



A New Look at Carbon Capture and Storage Opportunities in Pennsylvania

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Executive Summary

Carbon capture and storage (CCS) is one strategy to mitigate carbon dioxide (CO₂) emissions that contribute to climate change. CCS is particularly important for decarbonizing hard-to-abate industries, including steel, cement, and petrochemical production, with significant footprints Pennsylvania. There are multiple geologic formations in the western and northern portions of the state that have been identified for potential use for permanent geologic storage of CO₂. This report details the magnitude of storage capacity for CO₂ in Pennsylvania based on publicly available and private data. Key findings of this assessment are as follows:

- CATF identified 219 facilities in Pennsylvania which could benefit from CCS technology subsidized by the 45Q tax credit to transition to a decarbonized future. These facilities have CO₂ emissions above the current Internal Revenue Service (IRS) thresholds and are therefore eligible for receiving tax incentives (18,750 metric tons per year for 59 electricity generation facilities; 12,500 metric tons per year for another 160 other industrial facilities), totaling nearly 82.5 million metric tons per year. These are distributed relatively evenly from east to west across the state, with a somewhat greater percentage in the

southern half of Pennsylvania. Of these facilities, those in the western part of the state are closer to the better quality storage potential.

- The geologic formations (saline aquifers) with sufficient, publicly available data to serve as the basis of an assessment were the Knox, Oriskany, Lockport, Onondaga, Bass Islands, and Medina formations. The best formations appear to be the Lockport and Knox formations, with the combined theoretical CO₂ storage capacity of 510 to 1,640 million metric tons. These figures represent a higher-confidence estimate of true storage capacity than previous analysis and signal promising potential. As more formations are characterized and more data is available for closer analysis, confidence of true storage capacity will increase.
- Based on data primarily from analog oil fields and information in the National Carbon Sequestration Database (NATCARB),¹ the assessed formations are mostly characterized with very low permeability, which may make CO₂ injection at commercially viable rates challenging. However, if high permeability areas – closer to the upper limit of their ranges found in the literature – are found in these formations, CO₂ storage volumes sufficient for smaller emissions industrial facilities may be achievable.

¹ <https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas>

■ Other possible storage options potentially exist in Pennsylvania other than deep saline aquifers. Perhaps most promising of these are storage in depleted oil and gas fields. In theory, storage in the Marcellus and Utica shales may also be feasible, along with the commercial pursuit of geologic storage opportunities in states west of Pennsylvania.

■ In most cases, CO₂ pipelines will likely be necessary to transport CO₂ from where it is captured to where it will be stored due to geologic considerations of the emissions site and the geographical distribution of sources. This is particularly true for the 109 45Q-eligible facilities emitting more than 50 million metric tons of CO₂ in the eastern part of the commonwealth, where the geology is likely unsuitable for storage.

Figure ES-1: Stylized Relationship between CO₂ Sources and Potential Storage Capacity for the Combined Lockport and Knox Formations

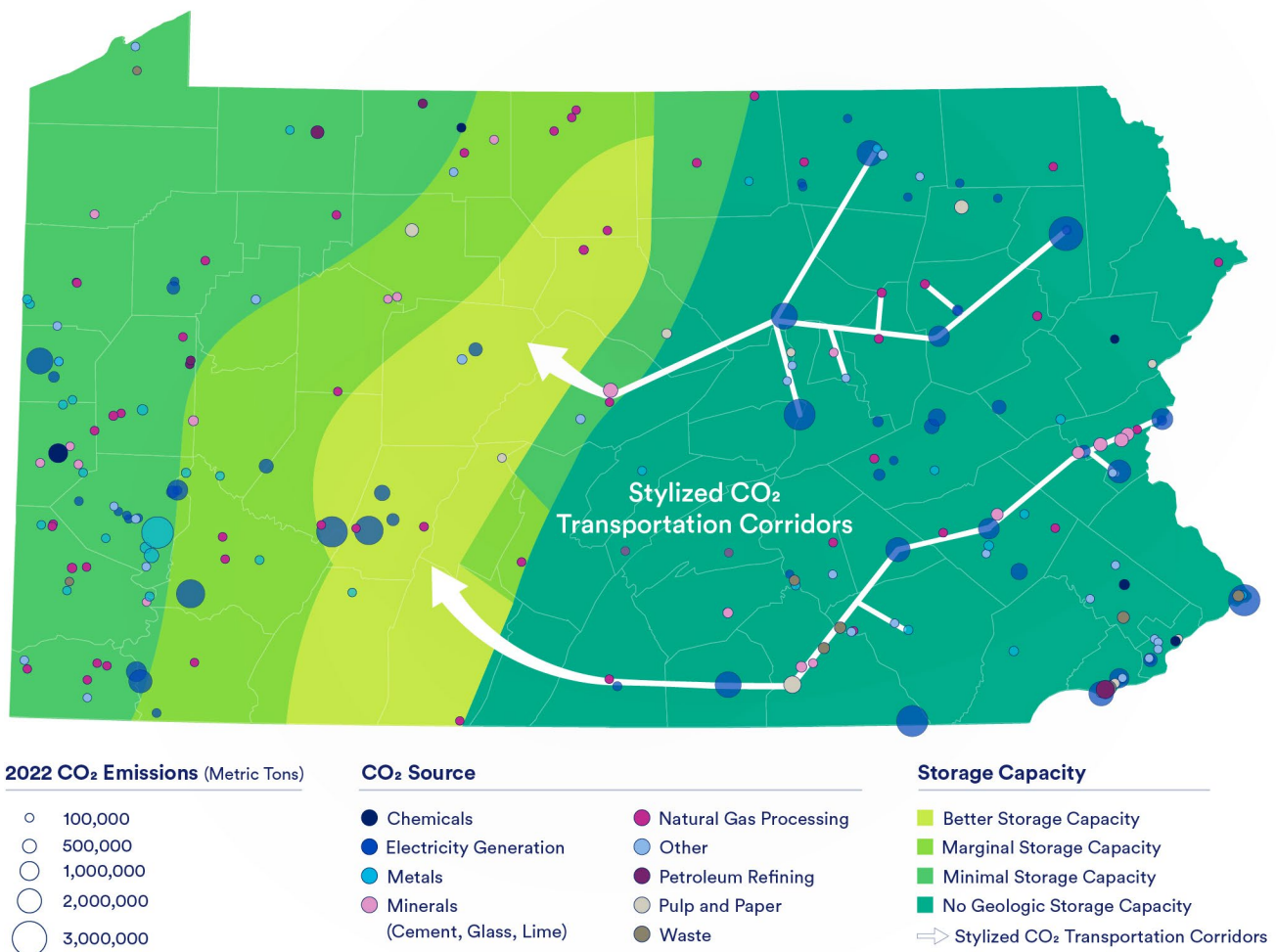


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SECTION 1

Introduction and Objective

Carbon capture and storage (CCS) is one strategy to mitigate fossil carbon dioxide (CO₂) emissions that contribute to climate change. Carbon capture and storage involves capturing CO₂ emissions from industrial facilities and fossil-fuel-burning power plants that would otherwise be emitted to the atmosphere, the transport, and the subsequent storage of the CO₂ in porous, subsurface geologic formations via CO₂ injection wells.

