, relevant state / regional authorities	Moderate	800 m	Line
Existing operating industrial facility or power plant		Coordinated with power providers and state / regional authorities	Moderate	1 km	Point
Mineral Extraction	-Pipeline construction and operation could affect sensitive operations. -Underground pipeline leak could pose a suffocation hazard to mine workers.	Operational buffer of footprint of underground mine recommended.	Moderate	1 km	Point
<b>Category: Sensitive Areas – Environmental and Cultural</b>					
<i>Rationale: Protect environmentally and culturally sensitive areas</i>					
Critically imperiled species or ecological community	-Critically imperiled species and ecological communities are considered HCAs for hazardous liquid pipelines (49CFR§195.6)	Do not site pipelines where these areas are located	High	No	Polygon
Multi-species assemblage area					
Migratory bird concentration area					
Areas containing imperiled aquatic, aquatic dependent, or limited range species or ecological communities	-Areas with critically imperiled species or ecological communities, multi-				

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**Table 4-4 (continued). Shapefiles of environmentally and culturally sensitive areas that will help inform the MRCI infrastructure assessment. Adapted from Battelle (2019).**

Description	Consequences	Potential Mitigation Options	Protective Protocol	Buffer	Shape Type
Sensitive species with EORANK of A or B	species assemblage. migratory birds, aquatic wildlife, and sensitive wildlife are environmentally sensitive areas that are important with many communities and groups -Building pipelines through critical habitats could lead to significant opposition from environmental NGOs.				
Coastal Beach	National Parks are significant environmentally sensitive areas Building through them could lead to opposition from communities or NGOs.	Do not site pipelines where these areas are located	High	No	Polygon
Other Coastal Waters	-PAD-US Gap Status Areas #1 and #2 prevent the development of these environmentally sensitive areas. -Although the PAD-US is not mentioned specifically in 49CFR§195.6, they are likely considered HCAs due to their high ecological issues.	Do not site pipelines where these areas are located	High	No	Polygon
Gap Status 1&2	-Outstanding or exceptional state waters and National Wild and Scenic Rivers are environmentally sensitive areas that are important with many communities -Building through these areas could lead to significant opposition from environmental NGOs.	Do not site pipelines where these areas are located	High	No	Polygon
National Wild and Scenic River or State Agency, Outstanding National Waters	-PAD-US Gap Status Areas #3 allow for the development of these areas. -Although this is allowed, each Gap Status #3 area needs to be evaluated to determine potential environmental or public opposition issues.	Avoid PAD-US Gap #3 areas, where possible	High	No	Polygon or Line

#### 4.0 Evaluating Regional Infrastructure (Task 4)

**Table 4-4 (continued). Shapefiles of environmentally and culturally sensitive areas that will help inform the MRCI infrastructure assessment. Adapted from Battelle (2019).**

Description	Consequences	Potential Mitigation Options	Protective Protocol	Buffer	Shape Type
Gap Status 3	PAD-US Gap Status Areas #4 contain no orders for protection. Although this is allowed, each Gap Status #4 area needs to be evaluated to determine potential environmental or public opposition issues.	Evaluate Gap #4 study areas to determine potential environmental or public opposition issues	Moderate	No	Polygon
Critical Habitat			High	No	Polygon and Line
Wetlands	-Native American communities are often vocal opponents of pipeline projects -Native American land can contain cultural, historical, and religious significance	Do not site pipelines where these areas are located	High (>18")/ Moderate	No	Polygon
NRHP	-The NRHP is a database of areas with cultural or historical significance. -Building through these areas can lead to public opposition.	Do not site pipelines where these areas are located	High (>18")/ Moderate	1 km	Point or Polygon
Other water bodies (NHD, Areas)	Substantial surface waters can be obstacles to pipeline construction	Avoid where possible	Moderate	No	Polygon

**Offshore Development Issues:** Most of the areas that have been evaluated for geologic CO<sub>2</sub> storage in the Mid-Atlantic Offshore Area are on the continental shelf where the ocean floor is at a depth of less than 200 ft below mean sea level (Figure 4-7). This means that reaching these areas will require a pipeline that is either buried 12 inches below the ocean floor surface or above ground (i.e., mean sea level) and supported by additional infrastructure. Areas around Cape Cod, Massachusetts, and Long Island, New York (Figure 4-7) as well as Delaware/New Jersey and Maryland have large areas where the ocean floor is less than 12 ft below mean sea level, meaning these areas may be difficult to access with offshore pipeline infrastructure due to the need to bury them 36 inches or more below the ground surface. Sensitive areas in and around the Atlantic Offshore area are shown in Figure 4-8.

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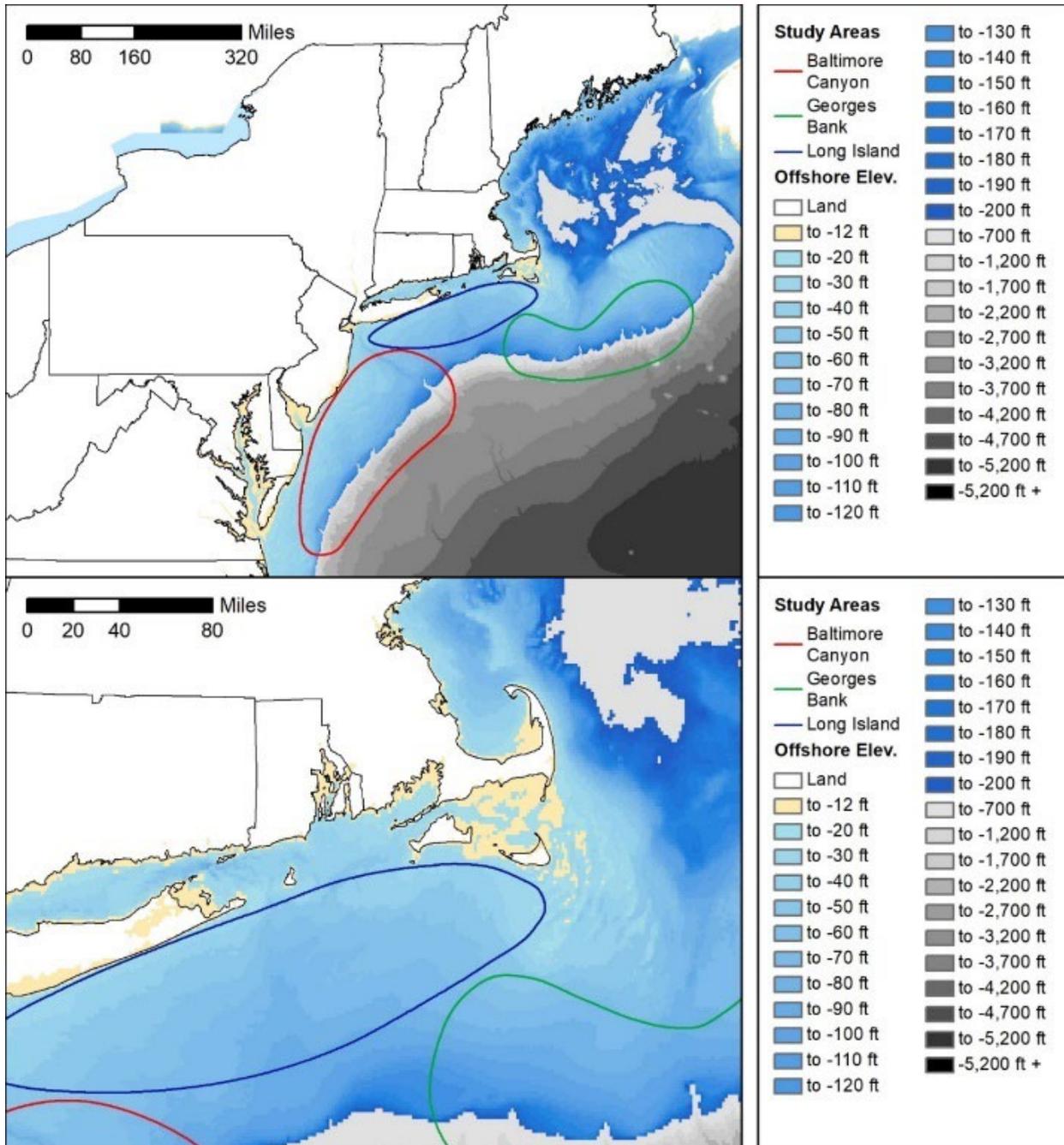
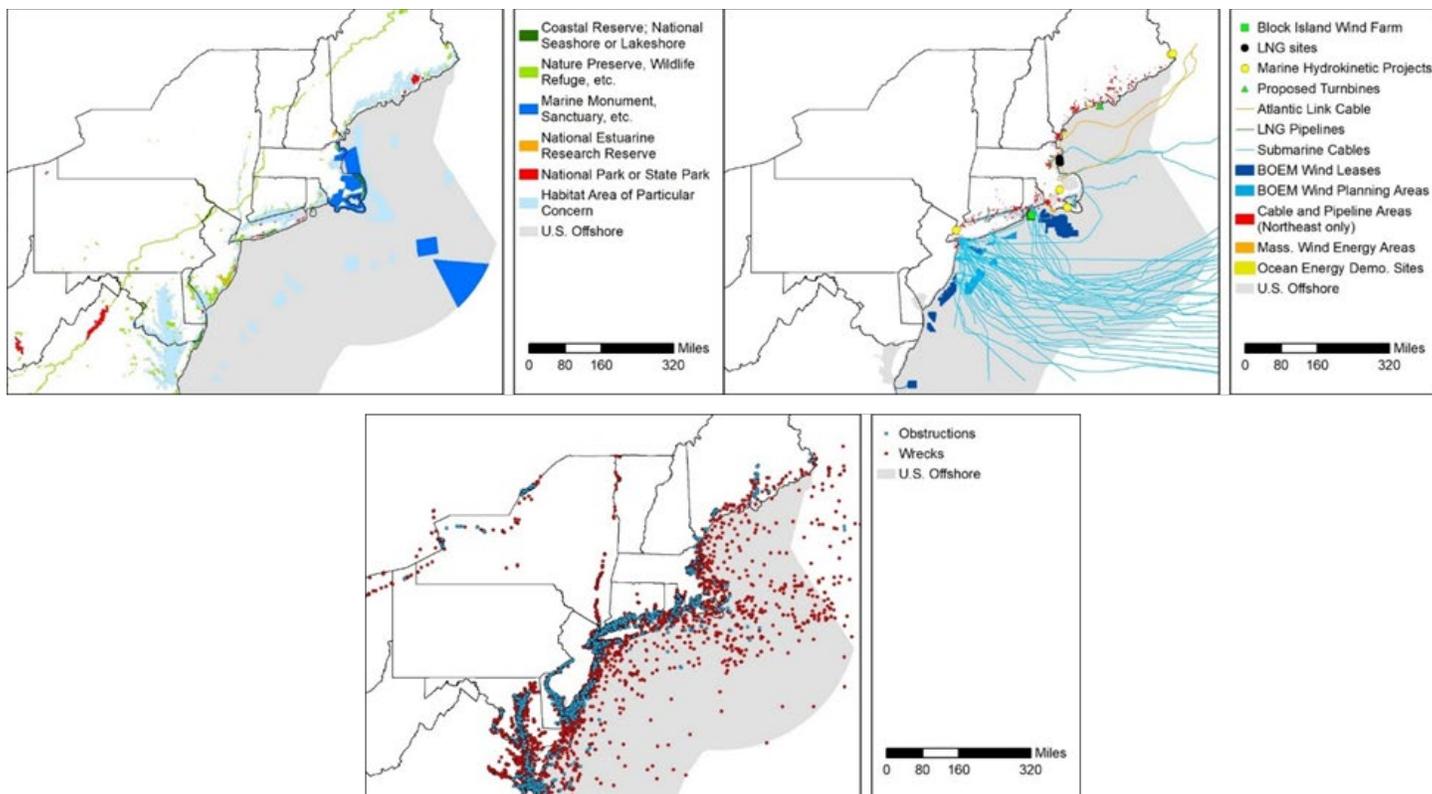


Figure 4-7. Offshore floor elevation for the Mid-Atlantic Offshore (National Oceanic and Atmospheric Administration [NOAA], 2022; Battelle, 2019) (left) and offshore elevation for the Cape Cod and West Long Island Area (National Oceanic and Atmospheric Administration [NOAA], 2022; Battelle, 2019) (right).

