Developing CO_2 Source and Storage Opportunities across the Illinois Basin
Subtask 5.3 – Regional Roadmap for Source Network and Storage Deployment
Topical Report

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CARBONSAFE ILLINOIS EAST SUB-BASIN

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Executive Summary

Large-scale anthropogenic CO_2 sources (>100,000 tonnes/year) were catalogued for the CarbonSAFE Illinois East Sub-Basin carbon capture and storage pre-feasibility study. The source portfolio is diverse, consisting of fossil-base power production, ethanol production operations, chemical development, and refinery facilities, most of which are relatively new or modernized (i.e. post year 2000). Ten facilities were considered for potential commercial-scale geological storage in a regional CO_2 source and storage network study. The study area has a number of potential geologic sequestration targets, including three significant deep saline reservoirs with corresponding seals, and potential enhanced oil recovery (EOR) opportunities. Recent research has focused on a high-porosity, highly arkosic zone within the Lower Mt. Simon Sandstone. Based on this work, we present a conceptual CO_2 source and storage network, which focuses on the arkosic zone in the Lower Mt. Simon as a prospective storage resource play in the Illinois East Sub-Basin region.

Introduction

Large-scale anthropogenic CO_2 sources (>100,000 tonnes/year) were catalogued for the CarbonSAFE Illinois East Sub-Basin project source assessment (Topical Report DOE/ FE0029445-2) to study the potential for commercial-scale (50 million metric tons or more) carbon capture and storage in the region. Annual emissions data for each facility were collected from the Midwest Geological Sequestration Consortium and United States Environmental Protection Agency (US EPA) databases. Facilities listed in Table 1, and highlighted in Figure 1, were considered in a regional commercial-scale CO_2 source and storage network study presented here.

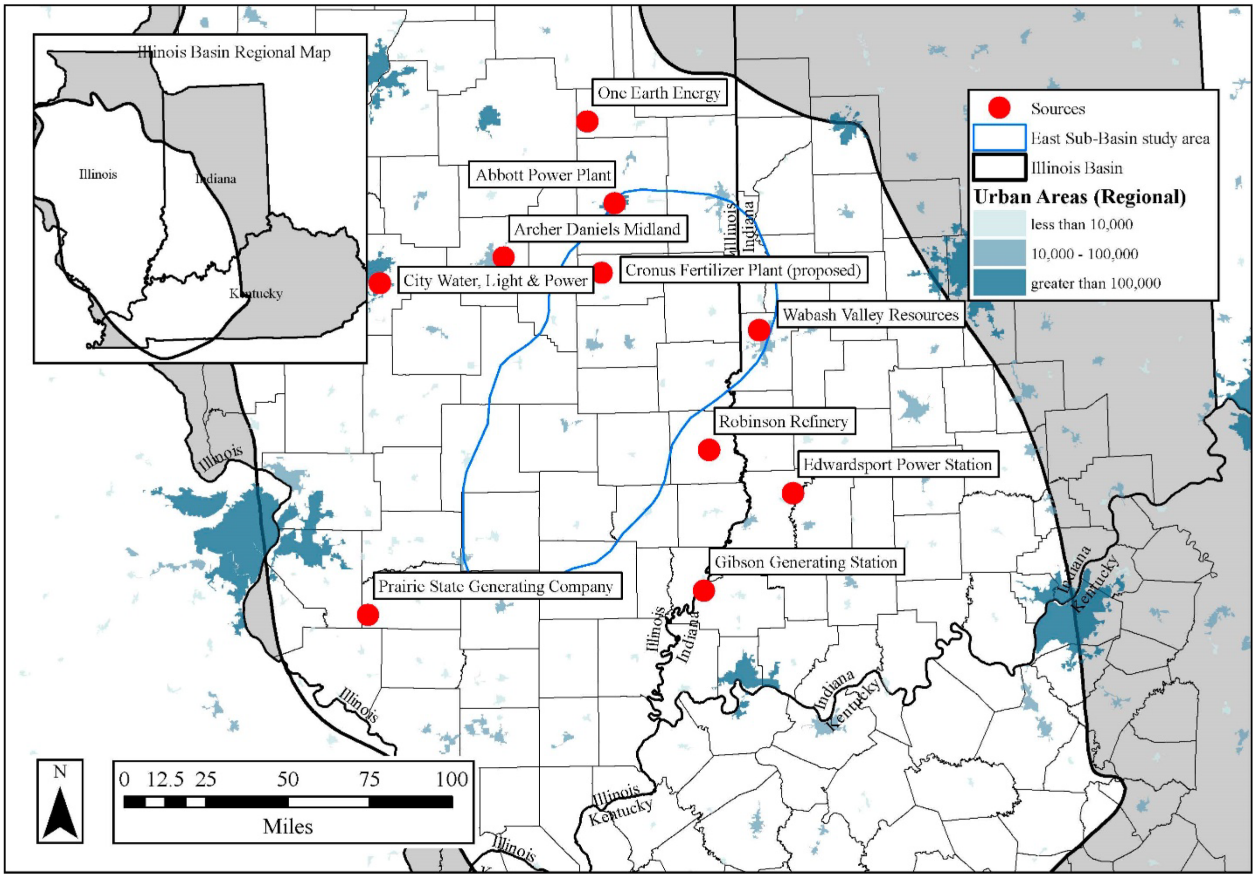

Figure 1: Selected anthropogenic CO_2 sources in the CarbonSAFE Illinois – East Sub-Basin region (CO_2 emissions greater than 100,000 tonnes/year) are shown as red circles, with plant names labeled.

Table 1: Selected large-scale anthropogenic CO_2 sources (>100,000 tonnes/year) considered in the CarbonSAFE Illinois – East Sub-Basin source and storage network study.