Pennsylvania has multiple geologic formations in the western and northern portions of the state that have been identified as potential targets for permanent geologic storage of CO₂. In fact, a recent study by the Great Plains Institute identified western Pennsylvania as a potential area to act as a major CCS hub.²

The objective of this report is to assess and characterize the options for CO₂ storage in Pennsylvania. The report examines local storage capacity to allow CO₂ emissions sources sitting above potential CO₂ storage reservoirs to gauge their potential for a CO₂ sequestration project. Storage capacity estimates were developed using publicly available information, along with proprietary data contained in Advanced Resources International's (ARI's) database of geologic and reservoir information on oil fields potentially amenable to CO₂ EOR. Options for regional storage outside of Pennsylvania were also considered.

² Great Plains Institute, An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization, February 2022.

CO₂ Emissions Sources in Pennsylvania

Despite the technological maturity of carbon capture, economic challenges remain, as underscored in a 2022 Team PA report.³ Under the 2022 policy environment, many emissions sources in Pennsylvania were not economically capturable. Facility-level carbon capture costs depend on the volumetric flow rate of flue gas, as well as its CO₂ concentration and purity. Moreover, transport and storage costs depend on factors like distance to the storage site, scale, monitoring, and geologic considerations.

Later in 2022, the Inflation Reduction Act (IRA) provided critical enhancements to the 45Q tax credit, which offers economic incentives for carbon capture and storage. Originally enacted in 2008 and reformed in 2018, 45Q underwent further revisions, elevating the credit value from \$50/metric ton to \$85/metric ton for CO₂ captured from industrial and power generation sources and stored permanently in saline geologic formations.⁴ The IRA not only increased the credit value of 45Q, but also broadened the scope of qualified facilities through

a reduction in capture thresholds. The threshold was lowered from 500,000 metric tons of CO₂ emitted per year to 18,750 metric tons for power generation facilities and from 100,000 metric tons of CO₂ emitted per year to 12,500 metric tons for other facilities. Power generation facilities must capture at least 75% of the emitted CO₂ to be eligible for 45Q incentives.

CATF analysis found that the recent IRA enhancements allowed an additional 140 facilities in Pennsylvania emitting more than 7.5 million metric tons in 2022 to become eligible for 45Q incentives, up from the 79 previously eligible. Those 219 eligible facilities in Pennsylvania (that are above the current IRS thresholds for receiving 45Q tax credits) produced direct CO₂ emissions totaling 82.5 million metric tons in 2022.⁵ These 219 sources are distributed relatively evenly from east to west across the Commonwealth. Table 1 provides an overview of the eligible facilities, highlighting the impact of the latest 45Q enhancements based on reported 2022 emissions.

³ Since the release of Team PA's report "Successful Deployment of Carbon Management and Hydrogen Economies in the Commonwealth of Pennsylvania," the value of 45Q has been increased and minimum emissions eligibility thresholds have been lowered leading toward additional facility eligibility and increasingly favorable capture project economics. <https://teampa.com/wp-content/uploads/2022/09/Pennsylvania-Carbon-and-Hydrogen-Roadmap-2022.pdf>

⁴ CATF, Carbon Capture Provisions in the Inflation Reduction Act of 2022, https://cdn.catf.us/wp-content/uploads/2022/08/19102026/carbon-capture-provisionsira.pdf?_gl=1*twn9px*_gcl_au*MjQ5ODk2MTcwLjE2ODkxMDUzMDg

⁵ Coal-powered electricity generating facilities that have announced retirement were not included in these totals. Excluded facilities include Montour, LLC, Brunner Island, LLC, Homer City, Keystone, and Conemaugh which emitted 17.8 million metric tons of CO₂ in 2022.

Table 1: Summary of CO₂ Sources in Pennsylvania with Emissions Greater than Federal 45Q Tax Incentive Facility Category Thresholds

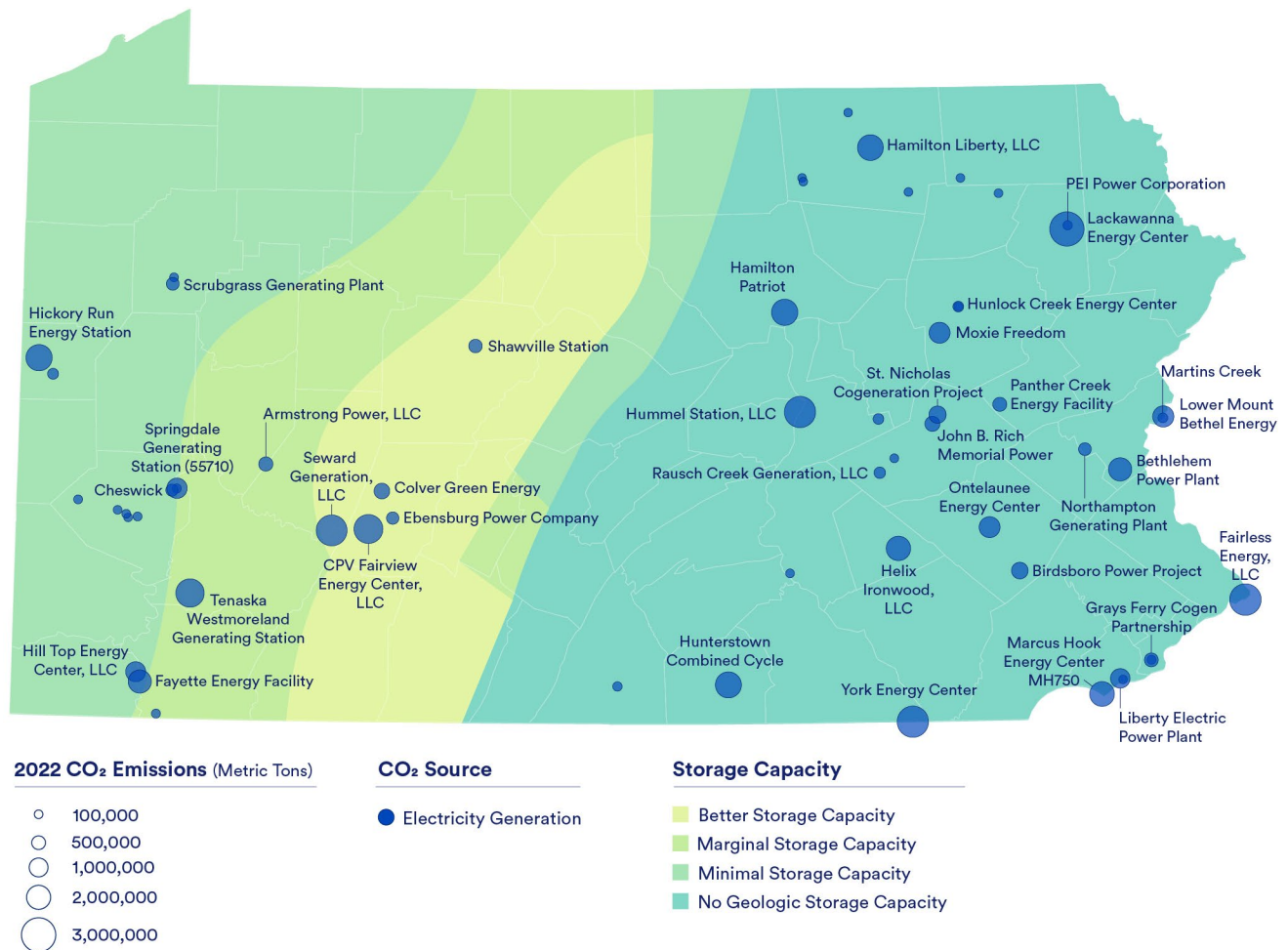
Type of Facility	Old 45Q (2018)		New 45Q (IRA 2022)		% Change in No. of Facilities	Change in Emissions above 45Q Threshold (metric tons per year)
	No. of Facilities	Total Emissions Above 45Q Threshold (metric tons per year)	No. of Facilities	Total Emissions Above 45Q Threshold (metric tons per year)		
Chemicals	3	1,766,966	7	1,941,665	133%	+ 174,698
Electricity Generation	32	54,676,365	59	57,592,571	84%	+ 2,916,206
Metals	11	5,263,985	30	6,151,365	173%	+ 887,380
Minerals (Cement, Glass, Lime)	9	4,282,663	19	4,894,670	111%	+ 612,007
Natural Gas Processing	5	607,557	50	2,520,899	900%	+ 1,913,342
Other	5	731,290	32	1,624,518	540%	+ 893,229
Petroleum Refining	3	1,963,321	5	2,061,904	67%	+ 98,582
Pulp and Paper	5	2,807,147	9	2,949,208	80%	+ 142,061
Waste	6	2,697,326	8	2,745,565	33%	+ 48,240
	79	74,796,619	219	82,482,363	177%	+ 7,685,745