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*Figure 4-8. Sensitive areas in the U.S. Mid-Atlantic and Northeast Offshore Area (National Park System [NPS], 2021; Department of Commerce (DOC), NOAA, Office Of National Marine Sanctuaries (ONMS), and National Marine Protected Areas Center [MPAC], 2022; NOAA, 2021) (top left); existing and planned infrastructure in the U.S. Mid-Atlantic and Northeast Offshore Area (Ducharme, 2017a, b; Shmookler, 2016, 2015, 2014, nd; BOEM, 2021a, b) (top right); Obstructions and wrecks in the U.S. Mid-Atlantic and Northeast Offshore Area (NOAA, 2016) (bottom).*

**Infrastructure Risk and Security Assessment:** Physical security and cyber security are becoming an important consideration for critical infrastructure in the United States. Recent ransomware attacks at the Colonial Pipeline have demonstrated the need for effective cybersecurity of infrastructure. Widespread CCS deployment will mean system components will be incorporated into potentially complex existing systems, such as electric power generation, industry and manufacturing, and oil and gas operations. As a result, it is important that system components are secure and/or digitally and physically isolated (where possible) from critical aspects of CO<sub>2</sub> source operations. The MRCI project is proposing the development of an approach to identify and mitigate risk created by potential physical disruptions or cyberattacks on CCS systems.

The MRCI team sought to establish a background in this emerging study area by defining CCS within the critical infrastructure framework, representing the importance of identifying criticality, threats, vulnerabilities, and consequences that equate to risk to CCS systems, and establishing additional research objectives and a path forward for researching CCS infrastructure security issues (Figure 4-9).

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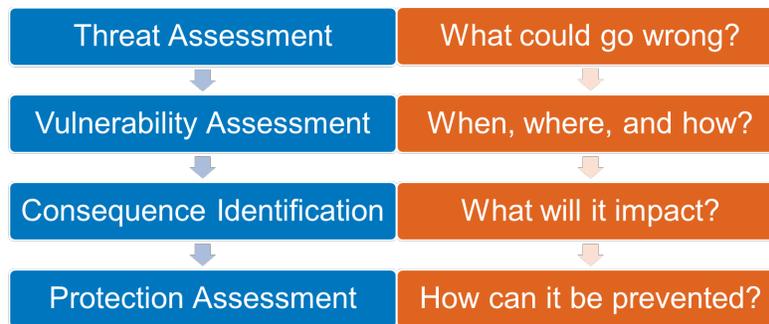


Figure 4-9. Process for Infrastructure Security Assessment.

The full Infrastructure Assessment report (Battelle, 2024g) provides a general threat assessment for CCS infrastructure. The example shown in Table 4-3 provides an example of a consequence identification for the Michigan Hub. The table shows where population centers, existing critical infrastructure, water resources, and environmentally sensitive areas are intersected by the hypothetical pipeline routes developed for the area. This could be followed by a protection assessment, which will determine how these consequences could be mitigated via physical controls like re-routing, pipeline design, safety equipment and alarms or digital controls like Supervisory Control and Data Acquisition (SCADA) systems.

### 4.3 Site Readiness

This section presents the results of Subtask 4.2, which evaluated the readiness of states and sites to deploy CCS. This process employs a logical screening process for readiness assessments on the state level and on the sub-regional/reservoir/site level. The process involves determining a site readiness level related to four areas: 1) subsurface readiness (i.e., the reservoir and caprock system); 2) infrastructure readiness (i.e., infrastructure deployment and planning issues); 3) regulations, permitting, and incentives; and 4) social dynamics. The DOE Site Screening and Site Selection guidance (DOE/NETL, 2017) was used to develop a list of criteria to assess site readiness. Four categories of considerations are included in the guidance: subsurface readiness; infrastructure readiness; regulations, permitting, and incentives; and social dynamics.

- **Subsurface Readiness:** These considerations include reservoir, caprock, and storage considerations like the presence of adequate storage resources with good injectivity and hydrogeological conditions and overlying low permeable caprock, an understanding of the structural framework and trapping mechanisms, and sufficient information about geochemistry and geomechanics of relevant potential formations. Other considerations include the geologic conceptual modeling and numerical injection modeling for a better understanding of the storage feasibility, potential AoR, and engineering design of the project, including the different input parameters needed, boundary conditions, uncertainty, and the additional data needed to calibrate and refine models including integration of seismic and other new data, test models, and output validation comparisons.
- **Infrastructure Readiness:** These considerations include an assessment of the required infrastructure, access to CO<sub>2</sub> supply, land use and sensitive areas in the region impacted by project infrastructure or activities, and site planning. The evaluation included an accounting of pipeline right of ways, infrastructure needs, and surface requirements. The factor of access to CO<sub>2</sub> supply will be estimated by determining the amount of work that has been completed in the area to progress the site toward a viable CO<sub>2</sub> source. This could include

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hub level studies connecting sources to viable sinks, press releases from companies announcing their intention to capture CO<sub>2</sub> or construct a CO<sub>2</sub> pipeline, a front-end engineer design (FEED) of a capture system and pipeline system, or an operational CO<sub>2</sub> capture system or pipeline. In addition, an accounting of the land use and protective and sensitive areas, population centers, existing resource development is also included to facilitate the analysis of issues of concern to project stakeholders.

- **Regulations, Permitting, and Incentives:** These considerations include analyzing and defining the regulatory issues and requirements, including a review of applicable regulations, how the injection well(s) will be classified (i.e., Class II or Class VI), the development of well plans, and a plan to obtain a UIC Class II or Class VI permit; corrective action needed for existing wells in the AoR, injection pressure maximums, the mechanisms for containment, and plans for financial assurance for liability; and assembling all data needed for site permits.
- **Social Dynamics:** These considerations include aggregating social data for potential affected communities, including demographics and land use; conducting an initial social characterization, including gathering and assessing available social data for selected communities; assessing outreach needs, including defining goals and outreach activities, establishing an outreach team, defining stakeholders and the social climate, and developing a public outreach program; and updating and executing the outreach strategy, including being responsive to the project timeline and stakeholder concerns and continuing ongoing outreach efforts.

The rating system and a generic example of it are shown in Figure 4-10. The process was applied to three sites (one each in Ohio, Michigan, and West Virginia) by Battelle (2022). Site readiness factsheets have been prepared for Maryland, Michigan, Pennsylvania, and Ohio.

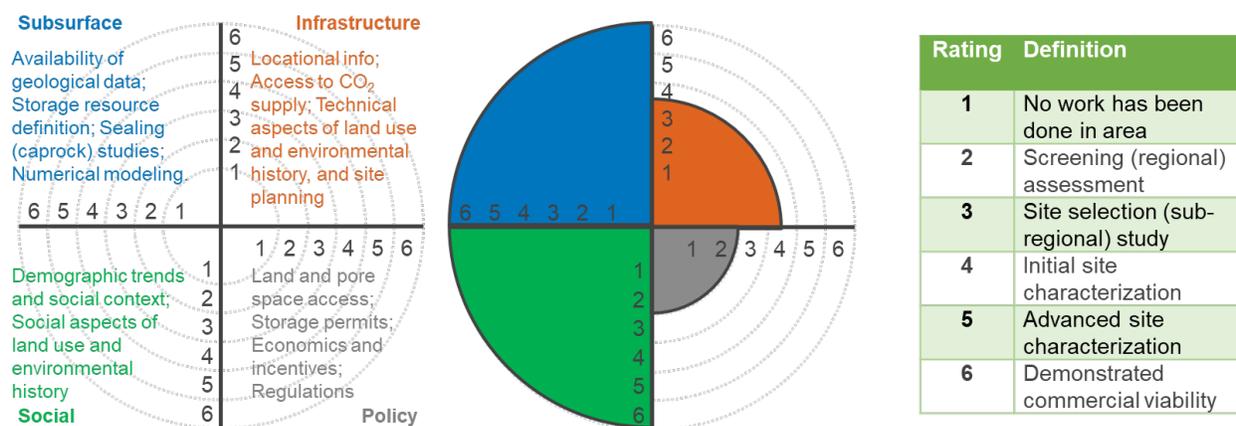


Figure 4-10. Definitions of the ratings and rating categories with an example of a rated state.

#### 4.4 Jobs, Economics, and Social Characteristics

**Social Characterization:** This section provides an overview of government-sponsored tools and provides an analysis of disadvantaged communities in the MRCI area using those tools. In addition, case studies using the DOE Energy Justice Screening Tool (DOE, 2022) and Climate and Economic Justice Screening Tool (CEJST) (White House Council on Environmental Quality [CEQ], 2022). This process can help accelerate deployment of CCS in the MRCI region by providing operators with a list of issues that must be addressed in stakeholder outreach efforts. Disadvantaged Communities were investigated using the DOE Energy Justice Screening Tool

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and the White House CEQ CEJST (Figure 4-11). The MRCI source regions and subregions were analyzed with the DOE EJ Screening tool and CEJST tool in Table 4-5 and Table 4-6, respectively. As projects develop, a more in-depth assessment will be required for the impacted area; however, the full Infrastructure Assessment report (Battelle, 2024g) provides a generalized assessment of the issues faced by each subregion of the MRCI area.