Facility/Company	Class	City	County	State	CO_2 Tonnes	Source	Feedstock/Fuel
Abbott Power Plant (University of Illinois)	Power Plant, Steam Generation	Champaign	Champaign	IL	236,628	EPA (2017)	Natural Gas, Fuel Oil, Coal
Archer Daniels Midland Co.	Ethanol Production, Injection of CO_2 Waste	Decatur	Macon	IL	4,490,465	EPA (2017)	Coal, Corn
City Water, Light, & Power	Power Plant	Springfield	Sangamon	IL	2,631,577	EPA (2017)	Coal
Cronus Fertilizer Plant (in development)	Urea, Ammonia	Tuscola	Douglas	IL	N/A	N/A	Natural Gas
Edwardsport Power Station	Power Plant	Edwardsport	Knox	IN	3,431,750	EPA (2017)	Coal, Petcoke
Gibson Generating Station	Power Plant	Owensville	Gibson	IN	16,331,848	EPA (2017)	Coal
Gibson City Energy	Ethanol Production, Waste	Gibson City	Ford	IL	175,020	EPA (2017)	Natural Gas, Fuel Oil, Corn
Prairie State Generating Company	Power Plant	Marissa	Washington	IL	11,086,886	EPA (2017)	Coal
Marathon Petroleum Co. Robinson Refinery	Petroleum Refinery, Petroleum Product Supplier	Robinson	Crawford	IL	1,723,628	EPA (2017)	Natural Gas, Crude oil
Wabash Valley Resources (in development)	Ammonia	Terre Haute	Vigo	IN	1,570,000	Company Projection	Coal, Petcoke

Each facility highlighted is a relatively new or modernized facility increasing the likelihood for successful transition to carbon capture capable. The portfolio of the expanded source network is diverse, consisting of fossil-base power production, ethanol production operations, chemical development, and refinery facilities.

A brief overview of each facility is presented below. Following the facilities overview, an upper-level capture and transport cost comparison is provided for selected sources, based on the memorandum titled "High-Level Cost Estimate for CO_2 Capture and Transportation Costs: CarbonSAFE Phase2 Illinois – Macon County, Rev. 1" hereafter referred to as the "CarbonSAFE Memo" (Trimeric, 2018).

CO_2 Sources: Facilities Overview

Abbott Power Plant

Abbott Power Plant, originally constructed in 1941, is a coal- and natural gas-fired power station, owned and operated by the University of Illinois, and located directly adjacent to a main railroad line in Champaign, IL. Abbott is a cogeneration facility, producing both steam and electricity, which has adjusted plant capabilities with additions and equipment alterations over the years to meet changing energy demands and adapt to variability in fuel price. During the 1970s, the original coal fired boilers were replaced with oil-fired boilers. Three coal-fired boilers were converted to natural gas boilers when fuel and oil prices increased during the early 1980s. In the early 1980s a flue gas desulfurization scrubber was installed to remove sulfur from the coal-burning emissions. Abbott's most recent expansion project was completed in 2005, in which two heat recovery steam generators (HRSGs), two gas turbine generators, two cooling towers, and three steam turbine generators were installed. Currently, there are five boilers, two HRSGs, two gas turbines, and nine steam turbine generators (STGs) with the capability to use fuel sources of natural gas, coal, or fuel oil in the boilers and to operate turbines.

The three coal-fired Stokes boilers burn high-sulfur Illinois bituminous coal to produce a combined capacity of 320 tonnes/hour of steam (equivalent to 35 megawatt [MW]), CO_2 concentration in the flue gas is approximately 6-8 volume % (CarbonSAFE Memo). Limitations prevent all three boilers from operating simultaneously. The natural-gas fired boilers each have a capacity of 140 tonnes/hour of steam (equivalent to 15 MW), with an estimated exhaust CO_2 concentration of 5-7% by volume (CarbonSAFE Memo). During winter months Abbott power plant operates the natural gas-fired boilers, and one coal boiler, occasionally, during extremely cold weather.

Gas turbines, fueled with natural gas or fuel oil, are operated continuously throughout the year. Each 12.5 MW gas turbine is connected to an HRSG that captures the hot exhaust gases to generate steam. The CO_2 concentration in the turbine exhaust is approximately 3% by volume (CarbonSAFE memo). HRSGs can produce 110 tonnes/hour of steam, boilers steam output, drive the operation of STGs which use the high pressure steam to spin the steam turbine produce electricity. The low pressure exhaust steam from the turbines is used to serve over 85 % of campus energy demands.

Abbott Power Plant meets or exceeds all Environmental Protection Agency (EPA) emission standards. Electrostatic precipitators (ESP) and a jet bubbling reactor (JBR) flue gas desulfurization scrubber (Chiyoda CT-121 system), supported by a Continuous Emission Monitoring System (CEMS) in the stack, remove 90% of air pollutants, providing significant environmental benefits compared to conventional electric generation and heat-only systems.

Archer Daniels Midland

Archer Daniels Midland's (ADM) ethanol production facility in Decatur, Illinois is capturing CO_2 from their corn ethanol facility to support their second major carbon capture and storage project, the Illinois Industrial Carbon Capture and Storage (IL-ICCS) project. IL-ICCS is designed to demonstrate the commercial-scale applicability of carbon capture and storage (CCS) in a deep saline reservoir, the Mount Simon Sandstone, at a projected potential injection of 5.5 tonnes of CO_2 over a five year period. The earlier Illinois Basin - Decatur Project (IBDP) successfully met the three year CCS feasibility demonstration goal to capture and store approximately one million tonnes of CO_2 into the Mount Simon Sandstone formation.

The Decatur ADM facility has existing infrastructure in place to eliminate much of the capital and labor investment necessary to address short and long term requirements for a commercial scale source. Considerable daily trucking activities and existing rail infrastructure has potential for immediate CO_2 transportation. Construction and extended operation of the compression and dehydration equipment, capable of delivering up to 2,000 tonnes of very pure (99%) supercritical CO_2 per day for storage, has been proven through success on two demonstration projects. Although expansion and development of a pipeline network would be a requirement for a long term CO_2 delivery, the cost is minimal considering the ADM's current level of investment in the facility and personnel.

City, Water, Light and Power (CWLP) CWLP Dalman #4

City, Water, Light and Power's (CWLP) Dallman plant, located in Springfield, IL, has four coal-fired units with a combined nameplate capacity of 572 MW and the ability to supply approximately 4,100 tonnes/day CO_2. CWLP's Dallman #4 unit was a host site for a previous slipstream carbon capture retrofit study (DOE Award Number: DE-FE0005795). Dallman Unit #4 is a modern subcritical, pulverized coal-fired power generation facility, operational since 2009, while the other three units were constructed between 1968 and 1975 and represent relatively old generation technology.