Source: CATF analysis of EPA GHGRP 2022 reported data

The locations of emissions sources in Pennsylvania associated with electricity generation facilities are shown in Figure 1, while those for other industrial facilities are shown in Figure 2. The figures show that

sources are geographically distributed somewhat evenly throughout the state, though trend a little more to the southern half of the state.

Figure 1: Pennsylvania Sources with CO₂ Emissions above 18,750 Metric Tons per Year: Electricity Generation



Source: CATF analysis of EPA GHGRP 2022 reported data

Figure 2: Pennsylvania Sources with CO₂ Emissions above 12,500 Metric Tons per Year: Industrial Facilities



Source: CATF analysis of EPA GHGRP 2022 reported data

SECTION 3

Saline CO₂ Storage Opportunities in Pennsylvania

Advanced Resources International (ARI) developed an approach to estimate the potential CO₂ storage capacity in Pennsylvania in deep saline aquifers and determined the portion of this capacity that could be technically and commercially accessible. Geologic storage capacity for CO₂ is often estimated using the porosity (i.e., the pore space in the rock that could effectively accommodate CO₂)⁶ and the thickness of the geologic formation that makes up the storage unit.

This approach is described in detail in the Appendix to this report.

The geologic formations that had sufficient, publicly available data that could be used in this assessment were the Knox, Oriskany, Lockport, Onondaga, Bass Islands, and Medina formations. Reservoir property data from NATCARB were used to develop capacity maps to characterize the spatial distribution of storage capacity in each formation. The maps distinguish higher quality capacity from total capacity using a threshold defined in terms of metric tons/square mile, thus illustrating the quality of the storage capacity in each formation.

The summary of the results of the application of this approach for the target formations investigated is shown in Table 2. A capacity threshold of 2.0 million metric tons per square mile was chosen to screen for areas that would allow a plume size less than 10 square miles (assuming an injection rate of one million metric tons per year for 20 years). This represents a smaller sized industrial facility instead of a large electricity generation facility.

As shown in Table 2, the higher capacity estimated in the Lockport and Knox formations are the result of much greater thicknesses derived from the isopach shapefiles used to make the maps. In these two formations, most of the storage capacity potential is more than the 2 million metric tons per square mile threshold, where most of the estimated capacities of the other formations are below the assumed threshold.

Thus, based solely on capacity, this would indicate that the Lockport and Knox formations in western Pennsylvania have the highest relative storage capacity in the state, with a total theoretical CO₂ storage capacity of 510 to 1,640 million metric tons.

Injectivity, or the ease with which fluids, like carbon dioxide, can flow through geologic formations, of the selected target formations in the state was also estimated. Injectivity is an important consideration since it determines the number of injection wells required to inject a given volume of CO₂ and is based on a formation's permeability. Most of the formations assessed have very low reported permeability values (generally less than 1 millidarcy (md)), which makes CO₂ injection at technically and commercially viable rates challenging, and thus makes these formations unsuitable for commercial CO₂ storage even if they have theoretically high storage capacities.

However, if high permeability areas – closer to the upper limit of their ranges found in the literature – are found in some of these formations, reasonable CO₂ storage volumes could be achievable, though finding target areas and formations of sufficiently high permeability may be a challenge. Pursuing potential saline storage opportunities could be like wildcat exploration for oil and gas; though in this case, the effort would involve “exploring” for adequate injectivity (based on reservoir permeability) necessary for commercially viable CO₂ storage.

⁶ The porosity is the volume of void space in the formation divided by the total volume of the same formation.

Table 2: Summary of Potential Theoretical CO₂ Storage Capacity in Saline Aquifers in Pennsylvania⁷

Target Information	Depth Range (feet)	Assumed Porosity (%)	Assumed CO ₂ Density (pounds per cubic foot)	Assumed Storage Efficiency (%)	Total Storage Capacity (thousand metric tons)	Storage Capacity in Areas Above 2.0 metric tones per square mile (thousand metric tons)	Percent of Capacity in Areas Above 2.0 metric tons per square mile
Onondaga	1,000 - 6,500	8.3	calc from depth map	7.4	5,471	0	0.0%
				24	8,474	1,641	19.4%
Oriskany	0 - 7,000	7.8	calc from depth map	7.4	2,398	0	0.0%
				24	10,100	57	0.6%
Bass Islands	See Note	13.2	33.67	7.4	4,376	0	0.0%
				24	10,947	0	0.0%
Lockport	See Note	4.7	45.46	7.4	112,507	112,021	99.6%
				24	337,522	337,522	100.0%
Medina	2,000 - 10,000	6.9	calc from depth map	7.4	15,847	0	0.0%
				24	48,685	23,848	49.0%
Knox	5,000 - 15,000	10.8	calc from depth map	7.4	401,400	401,400	100.0%
				24	1,304,267	1,304,267	100.0%
				7.4	541,999	513,421	94.7%
				24	1,719,995	1,667,335	96.9%

⁷ The two rows for each target formation represent the values for different assumed storage efficiencies. The Bass Islands and Lockport formations do not have structure maps in NATCARB. <https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas>

SECTION 4

Non-Saline Options for Possible CO₂ Storage in Pennsylvania

Other possible storage options exist in Pennsylvania beyond deep saline aquifers. These include storage within depleted oil and gas fields and storage in shales, as summarized below.