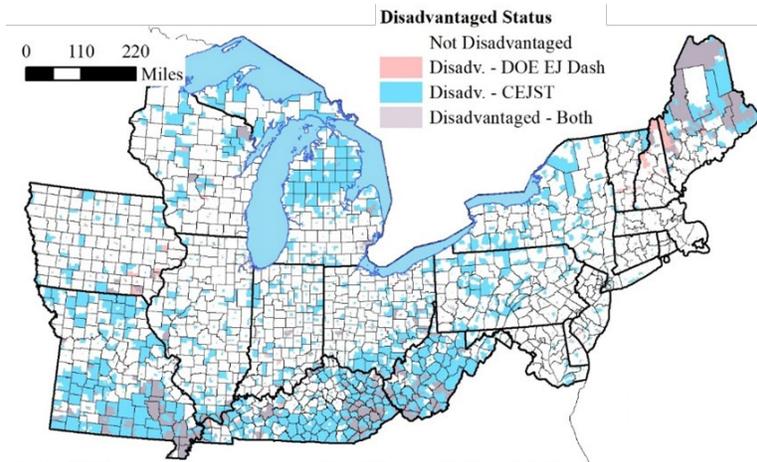


Figure 4-11. Disadvantaged communities according to the DOE Energy Justice Mapping Tool (DOE, 2022) and Climate and Economic Justice Screening Tool (CEJST) (White House CEQ, 2022).

**Table 4-5. Number of tracts considered disadvantaged, by source area. In addition, the number and percent of tracts in the 65<sup>th</sup> percentile for energy burden, fossil fuel employment, coal employment, unemployment rate, adults with less than a high school education, low income, proximity to traffic, and water discharge. These issues are reported regardless of whether the tracts are considered disadvantaged. Data are from DOE (2022).**

Source Region	No. of Tracts	Disadvantaged		Energy Burden		Fossil Fuel Employment		Coal Employment		Unemployment rate	
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
<b>Appalachian Basin</b>	<b>5,724</b>	<b>797</b>	<b>14%</b>	<b>1,837</b>	<b>32%</b>	<b>2,649</b>	<b>46%</b>	<b>2,865</b>	<b>50%</b>	<b>2,203</b>	<b>38%</b>
Appalachian Basin - North	2,286	97	4%	709	31%	780	34%	1,057	46%	754	33%
Appalachians Basin - South	1,569	319	20%	545	35%	1,281	82%	1,312	84%	689	44%
Appalachians Basin - West	1,869	381	20%	583	31%	588	31%	496	27%	760	41%
<b>Atlantic Coast</b>	<b>11,567</b>	<b>2,582</b>	<b>22%</b>	<b>1,688</b>	<b>15%</b>	<b>3,490</b>	<b>30%</b>	<b>2,537</b>	<b>22%</b>	<b>3,851</b>	<b>33%</b>
Atlantic Coast - North	5,993	1,430	24%	1,124	19%	132	2%	655	11%	1,975	33%
Atlantic Coast - South	5,574	1,152	21%	564	10%	3,358	60%	1,882	34%	1,876	34%
<b>Corn Belt</b>	<b>2,392</b>	<b>430</b>	<b>18%</b>	<b>635</b>	<b>27%</b>	<b>469</b>	<b>20%</b>	<b>537</b>	<b>22%</b>	<b>576</b>	<b>24%</b>
<b>Green Mountains Area</b>	<b>483</b>	<b>53</b>	<b>11%</b>	<b>202</b>	<b>42%</b>	<b>101</b>	<b>21%</b>	<b>220</b>	<b>46%</b>	<b>108</b>	<b>22%</b>
<b>Michigan Basin</b>	<b>3,322</b>	<b>631</b>	<b>19%</b>	<b>941</b>	<b>28%</b>	<b>575</b>	<b>17%</b>	<b>1,394</b>	<b>42%</b>	<b>1,305</b>	<b>39%</b>
<b>Arches to Illinois</b>	<b>8,567</b>	<b>1,618</b>	<b>19%</b>	<b>1,624</b>	<b>19%</b>	<b>920</b>	<b>11%</b>	<b>992</b>	<b>12%</b>	<b>2,791</b>	<b>33%</b>
Arches to Illinois - East	1,860	320	17%	378	20%	65	3%	32	2%	577	31%
Arches to Illinois - North	1,560	264	17%	283	18%	153	10%	258	17%	307	20%
Arches to Illinois - South	1,007	168	17%	191	19%	154	15%	154	15%	338	34%
Arches to Illinois - West	4,140	866	21%	772	19%	548	13%	548	13%	1,569	38%
<b>All MRCI</b>	<b>32,055</b>	<b>6,111</b>	<b>19%</b>	<b>6,927</b>	<b>22%</b>	<b>8,204</b>	<b>26%</b>	<b>8,545</b>	<b>27%</b>	<b>10,834</b>	<b>34%</b>

Source Region	No. of Tracts	Less than High School Education		Low Income		Proximity to Traffic		Water Discharge	
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
<b>Appalachian Basin</b>	<b>5,724</b>	<b>1,608</b>	<b>28%</b>	<b>2,147</b>	<b>38%</b>	<b>1,223</b>	<b>21%</b>	<b>2,751</b>	<b>48%</b>
Appalachian Basin - North	2,286	530	23%	656	29%	497	22%	882	39%
Appalachians Basin - South	1,569	569	36%	736	47%	298	19%	824	53%
Appalachians Basin - West	1,869	509	27%	755	40%	428	23%	1,045	56%
<b>Atlantic Coast</b>	<b>11,567</b>	<b>3,595</b>	<b>31%</b>	<b>2,653</b>	<b>23%</b>	<b>6,319</b>	<b>55%</b>	<b>4,370</b>	<b>38%</b>
Atlantic Coast - North	5,993	2,105	35%	1,500	25%	3,526	59%	1,808	30%

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Source Region	No. of Tracts	Less than High School Education		Low Income		Proximity to Traffic		Water Discharge	
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
Atlantic Coast - South	5,574	1,490	27%	1,153	21%	2,793	50%	2,562	46%
<b>Corn Belt</b>	<b>2,392</b>	<b>589</b>	<b>25%</b>	<b>811</b>	<b>34%</b>	<b>456</b>	<b>19%</b>	<b>908</b>	<b>38%</b>
<b>Green Mountains Area</b>	<b>483</b>	<b>67</b>	<b>14%</b>	<b>90</b>	<b>19%</b>	<b>56</b>	<b>12%</b>	<b>141</b>	<b>29%</b>
<b>Michigan Basin</b>	<b>3,322</b>	<b>883</b>	<b>27%</b>	<b>1,204</b>	<b>36%</b>	<b>1,325</b>	<b>40%</b>	<b>1,057</b>	<b>32%</b>
<b>Arches to Illinois</b>	<b>8,567</b>	<b>2,480</b>	<b>29%</b>	<b>2,865</b>	<b>33%</b>	<b>2,406</b>	<b>28%</b>	<b>4,415</b>	<b>52%</b>
Arches to Illinois - East	1,860	509	27%	655	35%	471	25%	1,035	56%
Arches to Illinois - North	1,560	230	15%	384	25%	548	35%	517	33%
Arches to Illinois - South	1,007	454	45%	442	44%	222	22%	476	47%
Arches to Illinois - West	4,140	1,287	31%	1,384	33%	1,165	28%	2,387	58%
<b>All MRCI</b>	<b>32,055</b>	<b>9,222</b>	<b>29%</b>	<b>9,770</b>	<b>30%</b>	<b>11,785</b>	<b>37%</b>	<b>13,642</b>	<b>43%</b>
Less than 20% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									
20%-30% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									
30%-40% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									
40-50% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									
More than 50% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									

**Table 4-6. CEJST Census Tracts considered disadvantaged and CEJST indicators exceeded. Percentages show the proportion of disadvantaged Census Tracts that exceed the indicator. Data are from the White House Council on Environmental Quality (2022).**

Source Region	No. of Tracts	Disadvantaged		Water		Workforce		Climate		Energy	
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
<b>Appalachian Basin</b>	<b>6,158</b>	<b>2,369</b>	<b>38%</b>	<b>385</b>	<b>16%</b>	<b>1,035</b>	<b>44%</b>	<b>663</b>	<b>28%</b>	<b>880</b>	<b>37%</b>
Appalachian Basin - North	2,401	687	29%	51	7%	320	47%	134	20%	258	38%
Appalachians Basin - South	1,696	846	50%	160	19%	316	37%	387	46%	285	34%
Appalachians Basin - West	2,061	836	41%	174	21%	399	48%	142	17%	337	40%
<b>Atlantic Coast</b>	<b>11,420</b>	<b>3,144</b>	<b>28%</b>	<b>1,212</b>	<b>39%</b>	<b>2,583</b>	<b>82%</b>	<b>325</b>	<b>10%</b>	<b>670</b>	<b>21%</b>
Atlantic Coast - North	6,056	1,905	31%	661	35%	1,585	83%	197	10%	336	18%
Atlantic Coast - South	5,364	1,239	23%	551	44%	998	81%	128	10%	334	27%
<b>Corn Belt</b>	<b>2,431</b>	<b>798</b>	<b>33%</b>	<b>78</b>	<b>10%</b>	<b>267</b>	<b>33%</b>	<b>487</b>	<b>61%</b>	<b>266</b>	<b>33%</b>
<b>Green Mountains Area</b>	<b>613</b>	<b>121</b>	<b>20%</b>	<b>8</b>	<b>7%</b>	<b>38</b>	<b>31%</b>	<b>30</b>	<b>25%</b>	<b>64</b>	<b>53%</b>
<b>Michigan Basin</b>	<b>3,370</b>	<b>1,198</b>	<b>36%</b>	<b>547</b>	<b>46%</b>	<b>628</b>	<b>52%</b>	<b>58</b>	<b>5%</b>	<b>583</b>	<b>49%</b>
<b>Basal Targets</b>	<b>9,058</b>	<b>3,027</b>	<b>33%</b>	<b>803</b>	<b>27%</b>	<b>1,536</b>	<b>51%</b>	<b>571</b>	<b>19%</b>	<b>903</b>	<b>30%</b>
Basal Targets - East	2,026	673	33%	76	11%	289	43%	75	11%	164	24%
Basal Targets - North	1,564	351	22%	90	26%	140	40%	32	9%	112	32%
Basal Targets - South	1,115	499	45%	43	9%	157	31%	151	30%	96	19%
Basal Targets - West	4,353	1,504	35%	594	39%	950	63%	313	21%	531	35%
<b>All MRCI</b>	<b>33,050</b>	<b>10,657</b>	<b>32%</b>	<b>3,033</b>	<b>28%</b>	<b>6,087</b>	<b>57%</b>	<b>2,134</b>	<b>20%</b>	<b>3,366</b>	<b>32%</b>