Dallman Unit #4 operates a 200-MW Foster Wheeler front and rear wall fired PC boiler with a maximum continuous high pressure steam output of 660 tonnes/hr. The unit burns 100% Illinois high-sulfur bituminous coal with an approximate heat content of 10,500 Btu/lb. Coal used for the unit is trucked from the Viper mine in Elkhart, IL to the coal-receiving yard at the plant. The power plant load varies over time as the demand changes instantly. If shutdown times are excluded, the electrical load of the unit varies between about 100 and 228 MW, with an average load of 165 MW.

This unit is installed with low-NOx burners, a selective catalytic reduction (SCR) for NOx removal, a hydrated lime injection (HLI) system for SO_3 and Hg removal, a fabric baghouse to capture particles, an FGD system to mitigate SO_2 emissions, and a wet ESP to remove liquid droplets such as sulfuric acid mist. The flue gas exiting the wet ESP is intended for withdrawal for CO_2 capture. Equipped with the advanced air pollution control devices, Dallman #4 unit is deemed one of the cleanest coal-fired generating units in the nation reducing the need for the pretreatment of flue gas entering the capture unit and thus reducing the equipment footprint and cost.

In April 2018, operating at 200MW, Dallman #4 produced gas at a flow rate of 32,604,000 ft^3/hour (923,240 m^3/hour) with CO_2 concentration of 10.6% by volume so assuming 90% capture 159 tonnes/hour or 1.4 MT/year of CO_2 would be available for injection (CarbonSAFE Memo).

Cronus Chemical Fertilizer Plant

Cronus Chemicals LLC plans to build a plant in Douglas County, IL to produce non-flammable nitrogen-based products, specifically urea and ammonia fertilizers and diesel exhaust fluid, using natural gas as a feedstock. The Cronus Fertilizer plant will have the capacity to produce 2,300 tonnes/day of ammonia and up to 2,000 tonnes/day of granular urea. Cronus has reached an agreement with Thyssenkrupp

Industrial Solutions, a fertilizer plant technology and construction company, to begin construction of the estimated $1.4 billion plant in 2019.

The plant will be built on a 235 acre agricultural area, at 765 E. U.S. Highway 36, two miles west of Tuscola near Interstate 57. This acreage is a designated “CSX Select Site”, a program that identifies and certifies sites ready for development along the CSX Railroad's network. Select Site certification criteria include size, access to rail services, proximity to highways, workforce availability, natural gas, electricity, and water, and wastewater, environmental and geo-technical standards (CSX 2019). The project will receive $12.3 million for road improvements through the Illinois Department of Transportation. The Urbana and Champaign Sanitary District will construct a pump station to supply treated wastewater via water pipeline at the projected volume of 6.3 million gallons/day to the Tuscola facility.

Edwardsport Power Station Integrated Gasification Combined Cycle (IGCC)

In June 2013, Duke Energy Indiana began operation of the Edwardsport Integrated Gasification Combined Cycle (IGCC) power plant, located in Vigo Township, Knox County, near the town of Edwardsport, Indiana. The modern cleaner-coal integrated gasification combined cycle facility retired the Edwardsport Power Station, a 160 MW, three coal-fired unit electrical plant. Edwardsport IGCC has a gross capacity of approximately 780 MW and a net capacity of 618 MW.

The Edwardsport IGCC facility consists of two oxygen-blown, coal slurry-fed parallel gasification/power generation trains that produce synthetic (syngas) gas. Illinois Basin coal, delivered by rail or truck, is the primary source to fuel the gasifier, but the facility can accept coal or petcoke, as feedstock. The syngas or natural gas-fired combustion turbines produce electricity while excess heat is captured and routed through heat recovery steam generators (HRSG). Two heat recovery steam generators, equipped with selective catalytic reduction for nitrogen oxide control, power the steam turbines to generate additional power and increase plant efficiency. The two combustion turbines have a gross capacity of 230 MW each and one steam turbine has a gross capacity of 320 MW.

During the construction of the facility, Duke Energy dedicated space to support potential carbon capture and storage efforts. Although further research indicated less potential for long term underground CO_2 storage at the site, the existing gasification infrastructure makes Edwardsport IGCC a cost effective source for commercial carbon sequestration in the region.

Gibson Generating Station

Gibson Generating Station, operated by Duke Energy Indiana, Inc. (DEI) and owned by DEI, Wabash Valley Power Association, Inc. and Indiana Municipal Power Agency, is a coal-fired electricity generation facility in the town of Owensville, Gibson County, Indiana. The facility is located approximately 35 miles north of Evansville, Indiana and immediately southeast of Mount Carmel, Illinois near the Wabash River, Patoka, and White Rivers with established rail and truck access. Gibson Station is Duke Energy’s largest power plant supplying energy to approximately 80 counties in Indiana and Kentucky through six high and extra high voltage transmission lines.

Gibson Generating Station was built as a two-unit coal-fired facility in 1972. Currently the pulverized coal-fired power facility consists of five General Electric 650 MW steam turbines that generate approximately 3,250 MW combined. The station is fully scrubbed, flue-gas desulfurization (FGD) systems were retrofitted on the units in the mid-1990s. A series of selective catalytic reduction (SCR) units have been installed to decrease NOx emissions, with final improvements to Unit 5 completed in 2008.

High sulfur coal, predominantly from southern Indiana, is delivered to the power plant by rail and truck to power the steam turbines. Six coal combustion waste (CCW) impoundments North Ash Pond, North Settling Basin, East Ash Ponds #1, #2, and #3, and the East Settling Basin, located adjacent to and northeast of the power plant, comprised the active coal combustion waste facility at the Gibson Generating Station. Historically, bottom ash and boiler slag from Units #1, #2, and #3 are wet sluiced to North Ash Pond where primary settling and temporary storage. Fly ash from Units #4 and #5 are collected dry and managed in onsite landfills. DEI has documented a significant effort to prepare for safely closing ash basins including the design and construction new retention basins for water management, installing state-of-the-art wastewater treatment systems, and installing new equipment to manage all coal ash dry rather than sending to fly ash basins (Duke 2019). Duke's extensive monitoring efforts can be reviewed at the following: https://www.duke-energy.com/our-company/environment/compliance-and-reporting/ccr-rule-compliance-data.

Gibson Generating Station was the focus of regional capture/transport/storage simulation work which examined a distribution of 15 potential geological storage sites located within 80km of the plant (Ellet et. al, 2017; Wang et al., 2017). The work incorporated stacked geological reservoir systems with explicit consideration of processes and costs associated with the operation of multiple CO_2 utilization and storage targets from a single geographic location; a key finding was the extent to which CO_2 utilization for enhanced oil recovery can help drive CCUS technology deployment and offset costs associated with CO_2 mitigation.