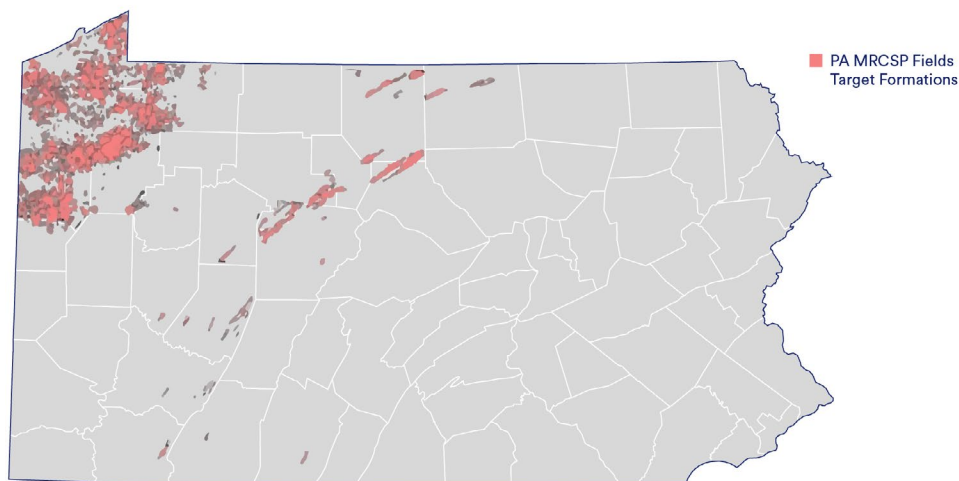
■ **Storage in Depleted Oil and Gas Fields.** Existing oil and gas fields (Figure 3) represent known reservoirs that contain pore space that once held hydrocarbons, and thus have an adequate seal or cap rock for keeping injected CO₂ in place. These fields may be the most promising initial targets for CO₂ storage in the state, though concerns exist pertaining to the many old wells known to exist in these fields. Old wells that have not been effectively plugged and abandoned may rule out the use of some prospective fields for secure storage, since these old wells could be potential conduits for CO₂ leakage from the storage reservoir. The Pennsylvania

Department of Environmental Protection has an active Well Plugging Program⁸ and continues to plug orphan and abandoned wells.

■ **Storage in Association with CO₂ Enhanced Oil Recovery Operations.** In Pennsylvania, 14 reservoirs with 1,360 million barrels of original oil in place (OOIP) were determined to be able to produce an incremental 160 million barrels of oil and require 550 Bcf (29 million metric tons) of CO₂ to facilitate this recovery.⁹ Most of these oil fields are in the northwestern part of Pennsylvania, Figure 3.

■ **Storage in Shales.** One study¹⁰ concluded that the Marcellus and Utica shales in the Appalachian Basin could facilitate the storage of nearly 50 billion metric tons of CO₂. See appendix for further discussion on storage in shale formations.

Figure 3: Oil Fields in Pennsylvania



⁸ <https://www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/LegacyWells/Pages/Well-Plugging-Program.aspx>

⁹ Bank G. C.; D. Riestenberg; and G. J. Koperna, "CO₂-Enhanced Oil Recovery Potential of the Appalachian Basin," SPE Paper 111282 presented at the 2007 SPE Eastern Regional Meeting held in Lexington, Kentucky, U.S.A., 17–19 October 2007.

¹⁰ Advanced Resources International, *Assessment of Factors Influencing Effective CO₂ Storage Capacity and Injectivity in Eastern Gas Shales*, Volume 1 Summary Report, Prepared for the U.S. Department of Energy, DE-FE-0004633, October 2013

SECTION 5

Options for Possible CO₂ Storage Outside of Pennsylvania

Most of the limitations regarding the capacity of potential geologic formations in Pennsylvania also exist for much of the rest of the Appalachian Basin. Prospect target formations in New York, West Virginia, Maryland, and eastern Ohio are also characterized by low reported permeability values. Thus, finding target areas and formations of sufficiently high permeability may be a challenge in these states as well.

Prospects could improve somewhat further to the west, in western Ohio and especially, into Indiana and Illinois. For example, a substantial amount of storage development activity is being pursued in Illinois, primarily

targeting the Mt. Simon formation. The Midwest Regional Carbon Sequestration Partnership (MRCSP) estimates that there are 37 billion metric tons of effective CO₂ storage capacity in saline aquifers in the state of Ohio, with another 8 billion metric tons of potential in shales in Ohio.¹¹ Most of Ohio's saline storage is in the Rose Run sandstone in the central part of Ohio; the characteristics of prospective formations in eastern Ohio are comparable to those in western Pennsylvania.

A complete assessment of opportunities for possible CO₂ storage beyond Pennsylvania was beyond the scope of this report.

¹¹ Midwest Regional Carbon Sequestration Partnership, Characterization of Geologic Sequestration Opportunities in the MRCSP Region: Phase I Task Report, Open-File Report 2005-01, 2010

SECTION 6

Linking Possible CO₂ Sources with Geologic Storage Prospects

Most of the prospective storage capacity in Pennsylvania exists in the western half of the state, while current sources of CO₂ that could be targets for carbon capture exist throughout the state, though lower emissions industrial sources that may be most feasible for commercially viable CCS projects exist in western Pennsylvania. Figure 4 shows the location of sources of

CO₂ emissions that could be targets for carbon capture, on top of an isopach map of storage capacity in the Lockport formation, with yellow indicating areas with higher storage capacity per square mile, and the dark green areas indicating regions of lower capacity per square mile.

Figure 4: Relationship of CO₂ Storage Capacity for the Lockport Formation with 45Q-Eligible CO₂ Sources in Pennsylvania