Source Region	No. of Tracts	Transportation		Housing		Pollution		Health	
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
<b>Appalachian Basin</b>	<b>6,158</b>	<b>642</b>	<b>27%</b>	<b>1,178</b>	<b>50%</b>	<b>1,018</b>	<b>43%</b>	<b>1,665</b>	<b>70%</b>
Appalachian Basin - North	2,401	127	18%	415	60%	269	39%	351	51%
Appalachians Basin - South	1,696	301	36%	254	30%	401	47%	675	80%
Appalachians Basin - West	2,061	214	26%	509	61%	348	42%	639	76%
<b>Atlantic Coast</b>	<b>11,420</b>	<b>1,461</b>	<b>46%</b>	<b>2,016</b>	<b>64%</b>	<b>1,606</b>	<b>51%</b>	<b>1,223</b>	<b>39%</b>
Atlantic Coast - North	6,056	1,008	53%	1,186	62%	929	49%	707	37%
Atlantic Coast - South	5,364	453	37%	830	67%	677	55%	516	42%
<b>Corn Belt</b>	<b>2,431</b>	<b>192</b>	<b>24%</b>	<b>366</b>	<b>46%</b>	<b>270</b>	<b>34%</b>	<b>457</b>	<b>57%</b>
<b>Green Mountains Area</b>	<b>613</b>	<b>17</b>	<b>14%</b>	<b>51</b>	<b>42%</b>	<b>32</b>	<b>26%</b>	<b>62</b>	<b>51%</b>
<b>Michigan Basin</b>	<b>3,370</b>	<b>405</b>	<b>34%</b>	<b>705</b>	<b>59%</b>	<b>352</b>	<b>29%</b>	<b>896</b>	<b>75%</b>
<b>Basal Targets</b>	<b>9,058</b>	<b>1,008</b>	<b>33%</b>	<b>1,648</b>	<b>54%</b>	<b>1,177</b>	<b>39%</b>	<b>1,743</b>	<b>58%</b>
Basal Targets - East	2,026	169	25%	361	54%	221	33%	480	71%
Basal Targets - North	1,564	95	27%	218	62%	133	38%	163	46%
Basal Targets - South	1,115	181	36%	153	31%	139	28%	356	71%
Basal Targets - West	4,353	563	37%	916	61%	684	45%	744	49%
<b>All MRCI</b>	<b>33,050</b>	<b>3,725</b>	<b>35%</b>	<b>5,964</b>	<b>56%</b>	<b>4,455</b>	<b>42%</b>	<b>6,046</b>	<b>57%</b>
Less than 20% of the Census Tracts are in the 65 <sup>th</sup> percentile of the United States for the indicator									
20%-30% of the Census Tracts considered disadvantaged are in the 65 <sup>th</sup> percentile of the United States for the indicator									
30%-40% of the Census Tracts considered disadvantaged are in the 65 <sup>th</sup> percentile of the United States for the indicator									
40%-50% of the Census Tracts are considered disadvantaged in the 65 <sup>th</sup> percentile of the United States for the indicator									
More than 50% of the Census Tracts considered disadvantaged are in the 65 <sup>th</sup> percentile of the United States for the indicator									

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Hawkins et al. (2023) provide an analysis of underserved communities in three of the areas selected for source/sink-transport studies (Figure 4-12; Table 4-7). The COBs where CCS might offer benefits, might potentially adversely affect, and where there is the potential to impact either positively or negatively are shown in Table 4-7. In addition, the impact of infrastructure development on disadvantaged communities was investigated by using information from the CEJST tool for the Michigan Basin Hub Scenario. The full Infrastructure Assessment Report (Battelle, 2024g) details this assessment and research organizations with interest in disadvantaged communities, minority populations, education, and several topics relevant in Bay City/Saginaw, Grand Rapids, Detroit, Monroe, and rural areas in Michigan were researched using a preliminary stakeholder mapping approach.

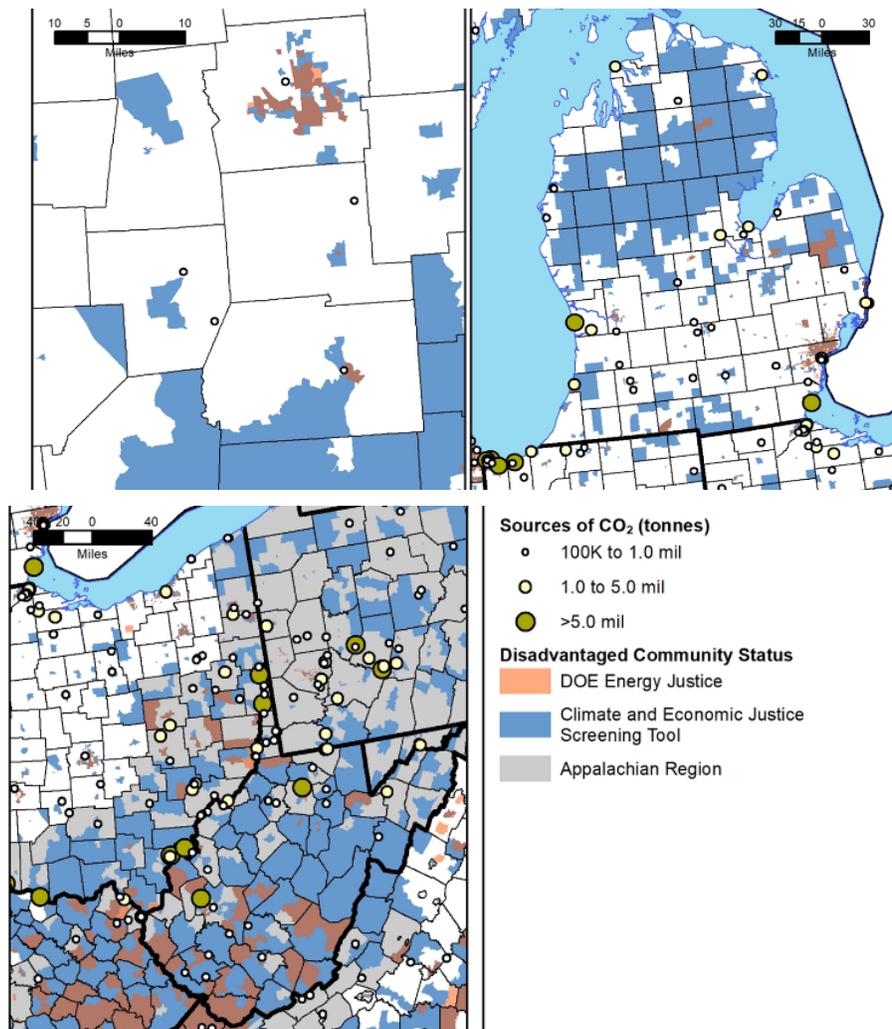


Figure 4-12. Disadvantaged community status for the local scenario in Central Ohio (top left), the hub scenario in the Michigan Basin (top right), and the distributed scenario in the Appalachian basin (bottom) (Data are from White House CEQ [2022]; DOE [2023]; and U.S. EPA (2022); maps are from Hawkins et al., 2023).

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**Table 4-7. Number of Disadvantaged Communities and exceedances of Categories of Burden for the Local, Hub, and Distributed Scenarios compared to all of MRCI (Data are from CEQ [2022]; table is from Hawkins et al., 2023).**

Scenario	No. Tract	Disadvantaged Communities		Climate Change		Energy		Health		Legacy Pollution	
Local	321	123	38%	5	1.6%	19	5.9%	99	31%	32	10%
Hub	3,060	1,106	36%	49	1.6%	575	19%	843	28%	313	10%
Distributed	2,581	1,013	39%	327	13%	359	14%	703	27%	374	14%
All MRCI	30,671	9,856	32%	1,783	5.8%	3,128	10%	5,515	18%	4,169	14%

Scenario	No. Tract	Disadvantaged Communities		Trans- portation		Water		Workforce Development		Housing	
Local	321	123	38%	31	10%	10	3.1%	72	22%	61	19%
Hub	3,060	1,106	36%	397	13%	529	17%	585	19%	656	21%
Distributed	2,581	1,013	39%	287	11%	145	5.6%	348	13%	422	16%
All MRCI	30,671	9,856	32%	3,421	11%	2,903	9.5%	5,835	19%	5,654	18%

Projects offer benefits to these categories. Well-designed projects are unlikely to negatively impact them.

Project could offer benefits to these categories. Poorly designed projects may negatively impact them.

Projects may negatively impact these categories. Well-designed projects will mitigate impacts and/or add benefits.

**CCS Jobs and Economic Impact Assessment:** This section details an analysis for a realistic, integrated project in the Appalachian Basin. A jobs and economic impact assessment was completed for the Tri-State Area of Eastern Ohio, Western Pennsylvania, and West Virginia. The eventual magnitude of regional benefits will depend on the number, type and location of CCS facilities, and the commensurate level of investment in planning, engineering, construction, and other associated project activities. This analysis estimates the potential magnitude of regional economic benefits associated with CCS project development in the Commonwealth of Pennsylvania based on two scenarios (Figure 4-13):

1. Construction and operation of a potential future storage network that includes six carbon CO<sub>2</sub> capture facilities (four natural gas-fired power plants and two natural gas processing facilities) with transport to four shared storage sites (Group A); and
2. The incremental addition of six additional capture facilities (hydrogen production facilities) to the existing Group A network (Group B).

These include direct employment (employment on project), indirect employment (employment of people providing goods and services for the project), and induced impacts (employment of people benefiting from the wages spent by direct and indirect workers).

The analysis uses hypothetical sources and storage locations that approximate the source types that currently exist (e.g., natural gas power plants and natural gas processing plants) and may exist in the future (e.g., hydrogen production plants) connected to hypothetical sink locations where government-funded modeling studies and pilot-scale studies have been conducted. This allows the project team to control the realistic parameters of the scenarios, simplifying the assumptions for capture and storage conditions. There is also the benefit of not mentioning specific sources or sinks, which might lead to confusion of residents that would be impacted by what is only a hypothetical scenario.

The project team used IMPLAN, a standard input-output model, to estimate the economic and employment impacts based on demand changes (e.g., project expenditure data) for this analysis. IMPLAN relies on anticipated project expenditure data. To generate these data, information (as relevant to each scenario) was reviewed and data modeled regarding potential future costs related to the permitting, construction, operation, and ultimate closure of facilities involved with the capture, transportation, and subsurface storage of CO<sub>2</sub> in Pennsylvania. Data were collected by operational phase (i.e., pre-injection, injection, and post-injection) as well as

#### 4.0 Evaluating Regional Infrastructure (Task 4)

by CCS category (i.e., capture, transportation, and storage). Primarily, modeled case study cost estimates developed by the DOE NETL were relied upon together with Battelle-developed estimates of storage cost based on internal engineering experience (Bureau of Economic Analysis, 2022).