One Earth Energy

One Earth Energy operates an ethanol production facility, located near Gibson City, Ford County, IL. The primary products are fuel-grade ethanol and distiller's grain, an animal feed supplement, with CO_2 gas generated through the ethanol production process.

The facility is a modern 228 MW simple cycle facility consisting of two steam driven W501D5A Siemens-Westinghouse turbine/generator units (Units GCTG 1 and GCTG 2). These units fire natural gas or fuel oil with two on-site 700,000 gallon oil storage tanks. The plant has a design capacity of 100 million gallons of ethanol and 320,000 tons/year (approximately 325,000 tonnes/year) of dried distiller grains.

One Earth Energy includes five local grain co-ops led by Alliance Grain Company and including TopFlight Grain, Fisher Farms, Ludlow Cooperative and Grand Prairie Cooperative. Five operational elevators near the plant are rail load-out accessible via Alliance's Bloomer Shippers Connecting Railroad (Bloomers Line), a 45-mile short line that provides an interchange between the Norfolk Southern (NS) and Canadian National Illinois Central (CN) lines. Along with rail accessibility, the facility is located on a well-traveled state highway near existing natural gas pipeline routes in close proximity to Interstate 57 (I-57) and Interstate 74 (I-74).

Prairie State Generating Company

The Prairie State Generating Company (PSGC), located east of Marissa, IL, is a modern coal-fired electricity generation facility that consists of two approximately 800 MW coal-fired, supercritical steam electric generating units (1,600 MW total) operational since 2012. Its supercritical design and state-of-the-art emissions control technologies (including nitrogen oxide and mercury controls, sulfur dioxide scrubbers, and wet and dry electrostatic precipitators) result in low NO_x, SO_x, and particulate matter. The Prairie State Generating Company and the adjacent Lively Grove coal mine form the Prairie State Energy Campus (PSEC). Illinois coal travels on conveyors directly from the underground coal mine to the plant.

The PSEC is owned by six public power entities and three electric cooperatives. All of PSEC member owners are community-owned, non-profit utilities. Electricity from the plant is distributed to eight Midwestern-based public power utilities serving nine states.

PSEC was built with the Best Available Control Technology (BACT) for criteria pollutants and Maximum Achievable Control Technology (MACT) for hazardous air pollutants and achieves one of the best levels of pollution control in the industry. The PSEC emissions profile is one of best in the nation, and in 2014, PSEC ranked as having the 15th lowest NOx emission rate among coal-fired generators. Based on case study assessments of a power generation facility with an approximate gross power output of 730 MW and 4.2 MT/year produced outflow of CO_2, post-combustion capture installed on one of the two existing units (90% capture) would produce 4.5 MT/year of CO_2 for injection (CarbonSAFE memo).

Robinson Refinery

Marathon Petroleum Company's (MPC) 920 acre refinery facility in Robinson, Crawford County, IL, located in the east central part of the state, has a crude oil refining capacity of approximately 231,000 barrels per day (nearly 10MT/year). The Robinson refinery, known as MPC's Illinois Refining Division, produces a full range of commercial, industrial and retail products, using a variety of crudes to produce products including gasoline, diesel fuel, kerosene, jet fuel, petroleum coke, propane, propylene, sulfur, slurry, and butane.

MPC's Illinois Refining Division is connected to an extensive pipeline system of approximately 250 miles. The system includes pipelines from the Robinson refinery to cities in Indiana (Indianapolis, Muncie, Lima, Mt. Vernon, Clermont, Griffith, and Hammond), Kentucky (Louisville), and Illinois (Martinsville, Wood River, and Champaign).

The Robinson refinery received its first ENERGY STAR certification in 2014, joining four other MPC refining facilities which earned ENERGY STAR certifications, and was recertified in 2015. The Robinson refinery underwent changes in piping and insulation systems, steam system maintenance, fired equipment tuning, process steam reduction, and conversion of steam turbines to more efficient electric drivers. MPC is also one of the only refining companies in the nation to have facilities, including the Robinson refinery, certified under the American Chemistry Council's Responsible Care® requirements.

Wabash Valley Resources LLC

In 2016, Wabash Valley Resources LLC (WVR, formerly Quasar Syngas LLC) acquired the Wabash Integrated Gasification Combined Cycle (IGCC) Plant north of Terre Haute, IN, the initial step in repurposing the facility for the production of ammonia for the domestic fertilizer market by 2021. The WVR facility is located directly adjacent to a main railroad line and near an existing nearby ammonia pipeline.

The facility can accept coal or petcoke, as feedstock, from several refineries in the region. The feedstock will be converted in the gasifier to syngas and then the hydrogen used to produce ammonia. The syngas will be purified using the Rectisol process to removes acid gases (H_2S and CO_2), which results in a very pure CO_2 stream that can be readily compressed and transported for storage or other utilization. The separated CO_2 will be greater than 95% pure, and WVR has increased the separation and planned capture of CO_2 from 65% to 95% of the gas stream, which equates to 179 tonnes/hour or, nominally, 1.57 MT/year. At full and continuous operation the WVR facility will deliver almost 1.6MT CO_2/year for storage or EOR use.

The reliability of the existing gasification infrastructure, simplicity of the design modifications for CO_2 separation, and experience of the operations and management team are all advantages to this proposed carbon management project.

CO_2 Capture and Transport Cost Comparison

The following is a synopsis of results presented in the CarbonSAFE Memo (Trimeric, 2018). Screening-level estimates for facility cost of capture and delivery were conducted for five potential CarbonSAFE sources (ADM Decatur, City, Water, Light and Power (CWLP), Wabash Valley Resources (WVR), Abbott Power Plant, and Prairie State Generating Company. The assessment determined that the two most cost effective capture sources, due in large part to the high-purity of their CO_2 streams, are ADM and WVR—noting that pipeline requirements (e.g. if storing CO_2 off-site) would result in higher associated costs. The two coal-fired power facilities, Prairie State Generating Company and CWLP, were next with CO_2 separation and capture from flue gas. Prairie State was estimated at approximately 15% lower cost than CWLP due to scale of the operation. Abbott was determined to be the least cost effective for capture due to the low concentration of CO_2 emitted through exhaust gas, especially in comparison to the other screened sources.