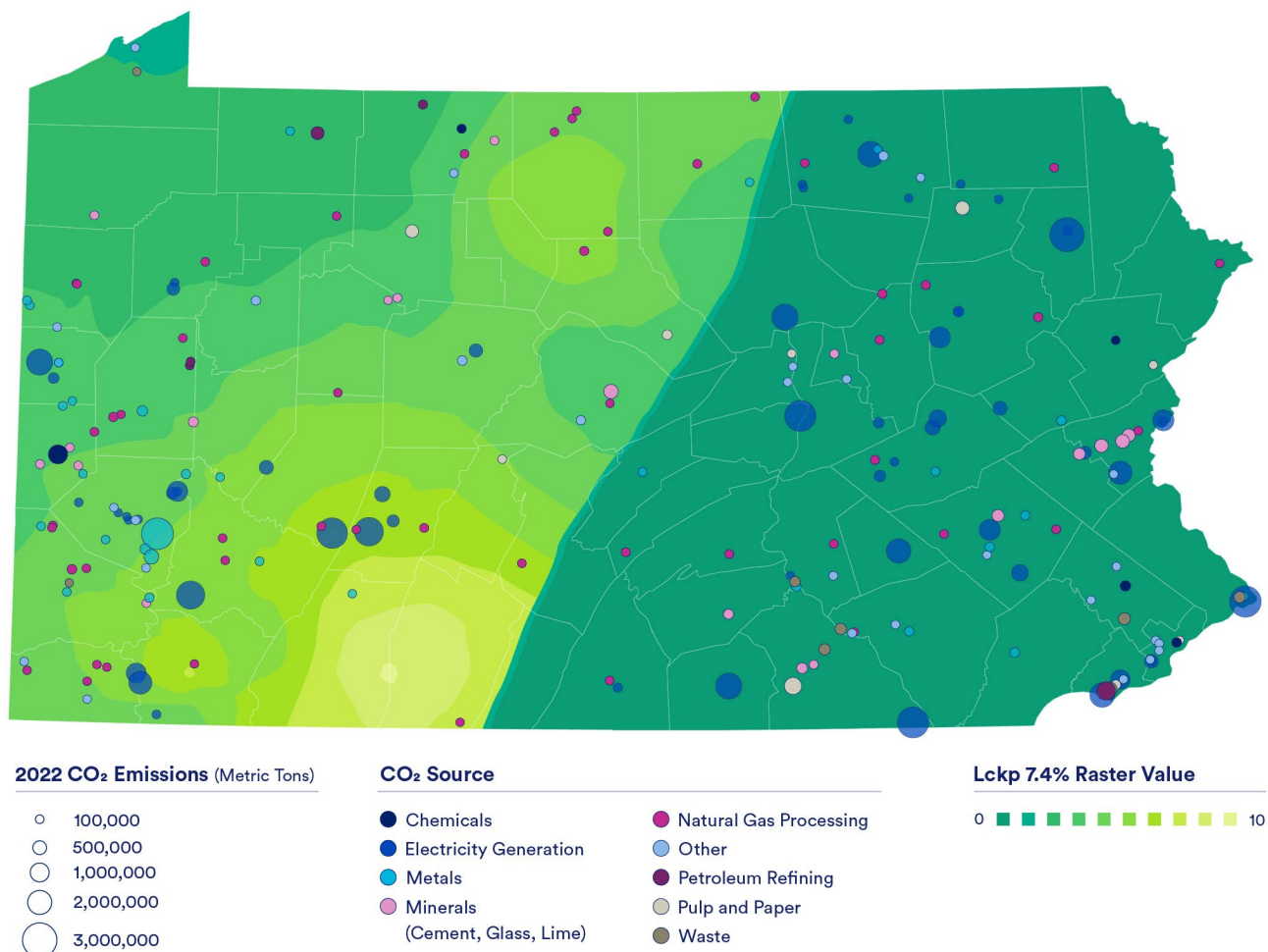


Figure 5 shows a similar map for the Knox formation. A fairly extensive – over 5,300-mile network – of natural gas pipelines exist in western Pennsylvania (Figure 6), in

addition to 1,400 miles of oil pipelines, that could help reduce potential logistical challenges to CO₂ pipeline deployment by following existing rights-of-way.

Figure 5: Relationship of CO₂ Storage Capacity for the Knox Formation with 45Q-Eligible CO₂ Sources in Pennsylvania