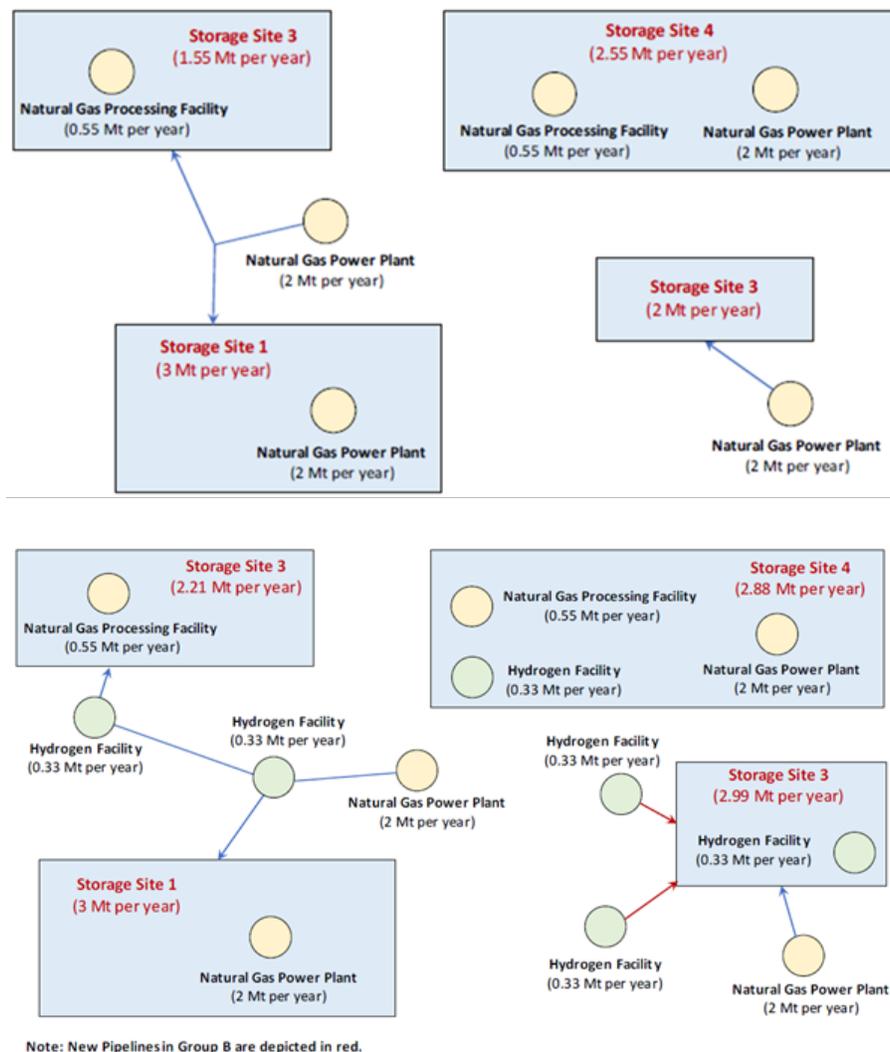


Figure 4-13. Layout of capture facilities, pipeline, and storage site for Group A scenario (top) Group B scenario (bottom) in Pennsylvania.

**Group A Results:** Table 4-8 summarizes the total regional economic impacts estimated for expenditures related to the Group A scenario, aggregated by phase (pre-injection, injection, post-injection) and by stage (capture, transport, storage).

Results are provided for the total phase time period as well as annually. Four categories of impacts are presented: employment, labor income, value added, and output.

- Total regional economic impacts estimated for Group A-related expenditures in all phases are estimated to be \$8.8 billion on output (sales) over approximately 53 years, or approximately \$161.2 million on average annually. Employment demand is estimated to increase by 46,400 jobs over the course of the project, or 900 jobs on average annually.

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- Regional economic impacts associated with expenditures in the pre-injection (planning and construction) phase on output are estimated to be \$5.2 billion over approximately three years, or \$1.7 billion annually. Employment impacts are estimated to be highest in this phase (planning and construction), with an estimated increase in employment demand of 8,600 jobs per year over approximately three years.
- Regional economic impacts associated with expenditures in the injection (operations) phase on output are estimated to be \$3.5 billion over 25 years, or \$141.5 million annually. Employment demand is estimated to increase by 800 jobs per year over this 25-year period.
- Regional economic impacts estimated for expenditures in the post-injection phase on output are estimated to be \$120.1 million over approximately six years, or \$4.8 million annually. Employment demand is estimated to increase by 20 jobs per year over approximately 25 years.

**Table 4-8. Regional Economic Impacts of Group A (53 years).**

Category	Employment	Labor Income	Value Added	Output
<b>Pre-Injection Phase (3 Years)</b>				
Storage	2,900	\$251.3 million	\$462.3 million	\$784.1 million
Transportation	2,300	\$172.2 million	\$218.5 million	\$419.0 million
Capture	20,700	\$1,600 million	\$2,400 million	\$3,900 million
<b>Total Effect of Pre-injection Phase</b>	<b>25,800</b>	<b>\$2,000 million</b>	<b>\$3,100 million</b>	<b>\$5,200 million</b>
<b>Injection Phase (25 Years)</b>				
Storage	1,300	\$115.8 million	\$188.0 million	\$325.3 million
Transportation	600	\$113.8 million	\$161.2 million	\$240.0 million
Capture	18,100	\$1,100 million	\$1,600 million	\$3,000 million
<b>Total Effect of Injection Phase</b>	<b>20,000</b>	<b>\$1,400 million</b>	<b>\$1,900 million</b>	<b>\$3,500 million</b>
<b>Post-Injection Phase (25 Years)</b>				
Storage	600	\$48.5 million	\$70.1 million	\$120.1 million
<b>Total Effect of Post-Injection Phase</b>	<b>600</b>	<b>\$48.5 million</b>	<b>\$70.1 million</b>	<b>\$120.1 million</b>
<b>Total, All Phases (53 years)</b>				
Pre-Injection phase (~3 years)	25,800	\$2,000 million	\$3,100 million	\$5,200 million
Injection phase (25 years)	20,000	\$1,400 million	\$1,900 million	\$3,500 million
Post-Injection phase (~25 years)	600	\$48.5 million	\$70.1 million	\$120.1 million
<b>Total Effect, All Phases (~53 years)</b>	<b>46,400</b>	<b>\$3,500 million</b>	<b>\$5,000 million</b>	<b>\$8,800 million</b>
<b>Total, Average Annual</b>				
Pre-Injection phase (3-yr average)	8,600	\$676.2 million	\$1,000 billion	\$1,700 billion
Injection phase (25-yr average)	800	\$55.0 million	\$76.1 million	\$141.5 million
Post-Injection phase (25-yr average)	20	\$1.9 million	\$2.8 million	\$4.8 million
<b>Total (53-yr average)</b>	<b>900</b>	<b>\$65.2 million</b>	<b>\$94.9 million</b>	<b>\$166.2 million</b>

*Group B Results:* Table 4-9 summarizes the total regional economic impacts estimated for expenditures related to Group B, aggregated by phase (pre-injection, injection, post-injection) and by stage (capture, transport, storage).

Results are provided for the total phase time period as well as annually. Four categories of impacts are presented: employment, labor income, value added, and output.

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- Total regional economic impacts estimated for Group B-related expenditures in all phases are estimated to be \$1.9 billion on output (sales) over approximately 48 years, or approximately \$40.2 million on average annually. Employment demand is estimated to increase by 7,800 jobs over the course of the project, or 160 jobs on average annually.
- Regional economic impacts associated with expenditures in the pre-injection (planning and construction) phase on output are estimated to be \$390.3 million over approximately three years, or \$130.1 million annually. Employment impacts are estimated to be highest in this phase, with an estimated increase in employment demand of 700 jobs per year over approximately three years.
- Regional economic impacts associated with expenditures in the injection (operations) phase on output are estimated to be \$1.5 billion over 20 years, or \$76.8 million annually. Employment demand is estimated to increase by 300 jobs per year over this 20-year period.
- Regional economic impacts estimated for expenditures in the post-injection phase on output are estimated to be \$2.2 million over approximately 25 years, or \$88.8 thousand annually. Employment demand is estimated to increase by less than one job per year over approximately 25 years.

*Jobs Assessment:* Different jobs are required to construct and operate each phase of an integrated CCS project. Jobs required to **construct the system** are in the following Bureau of Labor Statistics (BLS) major categories:

- General and Operations Managers BLS Standard Occupational Code [SOC]# 11-1021); Architecture and Engineering (SOC# 17-0000); and Life, Physical, and Social Scientists (SOC# 19-0000) to design, characterize, and permit the system.
- Production Occupations (SOC# 51-0000) to create materials used for the system and drill storage wells.
- Construction and Extraction (SOC# 47-0000) and Installation, Maintenance and Repair (SOC# 49-0000) to build the system.

Jobs required to **operate the system** are in the following BLS major categories:

- Managers (SOC# 11-0000) Architecture and engineering (SOC #17-0000) to oversee system operation.
- Production Occupations (SOC# 51-0000) to create materials used for the system and monitor storage operations (i.e., drilling services).
- Installation, Maintenance and Repair (SOC# 49-0000) to operate the system and execute repairs.

Jobs required to execute **post-injection site case (PISC) and site closure** are in the following BLS major categories:

- Managers (SOC# 11-0000) Architecture and Engineering (SOC# 17-0000) and Life, Physical, and Social Scientists (SOC# 19-0000) to oversee PISC and plume stabilization.
- Production Occupations (SOC# 51-0000) to create materials used for the system and monitor storage plume stabilization and plug and abandon wells (e.g., drilling services).

Current employment and wage statistics for the relevant jobs categories were researched using data from BLS (2024a, b) (Table 4-10). Currently around 3.6 million people work in relevant industries in the three states impacted by the conceptual project, equivalent to around 213, 190, and 212 workers per 1,000 workers in Ohio, Pennsylvania, and West Virginia, respectively. Many of these workers are currently employed in construction and extraction; installation,

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maintenance, and repair; and production occupations, which account for a combined 159, 137, and 163 workers per 1,000 workers in Ohio, Pennsylvania, and West Virginia, respectively.

**Table 4-9. Regional Economic Impacts of Group B (Addition of Hydrogen Facilities, 48 years).**

Category	Employment	Labor Income	Value Added	Output
<b>Pre-Injection Phase (3 Years)</b>				
Storage	200	\$20.1 million	\$38.2 million	\$64.4 million
Transportation	900	\$66.2 million	\$83.0 million	\$159.3 million
Capture	1,200	\$89.7 million	\$119.9 million	\$225.2 million
<b>Total Effect</b>	<b>2,300</b>	<b>\$176.0 million</b>	<b>\$241.1 million</b>	<b>\$448.9 million</b>
<b>Injection Phase (25 Years)</b>				
Storage	100	\$9.3 million	\$15.2 million	\$26.4 million
Transportation	200	\$37.3 million	\$46.1 million	\$60.0 million
Capture	5,500	\$488.6 million	\$773.8 million	\$1,500 million
<b>Total Effect</b>	<b>5,800</b>	<b>\$535.1 million</b>	<b>\$835.2 million</b>	<b>\$1,500 million</b>
<b>Post-Injection Phase (25 Years)</b>				
Storage	10	0.09 million	1.3 million	2.2 million
<b>Total Effect</b>	<b>10</b>	<b>0.09 million</b>	<b>1.3 million</b>	<b>2.2 million</b>
<b>Total, All Phases (53 years)</b>				
Pre-Injection (~3 years)	2,300	\$176.0 million	\$241.1 million	\$448.9 million
Injection (20 years)	5,800	\$535.1 million	\$835.2 million	\$1,500 million
Post-Injection (~25 years)	10	\$0.09 million	\$1.3 million	\$2.2 million
<b>Total Effect</b>	<b>8,000</b>	<b>\$712.0 million</b>	<b>\$1,100 million</b>	<b>\$2,000 million</b>
<b>Total, Average Annual</b>				
Pre-Injection phase (3-yr average)	800	\$58.7 million	\$80.4 million	\$149.6 million
Injection phase (20-yr average)	300	\$26.8 million	\$41.8 million	\$76.8 million
Post-Injection phase (25-yr average)	<1	\$0.04 million	\$0.05 million	\$0.09 million
<b>Total (48-yr average)</b>	<b>170</b>	<b>\$14.8 million</b>	<b>\$22.4 million</b>	<b>\$41.4 million</b>