Sub-Basinal Storage

The study area has a number of potential geologic sequestration targets, including three significant deep saline reservoirs with corresponding seals, and potential enhanced oil recovery (EOR) opportunities. East Sub-Basin work has built upon the FutureGen DOE initiative, research of the DOE's Regional Carbon Sequestration program, and other DOE funded projects such as the evaluation of the Cambrian-Ordovician strata and reservoir characterization studies in the Mississippian Cypress Sandstone.

The Mt. Simon Sandstone is considered the most significant sequestration target in the Midwest of the United States and is present throughout the study area. Characterization of the Mt. Simon was performed largely through extensive evaluation within the Illinois Basin by the Midwest Geological Sequestration Consortium (MGSC) as part of the Regional Carbon Sequestration Partnership (RCSP) program. This reservoir has been evaluated as a sequestration target in the Illinois Basin – Decatur Project (IBDP) where the lower Mt. Simon reservoir, at a depth of 7,000 feet (2135 m), had almost 30% porosity; some intervals had over one Darcy of permeability.

In the southern part of the study area there are additional sequestration opportunities in the Cambrian and Ordovician Knox Group and the Ordovician St. Peter Sandstone. A US DOE regional study assessed the potential storage capacity of these units, through numerically simulated CO_2 injection, at various reservoir conditions (Leetaru, 2014a). Simulation determined that each reservoir independently has capacity to store almost 90 million tonnes of CO_2 at a single site. In the Illinois Basin, tens-of-millions of gallons of waste water have been injected annually into the Potosi Dolomite of the Knox Group. In addition, approximately 100 miles to the south, CO_2 was successfully injected into numerous intervals within the Knox at the Blan well in Hancock County, Kentucky (Bowersox, 2013). The St. Peter Sandstone provides another alternative storage target, although reservoir conditions are unsuitable for long term CO_2 storage regionally. In the northeastern portion of study area the St. Peter is either too shallow or contains fresher water, while east into Indiana and Kentucky the reservoir pinches out rapidly and is therefore not suitable as a CO_2 storage target.

Illinois State Geological Survey (ISGS) conducted a pilot study of multiple existing petroleum fields in the Illinois Basin for the CO_2 storage potential through EOR activities to assess dual benefit of increased oil production and storage of anthropogenic CO_2 (Damico et al., 2014). Research on the Mississippian

Cypress Sandstone (Knepp et al., 2009) suggests that this formation offers both potential for storage or a target for CO_2 EOR. The sandstone can be over 100 feet (30 m) thick in the East Sub-Basin and is predominantly a saline reservoir except on structural high areas where it contains hydrocarbons. Current research is exploring residual oil zones (ROZ) within these thick, fluvial facies to determine the CO_2 storage and EOR resource potential.

Mt. Simon Sandstone

The Mt. Simon has excellent properties for large-scale carbon storage: it is deeply buried with pressures and temperatures maintaining CO_2 as supercritical; contains highly saline formation fluids; has a tremendous storage capacity (12 to 172 GT; US DOE, 2015); is overlain by numerous laterally extensive sealing formations; and has suitable petrophysical characteristics for injection. In the East Sub-Basin study area, the Mt. Simon Sandstone can be 1,000 to over 2,000 feet (305 to over 610 m) in thickness occurring 6,000 to 10,000 feet (1830 to 3050 m) in depth (Figures 2 and 3). The Mt. Simon Sandstone can be divided into Lower, Middle, and Upper sections based on petrophysical, depositional and diagenetic attributes (Leetaru and McBride, 2009; Medina and Rupp, 2012; Freiburg et al., 2016).