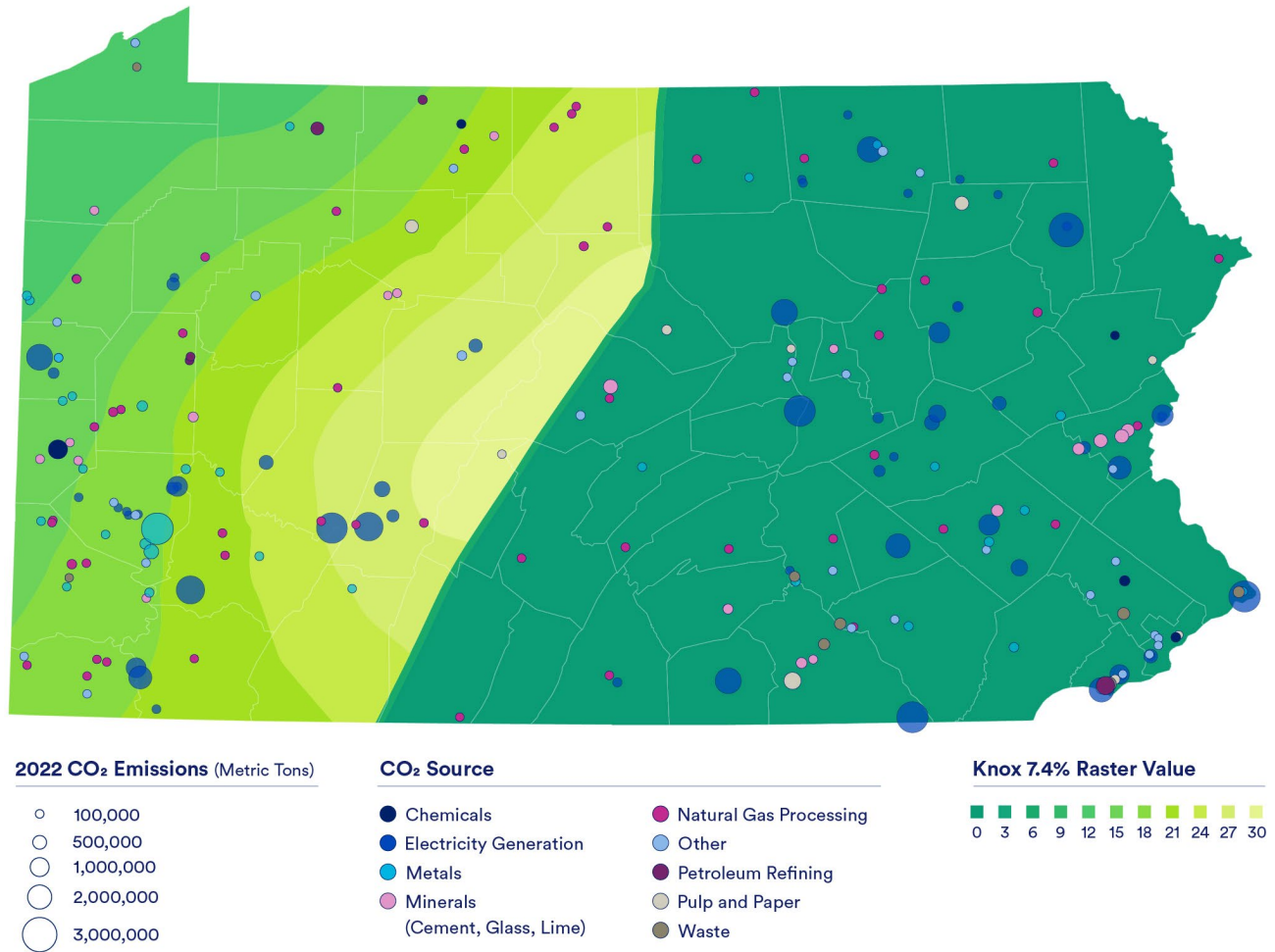
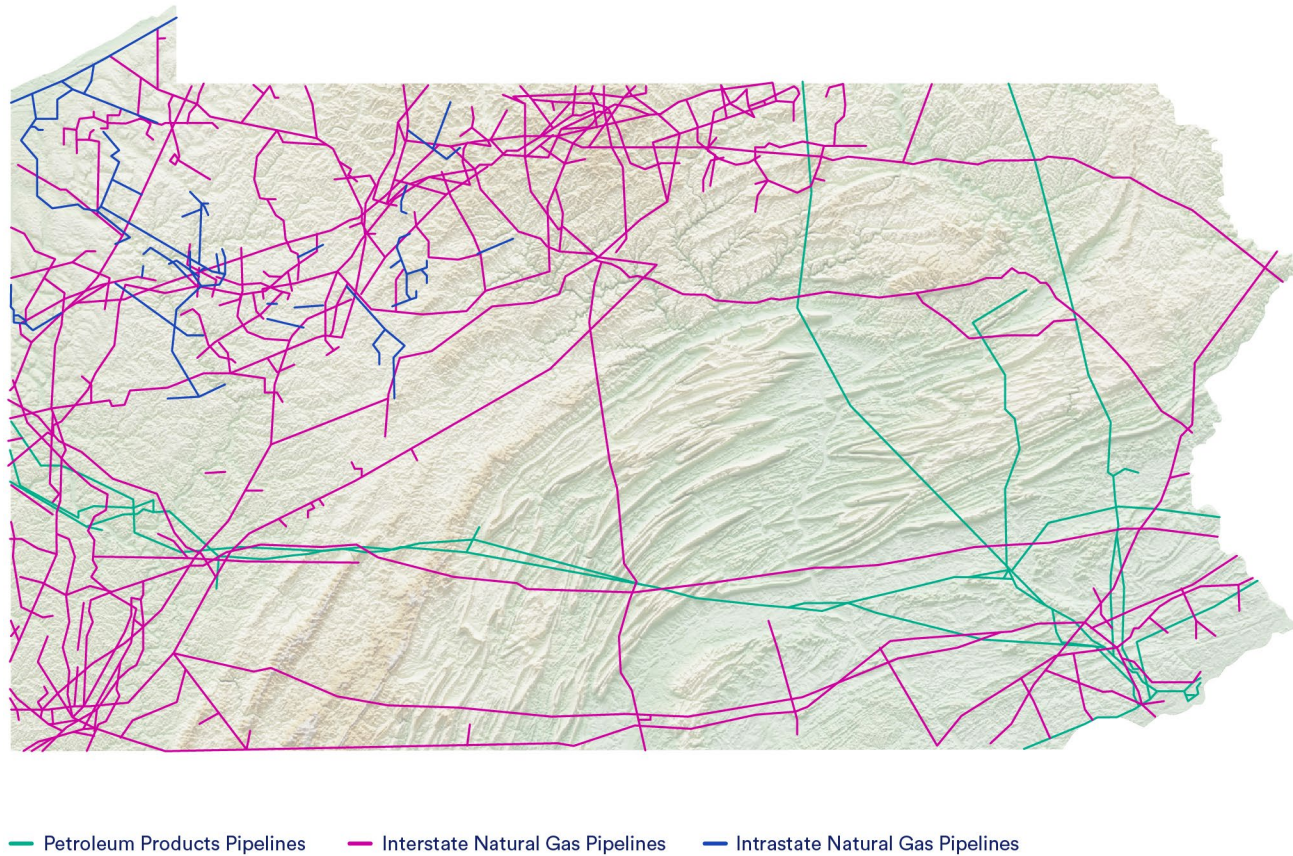


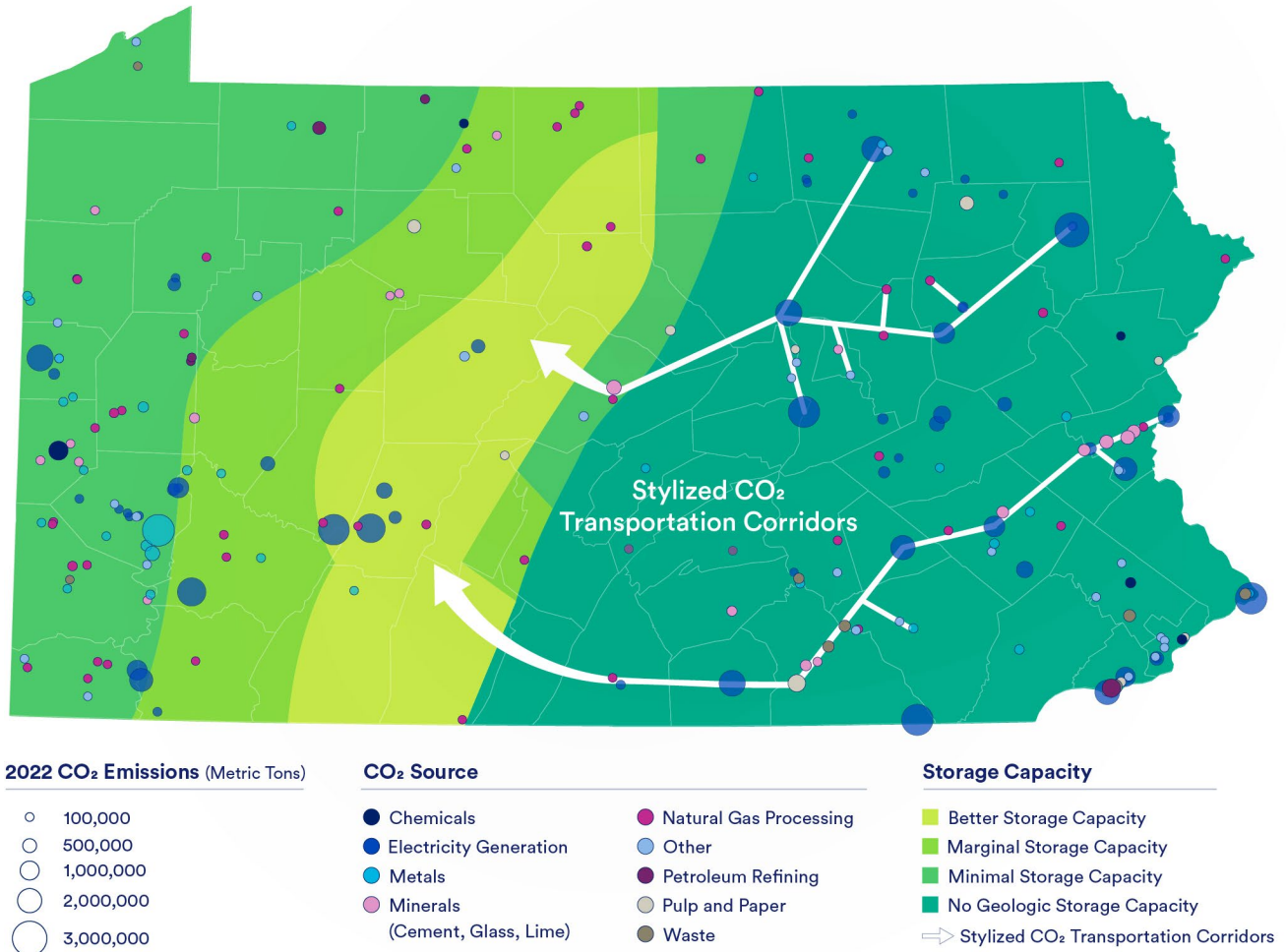
Figure 6: Existing Oil and Natural Gas Pipeline Network in Pennsylvania