**Table 4-10. Broad Occupational Categories required to construct, operate, and decommission an integrated CCS project. Data are from BLS (2024a, b).**

Jobs Codes	Occupation Title	Employment (value)				Employment (per 1000) <sup>1</sup>		
		Ohio	Pennsylvania	West Virginia	USA	Ohio	Pennsylvania	West Virginia
00-0000	All Occupations	5,469,160	5,948,490	688,670	151,853,870	1000	1000	1000
11-1021	General and Operations Managers	143,080	145,770	14,950	3,507,810	26.161	24.505	21.707
17-0000	Architecture and Engineering Occ.	99,620	96,850	9,290	2,539,660	18.215	16.281	13.492
19-0000	Life, Physical, and Social Science Occ.	36,780	49,480	6,760	1,389,430	6.724	8.318	9.814
47-0000	Construction and Extraction Occ.	185,300	216,770	41,570	6,225,630	33.881	36.442	60.363
49-0000	Installation, Maintenance, and Repair Occ.	217,230	229,810	35,910	5,989,460	39.719	38.633	52.145
51-0000	Production Occupations	465,360	369,130	34,460	8,770,170	85.088	62.054	50.035
	<i>Total of Relevant Job categories</i>	<i>1,693,790</i>	<i>1,701,290</i>	<i>199,920</i>	<i>42,174,920</i>	<i>213</i>	<i>190</i>	<i>212</i>

Jobs Codes	Occupation Title	Mean Hourly Wage (\$/hr)				Mean Annual Wage (\$/yr)			
		Ohio	Pennsylvania	West Virginia	USA	Ohio	Pennsylvania	West Virginia	USA
00-0000	All Occupations	\$28.79	\$29.77	\$25.10	\$31.48	\$59,890	\$61,920	\$52,200	\$65,470
11-1021	General and Operations Managers	\$55.75	\$58.47	\$45.26	\$62.18	\$115,950	\$121,610	\$94,150	\$129,330
17-0000	Architecture and Engineering Occ.	\$44.38	\$44.69	\$41.34	\$47.64	\$92,310	\$92,950	\$85,980	\$99,090
19-0000	Life, Physical, and Social Science Occ.	\$38.08	\$39.53	\$34.01	\$42.24	\$79,200	\$82,210	\$70,740	\$87,870
47-0000	Construction and Extraction Occ.	\$29.34	\$29.72	\$26.80	\$29.57	\$61,020	\$61,810	\$55,740	\$61,500
49-0000	Installation, Maintenance, and Repair Occ.	\$26.93	\$27.50	\$24.86	\$28.13	\$56,020	\$57,200	\$51,710	\$58,500
51-0000	Production Occupations	\$22.24	\$23.13	\$22.23	\$22.90	\$46,250	\$48,120	\$46,230	\$47,620

Note: 1. Not calculated for USA.

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Average wages for many of the jobs required to plan and construct the system are higher than the average of all occupations (Table 4-10). For example, the hourly wages of general and operations managers, engineers, scientists, and construction and extraction workers are higher than the average of all occupations in most of the states impacted by the conceptual project. While the average wages of installation, maintenance, and repair workers; production workers; and transportation and materials moving workers are lower than the average wages of all occupations, relevant minor categories and individual broad and detailed occupations within the major category have higher wages. For instance, the average hourly wages of industrial machinery mechanics (SOC# 49-9041), who will be needed for installation and maintenance of capture systems, is between \$27.88 and \$30.25 an hour in the relevant states, more than 10% higher than the equivalent installation, maintenance, and repair occupational category. Because production occupations include many different skilled and unskilled occupations, the difference can be even greater. For instance, the average wage for Petroleum Pump System Operators, Refinery Operators, and Gaugers (51-8093) (the job category that include pipeline operators) is \$44.42 an hour (nearly double the average wage for the category), \$38.08 an hour (more than 70% higher than the average wage for the category), and \$31.86 (more than 40% higher than the average wage for the category) an hour for Ohio, Pennsylvania, and West Virginia, respectively.

While this analysis can be used to frame the expected benefits for an integrated CCS system, additional work must be completed on a project-specific basis. For instance, a detailed analysis of expected employment; the expected wages; requirements for education, training, and experience; and educational programs could help attract new workers and recruit existing workers to work on the project. Information about expected employment and wages and benefits could only be provided by project owners. Programs like MRCI and the other RIs, however, can help connect these project leaders to relevant training institutions and worker organizations and provide support for public outreach related to CCS projects.

Additional information and details about the jobs and economic impact analysis are available in the full Infrastructure Assessment report (Battelle, 2024g).

#### 4.5 Policy and Regulatory Analysis

Each state in the MRCI region has either developed carbon reduction goals or passed legislation encouraging CCS. As a part of the US Climate Alliance, 16 of the MRCI states have created climate action plans (Table 4-11) to set specific carbon reduction targets and implementation timelines. These initiatives are designed to increase energy efficiency, renewable energy generation, electric vehicles usage, climate finance, climate change resilience, and environmental conservation. Aside from terrestrial carbon sequestration, CCS is not included in the climate action plans of any of the MRCI states. Integration of CCS into their larger climate action plans, particularly regarding the various carbon reduction goals established throughout the region, presents a potentially attractive option for MRCI states. The climate action plans in each MRCI state are summarized in the full Infrastructure Assessment Report (Battelle, 2024g).

To encourage the inception of large commercial-scale storage projects in the region, MRCI states will need to pass new legislation designed specifically to address issues related to CCS. This includes the following issues elaborated below:

- **Pore Space Ownership:** Codified laws denoting ownership of pore space and methods to transfer pore space titles.

#### 4.0 Evaluating Regional Infrastructure (Task 4)

- **State Regulations and primacy for CO<sub>2</sub> injection:** Defined regulators for all project activities, CO<sub>2</sub> storage declared to be in public interest, and integrated resource plans.
- **Financing Options:** Include financing options (grants or low-interest loans), incentives for electric utilities (offtake agreements, utility cost recovery mechanisms, eligibility of CCS in clean portfolio standards), incentives for electric power and industrial sources (private activity bonds, low-carbon credit programs, and procurement programs), and tax credits.
- **Pore Space Unitization:** A defined process for aggregating project pore space based on the buy-in of a specific amount of pore space owners.
- **CO<sub>2</sub> Pipeline Routing:** Qualify CO<sub>2</sub> transport as pollution control devices, define and streamline the pipeline siting process, and qualify CO<sub>2</sub> pipelines for eminent domain.
- **Long-term CO<sub>2</sub> Ownership, responsibility, and trust funds:** Establishing CO<sub>2</sub> storage trust funds, defining rules for CO<sub>2</sub> ownership, and CO<sub>2</sub> responsibility. Also include long-term liability.

Updated CCS regulations and policy are outlined in the full Infrastructure Assessment report (Battelle, 2024g) and summarized in Table 4-12.

**Table 4-11. Table summarizing the adoption of Climate Action Plans and CCS legislation in the MRCI Region.**

State	Climate Action Plan	Enacted CCS Legislation
Connecticut	Yes	No
Delaware	Yes	No
Illinois	Yes	Yes
Indiana	No	Yes
Iowa	Yes	Yes
Kentucky	Yes	Yes
Maine	Yes	No
Maryland	Yes	No
Massachusetts	Yes	No
Michigan	Yes	Yes
Missouri	Yes	No
New Hampshire	Yes	No
New Jersey	Yes	No
New York	Yes	Yes
Ohio	Yes	Yes
Pennsylvania	Yes	Yes
Rhode Island	Yes	No
Vermont	Yes	No
West Virginia	Yes	Yes
Wisconsin	Yes	No

**Table 4-12. Summary of regulations affecting CCS in the MRCI area (from CDR Law [2024] unless otherwise noted). MRCI states not listed do not have applicable CCS regulations.**

State	Pore Space Ownership	State Regulations	Financing <sup>a</sup>	Pore Space Unitization	CO <sub>2</sub> Pipeline Routing	Long-Term Ownership, Trusts
Illinois	Yes	Yes	Yes	Yes	Yes	Yes
Indiana	Yes	No	Yes	Yes	Yes	Yes
Iowa	No	No	Yes	No	No	No
Kentucky	Yes	No	Yes	Yes	No	Yes
Michigan	No	Yes <sup>b,d</sup>	Yes	No	Yes <sup>a</sup>	No
New York	No	Yes	Yes	No	No	No
Ohio	No	Yes	Yes	No	No	No
Pennsylvania	Yes	Yes <sup>c,d</sup>	No	Yes	Yes <sup>e</sup>	Yes
West Virginia	Yes	Yes <sup>d</sup>	No	Yes	No	Yes

## 4.0 Evaluating Regional Infrastructure (Task 4)

Notes: a. Not tracked by Columbia Law School and Arnold & Palmer (2024); b. Personal communication, Haagsma (2023); c. Personal communication K. Carter (2023); d. Indicates state has taken steps toward achieving Class VI primacy.

**Class VI Dataset:** Publicly available permit applications offer a special opportunity to better understand the developing CCS projects around the nation and the variability between the project parameters within each basin. Battelle has compiled publicly available information from 80 UIC Class VI permit applications submitted to the U.S. EPA and equivalent agencies in states with primacy (current as of July 2024) (herein referred to as the compiled Class VI application dataset). Publicly available information in UIC Class VI applications was used to determine several issues:

- **Location:** For example, the geologic basin, state, and county of the project.
- **Injection protocol:** For example, the number of injection wells, and the mass and rate of injection.
- **Geologic conditions:** For instance, the name, depth, thickness, depositional environments, porosity, permeability, and fracture gradient of reservoir and caprock formations and initial characterization approach.
- **Monitoring plan:** For example, the number of monitoring wells, monitoring approach, and timing.

The goal of this study is to understand how projects within geologic basins that are relevant to CCS gather geocharacterization data, establish project designs, and decide monitoring configurations based on the unique geology, legacy data, and surface conditions within each basin. General project parameters of each project application have been documented, and three case studies were chosen to highlight the nuances of carbon storage project configurations and monitoring approaches.

This analysis includes that 80 projects with UIC Class VI applications submitted to the U.S. EPA or equivalent agencies in states with Class VI primacy. Since some data in the Class VI application are considered proprietary, some data were not available for every parameter analyzed for each project. The projects included in the dataset are shown in Figure 4-14, including the project cumulative CO<sub>2</sub> injection rates and geologic basin. The total mass injected in each basin is also showed as well as current and past DOE-funded CCS projects and the four onshore Regional Carbon Initiatives are also highlighted. The dataset was used to analyze the following factors within several geologic basins: geologic depths and thicknesses of the subsurface components (USDWs, caprocks, and storage reservoirs), their project parameters (number of injection wells and monitoring wells, and their testing and monitoring plan, which ensures long-term retention of CO<sub>2</sub>).