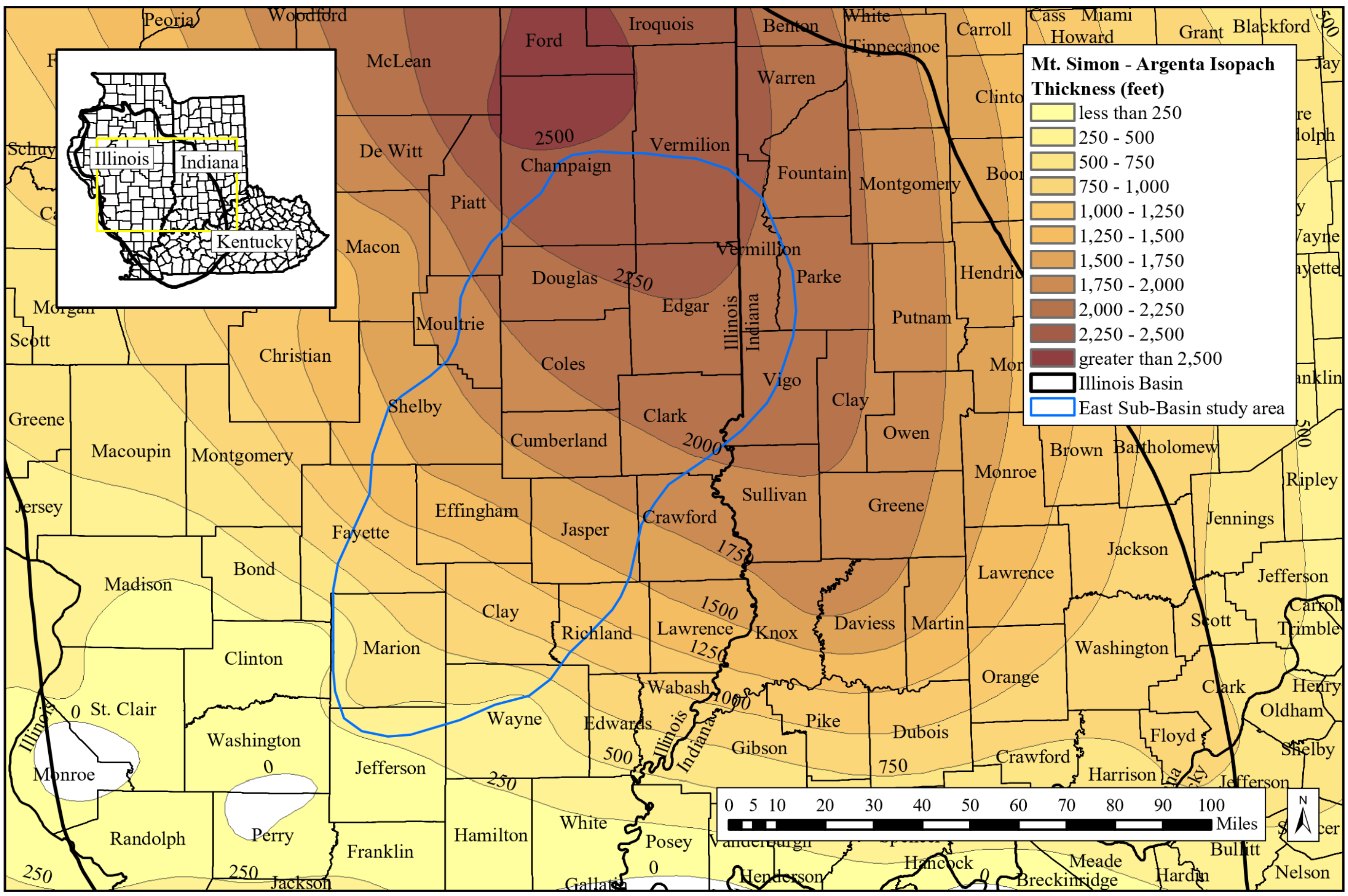

Figure 2. Regional Isopach (thickness in ft) of the Mt. Simon Formation in the expanded East Sub-Basin study area

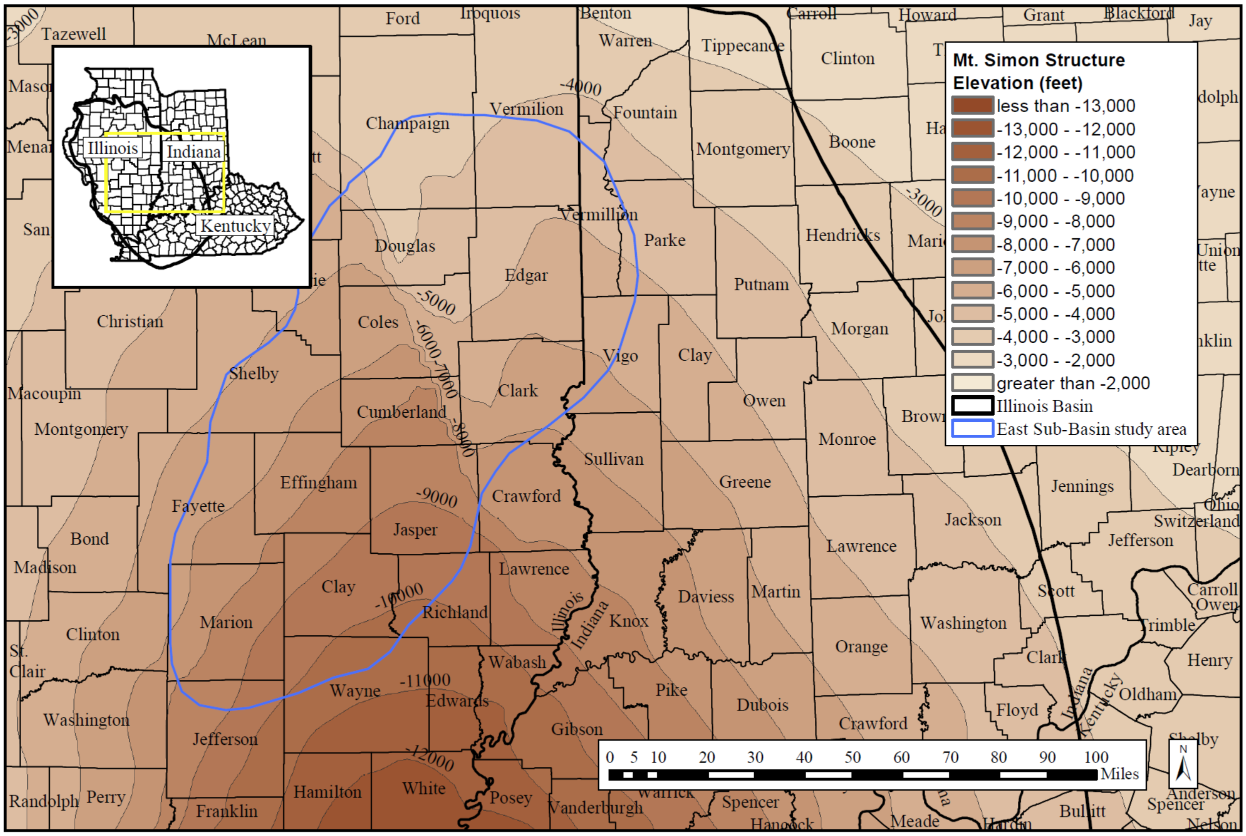

Figure 3. Regional Structure (elevation in ft) of the Mt. Simon Formation in the expanded East Sub-Basin study area.

The Lower Mt. Simon is considered the best potential reservoir for carbon storage, with the highest quality reservoir found within a highly arkosic zone. Lower Mt Simon well logs and regional trends indicate porosity and permeability are 16.3% and 11.1 mD (Mehnert et al., 2014). The Hinton #7 well, located in the Manlove Natural Gas Storage Field, Champaign Co., Illinois, has 215 feet (66 m) of excellent quality reservoir in the arkose zone with porosity and permeability values up to 25% and 600 mD. At IBDP and IL-ICCS the Lower Mt. Simon Sandstone has porosity and permeability as high as 27% and 400 mD, and a mean (log) porosity of 16.6%. Lateral continuity of the high quality reservoir in the Lower Mt. Simon is uncertain because of limited well control, but most wells within the southern half of the Mt. Simon depocenter that penetrate the Lower Mt. Simon show the occurrence of a porous zone (Figure 4).

The Middle and Upper Mt. Simon generally demonstrate poorer reservoir properties except in thin tidal flat channel sands in the Upper Mt. Simon where they are utilized for natural gas storage (Morse and Leetaru, 2005). The Upper Mt. Simon is a heterogeneous sandstone interbedded with shale that also possesses fair quality reservoir characteristics, and is used for natural gas storage and waste disposal. Regional log averages of Upper Mt. Simon porosity and permeability are 8.5% and 5.4 mD, respectively, although more porous and permeable units are present.