Though some capacity may exist near current sources of CO₂ emissions, it is reasonable to assume that transport of CO₂ from sources to sinks will be required, as shown in a stylized manner in Figure 7. This will be true for

both prospective formations in Pennsylvania, as well as perhaps better storage prospects in states west of Pennsylvania or offshore in the Mid-Atlantic.¹²

Figure 7: Stylized Relationship between CO₂ Sources and Potential Storage Capacity for the Combined Lockport and Knox Formations



¹² OceanKind: CCS Potential in the US Mid-Atlantic using Offshore Storage, <https://cdn.catf.us/wp-content/uploads/2024/01/11161350/Carbon-Solutions-Offshore-Atlantic-CCS-Report.pdf>

Supporting Technical Information

CO₂ Emissions Sources in Pennsylvania

CO₂ from a variety of emission sources in Pennsylvania could be captured and stored in Pennsylvania. An up-to-date inventory of current CO₂ sources was developed, based on public data. This inventory included total biogenic and non-biogenic CO₂ emissions associated with each source facility, and included information on the type of facility, geographic location coordinates, and the estimated mass of CO₂ that could be captured annually. Facilities are categorized into nine major categories of CO₂ emission sources: chemicals, electricity generation, metals, minerals (cement, glass, lime), natural gas processing, other, petroleum refining, pulp & paper, and waste.

Based on this assessment, the focus was on those facilities with emissions levels above the thresholds for different facility types, that would be eligible for tax credits as set forth in Section 45Q(d)(2) of the Internal Revenue Code (as of January 2023), and injected for purposes of geologic storage, specifically:

- 18,750 metric tons per year for electricity generation facilities
- 12,500 metric tons per year for other facilities, excluding direct air capture.

219 facilities in Pennsylvania have CO₂ emissions above the IRS thresholds, totaling nearly 82.5 million metric tons per year, as summarized in Table 1 and in Figure 1 for electricity generation facilities⁵ and Figure 2 for other industrial facilities.

Saline CO₂ Storage Opportunities in Pennsylvania

Theoretical Storage Capacity

ARI developed an approach to estimate the potential CO₂ storage capacity in deep saline aquifers for the northwestern half of Pennsylvania to determine the portion of this capacity that could be technically and commercially accessible. A spreadsheet database of Pennsylvania oil and gas fields furnished by the State of Pennsylvania and developed by the State in conjunction with the Midwest Regional Carbon Sequestration Partnership (MRCSP) provided the basic geologic data used in this assessment. Contour maps of formation thickness and structure were incorporated from the U.S. Department of Energy (DOE) Carbon Storage Atlas (NATCARB).¹³ ARI also used data from their proprietary Big Oil Fields Database.¹⁴

The only formations that had sufficient, publicly available data to use in this assessment were the Knox, Oriskany, Lockport, Onondaga, Bass Islands, and Medina formations. Reservoir property data were used to develop capacity maps using the contours from NATCARB to supply the full spatial distribution of each formation across the study area. ArcGIS Pro was used to create maps for storage capacity for each individual target storage formation.

¹³ <https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas>

¹⁴ https://adv-res.com/big_oil_fields_database.php

The following equation was used to calculate storage capacity for each formation:

$$\text{Storage Capacity} = (\text{Thickness}) \times (\text{porosity}) \times (\text{area}) \times (\text{CO}_2 \text{ density}) \times (\text{storage efficiency})$$

where, the data were estimated based on the following:

- **Thickness:** Derived from the NATCARB isopach map
- **Porosity:** Calculated as a geometric average from each field in each formation in the spreadsheet
- **Area:** The Commonwealth was divided into 0.3596 square mile cells, and capacity was individually calculated for each cell.
- **CO₂ density:** Calculated using the estimated temperature and pressure for the formations based on depths in the structure maps and National Institute of Standards and Technology's (NIST's) CO₂ properties database.¹⁵ There was no structure map for the Bass Islands and Lockport formations, so the CO₂ density was estimated using average estimated temperature and pressure for all of the fields from the PA spreadsheet.
- **Efficiency:** Efficiency values of 7.4% and 24% were assumed for the formations, representing a plausible range of efficiency factors corresponding to 10th and 90th percentile of probabilistic efficiencies.¹⁶

Using these inputs, potential storage capacity was estimated for each cell, and then converted to estimated capacity per square mile.

The limits of the isopach and structure maps that were used as inputs in the capacity equation define the limits of the capacity map, which is different for each formation depending on the unique regional distribution. Figure 3 shows the regional distribution of the Pennsylvania fields in the six target formations, most of which are in the northwestern part of the state.

The data used to develop the maps were refined to illustrate the quality of the storage capacity in each of the formations. The idea was to distinguish higher quality capacity from total capacity by using a capacity threshold defined in terms of metric tons/square mile. An example of one of these maps, for the Lockport formation, is provided in Figure 4.

This approach consisted of the following steps:

- Total capacity in each of the various capacity ranges (indicated for the Lockport case in Figure 4) was estimated by multiplying the area (square miles) times the capacity (million metric tons per square mile) in the capacity range.
- A capacity threshold of 2.0 million metric tons per square mile was defined, assuming a desire for keeping a plume size below 10 square miles for injection of 1 million metric tons per year for 20 years. This represents a smaller-sized industrial facility, but probably not a large electricity generation facility.
- The total capacity in the ranges above 2.0 million metric tons per mile was compared to the total capacity for the entire formation to determine the portion above the 2.0 million metric tons per square mile threshold.

The summary of the application of this approach for all the target formations investigated is shown in Table 2.

Theoretical CO₂ Injectivity and Dynamic Storage Potential

Capacity alone does not indicate the quality of potential geologic storage. Injectivity, or the ease with which fluids, like carbon dioxide, can flow through geologic formations, of the selected target formations in the state was also estimated. Injectivity determines the number of injection wells required to inject a given volume of CO₂. This is critical in determining the amount of available capacity that could be technically and/or commercially pursued.