#### 4.0 Evaluating Regional Infrastructure (Task 4)

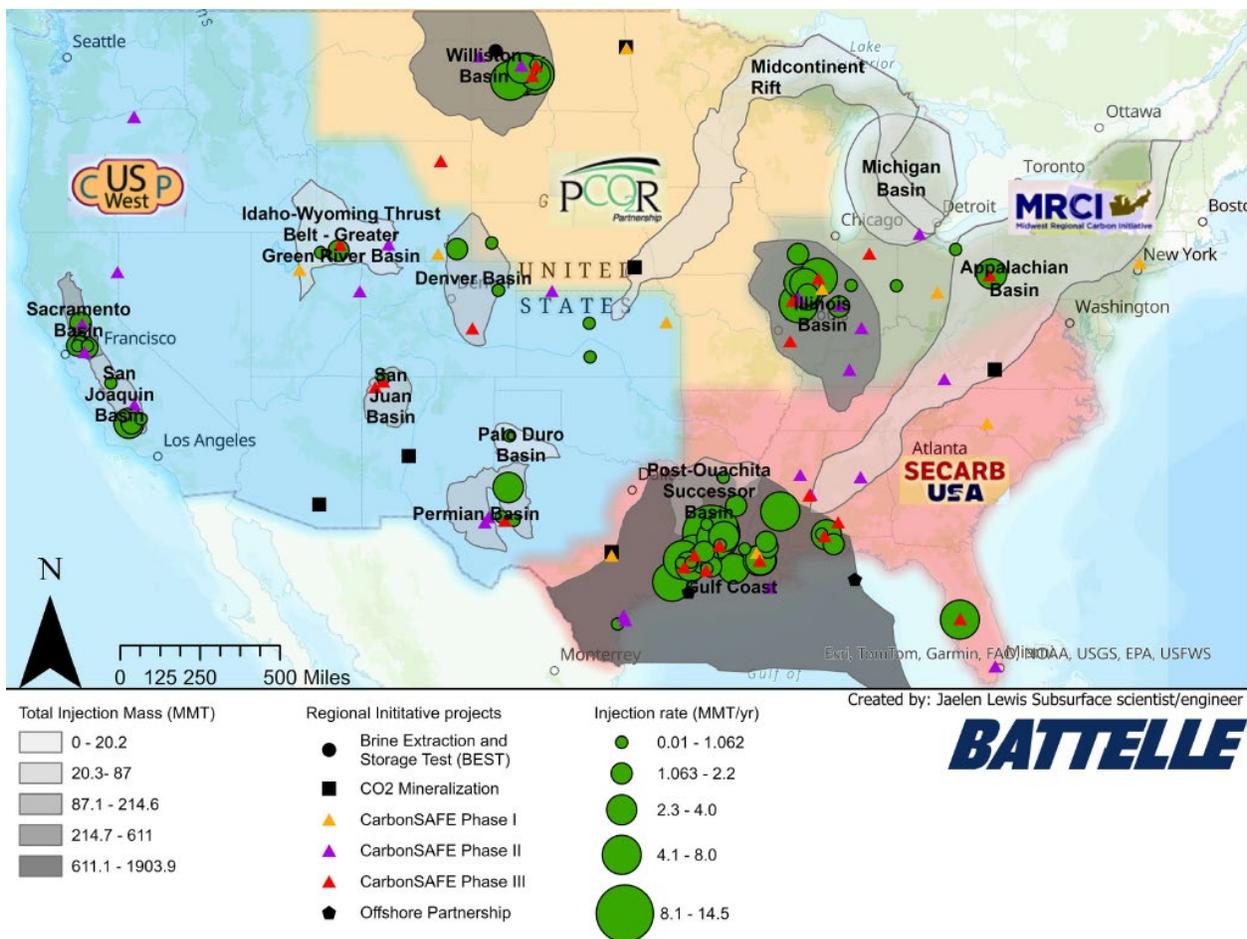


Figure 4-14. Overview of Class VI applications, their injections rates, and projects funded by the DOE by basin (current as of July 2024).

#### 4.6 Summary and Conclusions from Infrastructure Assessment

Researching the infrastructure of CCS is more than just the physical equipment that enables CCUS; it also includes the policy, economics, and people that make CCS work. The MRCI team advanced the understanding of infrastructure for CCS in the study area in four separate areas: Infrastructure readiness; site readiness; jobs, economics, and social characteristics; and policy and regulations. Infrastructure Readiness was evaluated by investigating the existing sources in the study area, modeling source/sink/transport scenarios for each study region, investigating the impact to high consequence areas and other sensitive areas, describing a pipeline routing philosophy, and developing an infrastructure security evaluation process. Site Readiness was evaluated using a qualitative assessment of the advancement of the site in the categories of geology, infrastructure, social issues, and policy. This process was demonstrated for three sites and readiness factsheets were generated for select states. Jobs and economic impacts were demonstrated using a realistic hypothetical scenario for natural gas power and blue hydrogen development in the tri-state area of Pennsylvania. The project team also evaluated DOE and CEQ tools that measure social data to determine the potential impacts of CCS projects on communities in the MRCI study area. Finally, state level policy enabling CCS (e.g., pore space access and unitization, long term liability, financing, CO<sub>2</sub> transport, and state primacy of UIC

#### 4.0 Evaluating Regional Infrastructure (Task 4)

Class VI) was also investigated. The Infrastructure Assessment task provides a basis to evaluate these aspects impacting CCS infrastructure development for projects within the MRCI study area.

## 5.0 Promoting Regional Tech Transfer (Task 5)

### 5.1 Technology Transfer Strategy

The goal of the MRCI Task 5 – Promoting Regional Technology Transfer is to leverage existing and new relationships with critical CCUS stakeholders (including state geological surveys, universities, industrial partners and advisors, fossil fuel production and utilization companies, and NGOs) within the regional initiative and globally and become a key resource for CCUS information, acceptance, and development. Work completed under Task 5 is categorized through four actions:

- Promote acceleration of CCUS deployment by providing general support for commercialization and technology transfer
- Compile and communicate information from previous tasks to interested stakeholders
- Engage with federal and state governments, industry consortia and NGOs
- Engage with global institutions

The approach taken by the Task 5 team to accomplish these four actions was the Three Phase Communications Plan, which are **Planning, Action, Maintain/Sustain**. This three-pronged approach to the MRCI communications strategy (described in detail below) was developed to ensure that the team took a measured and tactical approach to the outreach effort. By staging the steps taken to conduct this work, we ensured that necessary materials were created and in place to support any actions that took place relative to stakeholder outreach, making certain that messaging was clear and consistent across all platforms and coordinated with the messaging from the DOE.

### 5.2 Phase 1: Planning

The goal of this phase was to prepare materials/resources, initiate strategies, and make contacts that will support the CCUS campaign to come. During the Planning phase, the Task 5 team conducted research that provided the groundwork for the campaign that we initiated in the latter part of the Initiative. The team set up a website (<https://www.midwestccus.org/>), created a bi-monthly newsletter (<https://www.midwestccus.org/home/news/newsletters/>), mapped out stakeholders, and developed supporting collateral materials to facilitate outreach and engagement efforts (see Figure 5-1). Additionally, the planning phase involved the team's approach to Environmental Justice and offered support to stakeholders and partners for preparing Community Benefits Plans (CBP) for their projects.

These materials and approaches have been extensively utilized in support of other federally funded and commercial projects within the MRCI's 20-state region and beyond, including the ARCH2 Hydrogen Hub, the Central Appalachian Partnership, the Project Cypress DAC Hub, and the Southeast Michigan CarbonSAFE, among others external to Battelle projects/partners including CarbonVert and DTE Energy.

## 5.0 Promoting Regional Tech Transfer (Task 5)



Figure 5-1. Collateral materials created during the MRCI Planning Phase

### 5.3 Phase 2: Action

The goal of this phase was to take the information created/knowledge gained and actively reach out into targeted audiences with dedicated messaging about CCUS. During the Action phase, the Task 5 team ensured that we were well-prepared when engaging with our audiences. These tactics included:

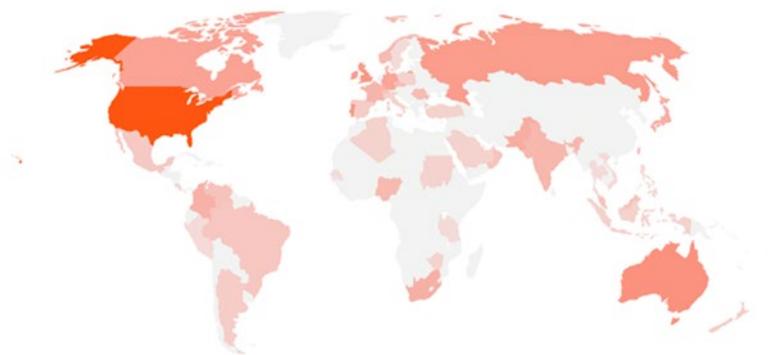
1. Presenting/Attending over 26 conferences and meetings that facilitated knowledge sharing and collaboration with industry and academic partners, like AAPG, GHGT18 and 18, and the annual NETL project review meetings (see Figure 5-2).
2. Creating an MRCI podcast that reached a global audience, averaging 177 plays per episode, and featured discussions on sustainability, carbon storage, and international CCUS projects. See distribution of listeners on world map in Figure 5-3.
3. Engaging government officials to discuss CCUS as a climate policy component, including the Ohio Legislature and Department of Energy Secretary Jennifer Granholm (see Figure 5-4)
4. Participating in public outreach events, showcasing CCUS concepts through interactive displays and demonstrations that aimed to educate the public and increase acceptance of CCUS technologies (see Figure 5-5).

## 5.0 Promoting Regional Tech Transfer (Task 5)

5. Providing educational materials for and staffing events to inform attendees about CCS, including the Center of Science and Industry annual science festival and community open houses.
6. Developing hands-on demonstration tools to illustrate CCS concepts, including build-your-own rock kits and the bicycle pump display (see Figure 5-5).
7. Developing and executing CCUS Seminars, providing insights into the energy transition and inspired participants to explore opportunities in carbon capture and storage.
8. Supporting STEM education aiming to inspire the next generation of scientists and engineers in the field of carbon management.



*Figure 5-2. MRCI Conference Presentation photos Sanjay Mawalkar (top left) and Autumn Haagsma (top middle) present at AAGP CCUS 2022. Devin Dickson (top right), Jared Hawkins (bottom left), and Joel Sminchak (bottom middle) present at Battelle's Innovations in Climate Conference 2022. Stuart Skopec (bottom right) presents at SEG/AAGP Image 2022.*



*Figure 5-3. Global listeners of the eGeos/MRCI Podcast*

## 5.0 Promoting Regional Tech Transfer (Task 5)



Figure 5-4. Presentations to government officials. (Top left) MRCI former co-Principal Investigator Sallie Greenberg (middle) leads US Secretary of Energy Jennifer Granholm on a tour of a CCS facility at the University of Illinois; (Top right) MRCI co-Principal Investigator Neeraj Gupta (left) participates in a panel discussion at a Department of Energy workshop on regional carbon management applicant education; (Bottom left) Battelle Energy and Resilience Division Manager Shawn Bennett testifies to the Ohio House on the importance of CCS to support a Hydrogen economy in the state; (Bottom right) Gupta testifies before the Ohio House Energy and Natural Resources Committee on the need for CCS in Appalachia in support of Hydrogen energy.