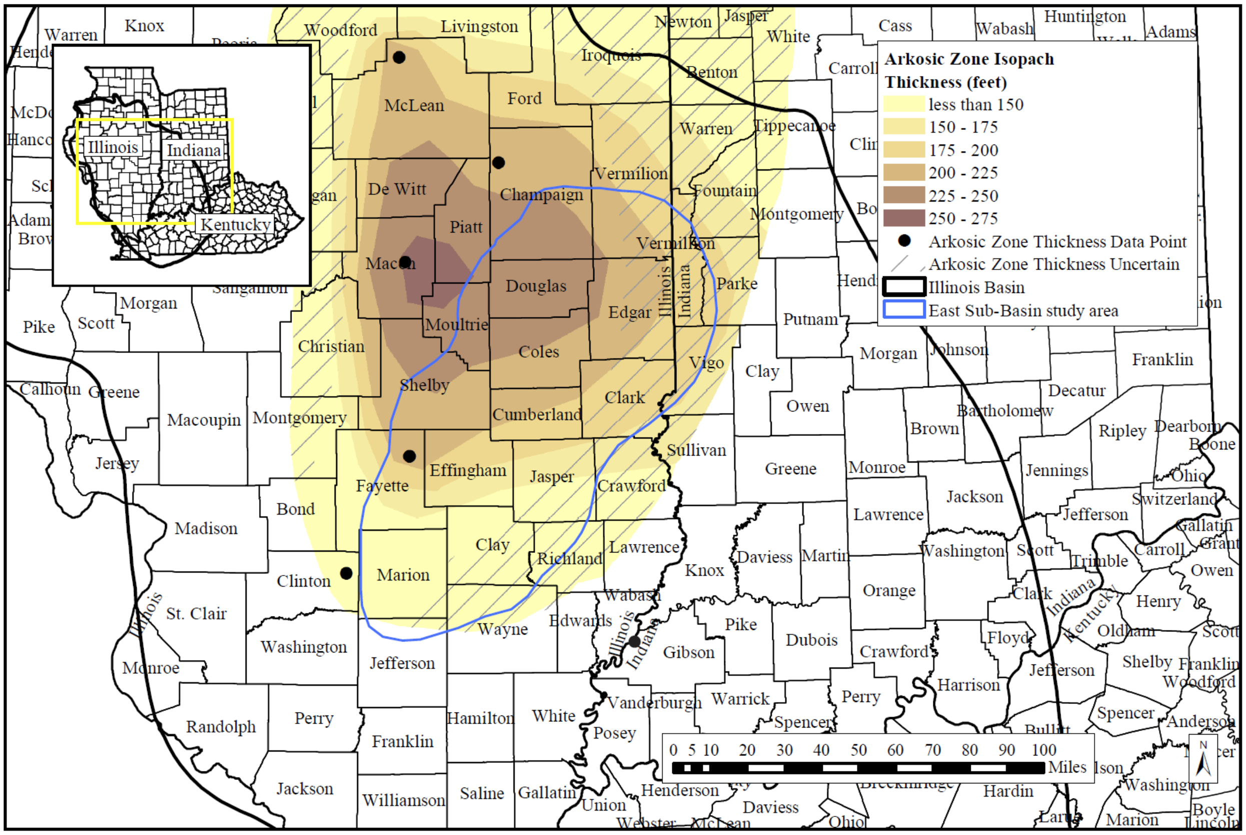

Figure 4. Regional Isopach (thickness in ft**)** of highly arkosic zone in the Lower Mt. Simon Sandstone.

Knox Carbonates

The Cambrian and the Lower through lowermost Middle Ordovician rocks of the Illinois Basin that overly the Mt. Simon Sandstone are classified as the Knox Dolomite Megagroup (Buschbach, 1975). There are over 2,000 feet (610 m) of Knox carbonates present in most of the East Sub-Basin. The Knox Group is an attractive target for CO_2 sequestration because these strata are laterally extensive, contain beds of porous and permeable dolomites and sandstones, and also contain numerous impermeable shale and carbonate seals. The Potosi Dolomite, a formation within the Knox, is characterized by up to 7 feet (2 m) thick vuggy intervals and brecciated zones that suggest a paleokarst environment (Freiburg and Leetaru, 2012), and is a viable storage target as reservoir modeling suggests that it could contain approximately 90 million tonnes of CO_2 from a single injection well (Will et al., 2014). The Potosi's excellent reservoir properties have been further documented by a chemical waste disposal project at Tuscola, Illinois, that has already injected over 50 million tonnes of CO_2 equivalent of liquid chemical waste into the dolomite (Leetaru, 2014a).

St. Peter Sandstone

The St. Peter Sandstone reservoir offers high potential for sequestration of CO_2, as it is porous and permeable across most of Illinois. About 50 miles southeast of the East Sub-Basin the St. Peter Sandstone has been used for natural gas storage (Udegbunam et al., 1993). In the East Sub-Basin study area the top of the St. Peter Sandstone occurs between 3,500 to 6,500 feet (1065 to 1980 m) and has a thickness of 20 to 200 feet (6 to 60 m). The following may be inferred from reservoir flow simulation using the rock properties expected in the study area (Will et al., 2014): at depths of 3,500 ft. (1065 m) an injection rate of

3.2 MTPA for a 30 year period may be achieved with a single well; at 4,000 feet (1220 m) and deeper, two or more injection wells would be required.

Cypress Sandstone

The shallowest of the potential targets are upper Pennsylvanian and lower Mississippian strata dominated by siliciclastic cyclic sediments with regional and localized shales. The Mississippian Cypress Sandstone has potential to be an EOR candidate and storage reservoir as it has numerous shales overlying it that have held hydrocarbons for over 260 million years. During the MGSC's Phase I Regional Partnership study, five fields in the East Sub-basin were selected for detailed analysis of improved oil recovery during CO_2 injection (Finley, 2005) including the Cypress Sandstone. Reservoir flow simulation suggested that there could be between 6 to 12% additional oil recovered using CO_2 injection in both immiscible and miscible conditions.

The Cypress has numerous opportunities for saline reservoir sequestration in the East Sub-Basin areas without oil fields – both as strict saline storage and storage associated with ROZ. The ISGS has developed a reservoir-specific workflow to identify non-conventional ROZ clastic reservoirs in the Illinois Basin through DOE funded research on the Cypress Sandstone (Webb et al., 2016). A northeast-southwest trend of thick Cypress Sandstone shows strong evidence that ROZs are pervasive. The associated storage potential in these ROZ fairways, not accounting for main pay zones or underlying brine formations, is estimated to 6.9 billion tonnes for continuous CO_2 flooding.