¹⁵ <https://webbook.nist.gov/cgi/cbook.cgi?ID=124-38-9>

¹⁶ Goodman, A, Hakala, A, Bromhal, G, Deel, D, Rodosta, T, Frailey, S, Small, M, Allen, D, Romanova, V, Fazio, J, Huerta, N, McIntyre, D, Kutchko, B, Guthrie, G, "U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale," International Journal of Greenhouse Gas Control, Volume 5, Issue 4, July 2011, Pages 952-965.

Thus, the next step was to estimate CO₂ injection capacity of the selected target formations in the state based on dynamic reservoir simulations using publicly available information. For each formation, available reservoir data, such as reservoir pay, porosity, and permeability for the regional seals and the injection zones, was collected, as available, from well logs and reports. Simple, single-well models (radial grid) were developed to estimate total mass injected and plume radius. The models assumed that CO₂ could be injected at a maximum allowable pressure for a fixed duration.

Ten locations were selected in the state to study the dynamic CO₂ storage potential of the formations identified. Public data were collected to construct numerical flow models to estimate CO₂ storage capacity. The most challenging data to find were permeability values for these formations.

Most of the formations have very low reported permeability values (generally less than 1 millidarcy (md)), which makes CO₂ injection at technically and commercially viable rates challenging, and thus likely making the formations unsuitable for CO₂ storage.

In summary, the following was concluded:

- **Oriskany:** Assuming 43 md permeability, and a 30-foot net pay interval, approximately 2 million metric tons (MMt) can be injected over 30 years of injection in an unbounded single-well scenario. The CO₂ plume covers an area with a 6,900-foot radius 100 years after the end of injection. Under a more optimistic case assuming the high-end of the permeability range (185 md), the formation might take 11 MMt of CO₂ over 30 years, with a plume radius of 1 to 3 miles.
- **Bass Island:** Assuming 22 md permeability, this formation achieved the highest injection volumes. This formation is deeper than the others, so there is a higher available pressure buildup before the well reaches the limit. Depending on depth and assumed thickness, annual injection rates of as much as 100,000 metric tons per year per well are possible. As much as 3.5 MMt can be injected over 30 years, with a 4,500-foot-radius CO₂ plume.
- **Lockport.** The permeability values reported for Pennsylvania are less than 1 md. At these levels of permeability, CO₂ storage volumes will be very small. As a sensitivity case, a higher permeability (which includes some values in Ohio) was assumed, and in this case, reasonable storage volumes could be achieved (based on a range of assumptions regarding reservoir depth and corresponding estimated thickness). However, it is questionable whether adequate permeability in the Lockport formation can be found in Pennsylvania.
- **Medina.** Permeability data found in the literature for Pennsylvania show very small values (less than 1 md), making it unsuitable for CO₂ storage.
- **Knox.** Assuming an average permeability ranging from 3 and 10 md for the Knox formation, a total of 2.9 and 11.3 MMt of CO₂ can be injected through a single well over 30 years, respectively. However, this assumes net thickness values of nearly 440 feet.

If high permeability areas – closer to the upper limit of their ranges found in the literature – are found in some of these formations, reasonable CO₂ storage volumes are achievable. However, finding target areas and formations of sufficiently high permeability may be a challenge. In fact, pursuing potential saline storage opportunities could be like wildcat exploration for oil and gas; though in this case, the effort would involve “exploring” for adequate capacity and injectivity for storage. Sources seeking to develop a project will likely need to collect local well data to prove project feasibility.

Non-Saline Options for Possible CO₂ Storage

Other possible storage options potentially exist in Pennsylvania beyond deep saline aquifers. These include storage in association with CO₂-EOR, storage in depleted oil and gas fields, storage in unmineable coal seams, and storage in shales. These are summarized in the following sections.

Storage in Association with CO₂ Enhanced Oil Recovery Operations

The Appalachian Basin states of New York, Pennsylvania, Ohio, West Virginia, and Kentucky have a long, rich history of oil production. Estimates of the original oil in-place (OOIP) in the region’s mature oil fields suggest that nearly 14 billion barrels were in-place prior to the beginning of production more than a century ago. Although early production data are often “best guesses”, the remaining oil in place in the Appalachian Basin appears to be on the order of 10 billion barrels.

A 2007 paper documents the potential for CO₂ EOR in Appalachia, including the potential in Pennsylvania.¹⁷ In eastern Pennsylvania 82 oil reservoirs, estimated to contain 2.5 billion barrels of original OOIP, were evaluated. Of these, assuming state-of-the-art technology (in 2007), 14 reservoirs with 1,360 million barrels of OOIP were determined to be able to produce an incremental 160 million barrels of oil and require 550 Bcf (29 million metric tons) of CO₂ to facilitate this recovery. This represents the storage capacity for the emissions from one or two relatively small industrial facilities.

For either CO₂ EOR applications or storage in depleted oil and gas fields, the maturity of oil production in Pennsylvania, along with the vast number of wells drilled prior to established spacing and completion practices suggests caution should be applied when assessing the CO₂ storage potential in association with CO₂ EOR in individual fields. However, fields that have been unitized and/or waterflooded may have located most of the orphaned wellbores within the unitized area. These fields may be the most promising initial targets for field-wide CO₂ EOR projects in the state.

Storage in Shales

Research on recovering methane and storing CO₂ in gas shales is significantly less advanced than that for coal seams. Ongoing reservoir characterization and reservoir simulation work in shales is demonstrating that shales can store CO₂ based on trapping through adsorption on organic material (like coals), as well as with the natural and induced fractures within the shales. Still lacking, however, is sufficient testing of this concept with site-specific geologic and reservoir data and detailed reservoir simulation, verified by field tests.

A research effort sponsored by U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) assessed the factors influencing effective CO₂ storage capacity and injectivity in selected gas shales in the Eastern United States. The goal of this cooperative research project was to build upon previous and on-going work to assess key factors that could influence effective enhanced gas recovery (EGR), CO₂ storage capacity, and injectivity in selected Eastern gas shales, including the Marcellus and Utica shales in Pennsylvania. This concluded that Marcellus and Utica shales contain nearly 1,200 Tcf of both primary production and EGR potential, of which an estimated 450 Tcf could be economic to produce with reasonable gas prices and/or modest incentives. This could facilitate the storage of nearly 50 Gt of CO₂ in the Marcellus and Utica shales.¹⁸

However, much about the mechanisms and potential for storing CO₂ and enhancing methane recovery in shales remain unknown and further research is required before storage efficacy and commercial feasibility is established. A more comprehensive assessment of the CO₂ storage potential of shales could be an appropriate and useful initiative for the state of Pennsylvania to pursue.

¹⁷ Bank G. C.; D. Riestenberg; and G. J. Koperna, "CO₂-Enhanced Oil Recovery Potential of the Appalachian Basin," SPE Paper 111282 presented at the 2007 SPE Eastern Regional Meeting held in Lexington, Kentucky, U.S.A., 17–19 October 2007.

¹⁸ Advanced Resources International, *Assessment of Factors Influencing Effective CO₂ Storage Capacity and Injectivity in Eastern Gas Shales*, Volume 1 Summary Report, Prepared for the U.S. Department of Energy, DE-FE-0004633, October 2013