Figure 5-5 2024 Science Festival outreach (left) Battelle Program Manager Marlon McKoy talks a display visitor through the concepts of rock porosity and permeability using the cap rock and reservoir rock bicycle pump demonstrator; (right) Battelle Outreach and Engagement Specialist Ivan Wehner shows a young visitor and her grown-up how water sprayed on sandstone sinks into the stone, much like supercritical CO<sub>2</sub> does when injected into a sandstone reservoir.

### 5.4 Phase 3: Maintain/Sustain

The goals of this phase is to ensure that all materials created are current with the science and messages of the campaign; leaders in communities targeted for CCUS projects are actively aware of and working in partnership with Initiative team-members to ensure community

## 5.0 Promoting Regional Tech Transfer (Task 5)

stakeholders are informed and their concerns are addressed; and relationships with our state geological surveys, academic institutions, and industry partners are nurtured to ensure project success. During the Maintain/Sustain phase, the Task 5 team continued outreach to support our efforts while building and nurturing relationships in target stakeholder groups. Information updates were shared with our target audiences to ensure they remained sustainably informed and educated.

Part of Task 5's knowledge sharing strategy took place through virtual and social media avenues, such as hosting a project website dedicated to informing partners and stakeholders on recent events in the 20-state region. Through the website, the Team promoted workshops and webinars, published 10 newsletters covering legislative activities, project spotlights, and learning opportunities (also emailed to the ~800 contacts on the MRCI mailing list), and hosted a database which includes over 750 research pieces from the MGSC and MRCSP projects.

Additionally, the MRCI also hosted a series of Annual Partner and Stakeholder meetings after its two initial virtual meetings held in February and November 2021. These three in-person meetings, hosted in September 2022 (Figure 5-6), October 2023, and September 2024, were multi-day, information-filled events that consisted of expert speakers with backgrounds in government, industry, and academia who presented on topics important to carbon capture utilization and storage. These meetings also included workshops, where attendees could focus on important topics such as Community Benefits Plans (CBP), Storage Resource Management Systems (SRMS), and the Hydrogen economy that provided attendees with practical insights.



*Figure 5-6. 2022 MRCI Partners and Stakeholders meeting in Columbus, OH (Left) Over 150 guests from across the MRCI region and beyond participated in the 2022 MRCI Partners and Stakeholders meeting. (Middle) The Geologic Survey Teams meeting brought together geo-scientists from across the region to discuss research and issues related to CCUS in the MRCI. (Right) The Stakeholder Engagement and Environmental Justice workshop required a high level of participation from attendees to foster their learning of the subject matter.*

Finally, the outreach team developed a branded fact sheet, titled “What is CCS?” that is scientifically accurate and provides crucial CCS information written in plain language so that it can be used for multiple audiences without a science background. Because the first fact sheet received such a warm welcome in the industry and beyond, Battelle intends to create additional fact sheets in future projects.

## 5.5 Conclusions from Regional Tech Transfer

With the end of the MRCI program, it is important to note that while industry-wide understanding of CCUS is steadily growing, public awareness has not yet caught up. When not addressed properly, gaps in knowledge can grow into opposition to CCUS projects. The MRCI's work has

## 5.0 Promoting Regional Tech Transfer (Task 5)

begun to address these issues, and the team remains committed to community engagement and stakeholder outreach to continue educating and informing the public about CCUS.

Significant progress was made in enhancing public understanding of CCUS through MRCI, and these sorts of activities and initiatives must continue. These include public-private partnerships to align outreach strategies, creating educational materials for the classroom, persistent messaging through media, providing community support for CarbonSAFE projects, and piloting environmental justice engagement strategies with communities.

Much has happened globally since the MRCI began that catapulted CCUS into the spotlight. What we learned was that scientists, companies, and government teams across the country, and world, are getting closer every day to seeing CCS fully executed as a carbon mitigation tactic. And with that comes the need to be sure that all of those who have an interest in it moving forward – including those who study it, execute it, mandate it, and live with it in their communities – have the information needed to make informed decisions.

## 6.0 Summary and Outlook on CO<sub>2</sub> Storage in MRCI Region

After five years of collaboration between Battelle and the team members, the MRCI has completed all the stated objectives of the Program, consisting of:

- Addressing Key Technical Challenges
- Facilitating Data Collection, Sharing, and Analysis
- Evaluating Regional Infrastructure
- Promoting Regional Tech Transfer

A summary of these activities and their key outcomes in terms of products useable for future CCUS deployment in the region is provided in the preceding sections. Significantly more detailed information on each task is included in the accompanying task reports submitted to the DOE OSTI system. MRCI program will now be transitioning to follow-on regional initiative efforts supported by the DOE, including the RITAP programs. This will provide continuity of regional collaboration and community assistance on a sub-regional scale. The progress will also continue under several CarbonSAFE projects, CCUS demonstrations, and private endeavours.

The midwestern and northeastern quadrants of the United States, spanning about 20 states, is experiencing a major spurt of growth in the development and deployment of CCS. The region, subject to CCS research and pilot-scale demonstrations since mid-1990s is fast transitioning into multiple CCS project clusters. Several factors make this diverse region a good microcosm for large-scale development of CCS and a precursor to how CCS will evolve globally over next several decades, beyond the initial “low-hanging fruit”. As can be deduced from the preceding chapters and accompanying reports for MRCI, there are many opportunities fostering the ongoing commercial scale deployment and pertinent challenges which could derail the momentum.

The MRCI region has long been the Industrial Heartland of the country accounting for over 900 million tonnes of CO<sub>2</sub> annually in recent years. Many of these sources, which include industry, manufacturing, and electric power plants, are hard to decarbonize and need additional solutions in a carbon-constrained future. The Northeastern Quadrant of MRCI region also is home to New England, which has some of the strictest carbon reduction goals in the US; however, much of their CO<sub>2</sub> emissions are from non-point sources, particularly the transportation sector. Finally, the area features several storage prospects, including onshore saline in three major basins, depleted oil and gas fields, unconventional shale resources, basalt rift basins, and offshore saline reservoirs. The potential and progress in this region are spurred in large part from the US federal investments under the Inflation Reduction Act, which expanded the 45Q tax credits, and the Bipartisan Infrastructure Law, which includes more than \$20 billion to support CCS deployment.

**Foundation for CCS in the Region** – CCS research in the region started as early as mid-1990s, with initial techno-economic analyses aimed at CO<sub>2</sub> storage in the Mt. Simon Sandstone. Beginning in early 2000s, there was a major growth based on the US Department of Energy funded Midwest Regional Carbon Sequestration Partnership and Midwest Geological Storage Consortium. These Partnerships conducted mapping of CO<sub>2</sub> resources, assessed stakeholder outreach strategies, and evaluated infrastructure scenarios. Most importantly, they conducted several small and large-scale pilots in the Illinois, Michigan, and Appalachian Basins, in diverse geologic settings ranging up to a million tonnes (at ADM ethanol plant in Illinois). The region also saw successful pilot testing of CO<sub>2</sub> capture and storage at the AEP Mountaineer Plant in

## 6.0 Summary and Outlook on CO<sub>2</sub> Storage in MRCI Region

West Virginia and completion of several Class V injection well permits and Class VI permits for ADM and FutureGen Sites. Starting in 2020, the MRCI, formed with the combination of MRCSP and MGSC, has fostered CCS deployment in the region. The MRCI has aimed to advance and derisk CCS by addressing key technical challenges, facilitating regional infrastructure planning, performing regional data and technology transfer, and engaging stakeholders.

All these research and pilot field programs, conducted with safe outcomes, boosted stakeholder confidence and industrial acceptance of technical viability of CO<sub>2</sub> storage for emission reduction, even if the business cases were not yet conducive to deployment. The rich technical foundation also identified uncertainties and disparate distribution of storage resources beyond the established Mt. Simon Sandstone corridor, especially the need for more characterization of deeper mature sedimentary basins, which are dominated by dense carbonates and shales. The Mt. Simon Sandstone in the Illinois Basin is a world class reservoir with proven capacity; however, additional reservoirs like the Cambro-Ordovician carbonates and saline reservoirs of the Mid-Atlantic Offshore need more characterization to move from prospective storage resources to proven capacity. In a similar vein, integrated subsurface management is required to effectively utilize the pore space in these reservoirs while planning and mitigating potential project interference issues.

**Emerging Commercial Deployment** – Numerous ethanol plants with high purity CO<sub>2</sub>, are the first movers for CCS deployment in the region even without the DOE funding due to investor interest. Most initial projects have focused on sub-million tonne scale storage at/near the source or in the centralized hubs supplied by pipeline networks. However, plans for regional pipelines have run into significant challenges due to insufficient regulation and local public opposition, resulting in cancellation of at least one major project. The region is home to about 10 projects across seven states under the DOE funded CarbonSAFE Initiative that began in 2016 with the goal of addressing the key gaps on the critical path towards CCS deployment. With more than \$300M in combined budget for feasibility studies and detailed characterization leading up permitting of the facilities and financial decisions, these projects represent CO<sub>2</sub> sourced from ethanol, industrial (steel, cement, refining, hydrogen), and power generation sources. Finally, the region has been selected for multiple DACCS projects and three major clean hydrogen hubs, including ARCH2 in Appalachian Basin and MachH2 in Illinois Basin, announced in 2023 that will lead to more than 40 million tonnes in captured CO<sub>2</sub>, with commensurate need for CO<sub>2</sub> transport and storage network within the next ten years. Two of the hubs named the ARCH2 in the Appalachian Basin and MachH2 in Illinois Basin include blue hydrogen production combined CCS. These full value chain projects will create tens of thousands in new jobs, facilitate energy transition and offer significant community benefits, which will also help gain stakeholder acceptance.

**Regulatory Progress underpinning Deployment** –As of 2024, there are more than 27 pending Class VI injection well permits across 11 sites in the region under review, with only one permitted for construction so far. This number is likely to grow substantially in the coming year, based on foreseen activity. In addition to permitting delays, progress has been hampered by lack of clear regulations for interstate pipelines, local county level requirements, and emerging framework for long-term liability, pore space ownership, eminent domain, and need to address local community benefits. States that are proactively developing a clear business and community framework to address these challenges are seeing enhanced project development activity, making them early movers in regional decarbonization.

## 6.0 Summary and Outlook on CO<sub>2</sub> Storage in MRCI Region

Overall, the opportunities, challenges, and growth path seen in the northeast/Midwest region of the US is seen as a key case study on the CCS deployment that will evolve in many parts of the world and next few years will be crucial in demonstrating whether CCS will form a major part of regional decarbonization aspirations in next three decades. Detailed reports for the research performed across the region by the MRCI team is being published through this series of reports and available at the US DOE's OSTI and EDX system. These reports include a new geologic storage framework for the region, an assessment of key technical challenges, a complete database of past CO<sub>2</sub> storage research, assessment of infrastructure, regulatory, and socio-economic aspects, and stakeholder outreach activities. Overall, the MRCI research and technology transfer will help with continued growth of CCS deployment across the region.

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