Saline Storage Complexes in the East Sub-Basin

Regional data in the US DOE's NATCARB system were used to estimate the CO_2 storage resource of the four reservoirs in the East Sub-Basin (Table 2): the Mt. Simon Sandstone, Knox Group, St. Peter Sandstone, and the Cypress Sandstone. The storage resource estimates are based on regional assessment work for the US DOE-NETL (RCSP and American Recovery and Reinvestment Act (ARRA) Site Characterization programs, and are supplemented with new mapping focused on the lower Mt. Simon Sandstone.

Table 2. Regional CO_2 storage resource estimates (million tonnes) for saline formations in the Illinois East sub-basin. *The P50 scenario was not assessed for the Knox group, but a reasonable P50 approximation is 36% of the P90 storage value. Figures have been rounded.

Reservoir	CO_2 Storage Resource - East Sub-Basin (Mt)		
	P10	P50	P90
Cypress Sandstone	8	38	105
St. Peter Sandstone	83	325	877
Knox Carbonate	1,662	5,157*	14,325
Mt. Simon Sandstone	1,997	9,988	27,468
Total	3,750	15,508	42,775

Recent work in the East Sub-Basin region has focused on a high-porosity, highly arkosic zone within the Lower Mt. Simon Sandstone. Because of the sparsity of wells in the Illinois Basin that penetrate into the Lower Mt. Simon, the lateral extent of this reservoir is not well known. Figure 4 shows the preliminary interpolated regional extent and thickness of this 'arkosic zone,' from which updated CO_2 storage resource estimates were derived.

Previous regional storage estimates of the Mt. Simon Sandstone assumed a conservative 8% porosity over the entire Mt. Simon thickness. However, log analysis shows the arkosic zone in the Lower Mt. Simon has average porosities approaching 19%. Using an average porosity representative of the arkosic zone (20%) yields total Mt. Simon CO_2 storage resource estimates ranging from 2.0 to 27.5 billion tonnes over the East Sub-Basin project area (primary and secondary areas of interest). The incremental storage (0.4 to 5.0 billion tonnes) in the refined arkosic zone map represents roughly a 22% increase in the estimated Mt. Simon storage resource over the East Sub-Basin study area, and highlights the importance of this reservoir zone as a prospective storage resource play (SPE, 2016) within the Lower Mt. Simon Sandstone in the eastern Illinois Basin.

Regional CCS Network Example

Commercialization of large-scale Carbon Capture and Storage in the Illinois Basin may be realized by taking advantage of CCS tax credits (under 26. U.S. Code § 45Q and 2018 FUTURE Act amendments) and potential revenue from sale of CO_2 for EOR. A 50 million tonnes CO_2 storage operation would primarily target capacious saline reservoirs able to store this large volume at a single location, the cost of which may be offset, at least partially, by regional CO_2 EOR interests in the long-term. Prospects for CO_2-EOR in the Illinois East Sub-Basin are discussed in a separate topical report, thus a saline storage case study is presented here that focuses on a specific arkosic reservoir zone in the Lower Mt. Simon Sandstone.

Recent research in the East Sub-Basin region has focused on a high-porosity, highly arkosic zone within the Lower Mt. Simon Sandstone, the reservoir zone on which two CO_2 storage projects at Decatur, IL (IBDP and IL-ICCS) have focused their CO_2 injection activities. Because of the sparsity of wells in the Illinois Basin that completely penetrate the Lower Mt. Simon, the lateral extent of this reservoir is not well defined. Figures 4 and 5 show the preliminary interpolated regional extent and thickness of this arkosic zone, from which updated CO_2 storage resource estimates were derived. Based on this work, we present a conceptual CO_2 source and storage network, which focuses on the arkosic zone in the Lower Mt. Simon as a prospective storage resource play in the region including the Illinois East Sub-Basin.

The optimal locations for CO_2 injection in the Lower Mt. Simon's arkosic zone do not necessarily match the locations of CO_2 sources. For example, some sources like ADM, Abbott Power Plant, One Earth Energy, and the proposed Cronus Chemical Fertilizer plant, are located close to known and inferred areas of thick arkosic strata, while other sources, like Gibson Generating Station, Edwardsport Power Station, and Prairie State Generating Company, are located where the arkosic zone is not mapped (Figure 5). The proximal sources to the arkosic zone would generally require less additional pipeline infrastructure than the distal sources. The latter group of distal sources may require additional characterization of the Lower Mt. Simon or consideration of alternative stratigraphically higher storage targets, such as the Knox group or St. Peter Sandstone, as more economical local storage targets.

In our regional CCS network example, pipeline routes would likely follow existing rights-of-way. By leveraging existing corridors, financial, environmental, and social benefits may help minimize the impact of any new potential pipeline construction. Example corridors presented in the map (Figure 5) are highways, railroads, electrical transmission lines, and generalized natural gas pipelines. Although this is an incomplete picture of potential pipeline rights-of-way (e.g. oil pipeline locations are deemed confidential, and are not shown here), it illustrates conceptual transport routes for an example network of sources tied to a prospective storage resource play in the Lower Mt. Simon Sandstone. The CO_2 sources presented here are located near lines of transport, and routes can be traced from each source toward a hypothetical injection site near the projected area where the arkosic zone in the Lower Mt. Simon is thickest, in east-central Illinois.

Once a saline reservoir storage location is established for a large-scale source(s), it is possible that relatively smaller sources (e.g., University of Illinois) could take part in a storage 'hub' context, thereby leveraging the injection operations and infrastructure of a larger project. This is akin to the idea for CO_2 EOR at smaller vs. larger oil fields presented in Monson et al. (2014), whereby small oil fields (near larger fields) can tie into a larger field's CO_2 infrastructure. Although the economics are somewhat different for CO_2 EOR operations than for saline storage, the Monson et al. CO_2 EOR study showed that the distance away from a storage hub location (i.e. large oilfield/CO_2 EOR operation) impacted small-field cost/benefit considerations—and that distance-related economic limits (primarily due to pipeline diameter/length and cost) may exist for small fields/projects.

Transportation costs have not been considered in the regional source and storage network example presented here, but simulation and system analysis of CO_2 capture, transport, and storage options can be a next step, especially for interested parties or early adopters.

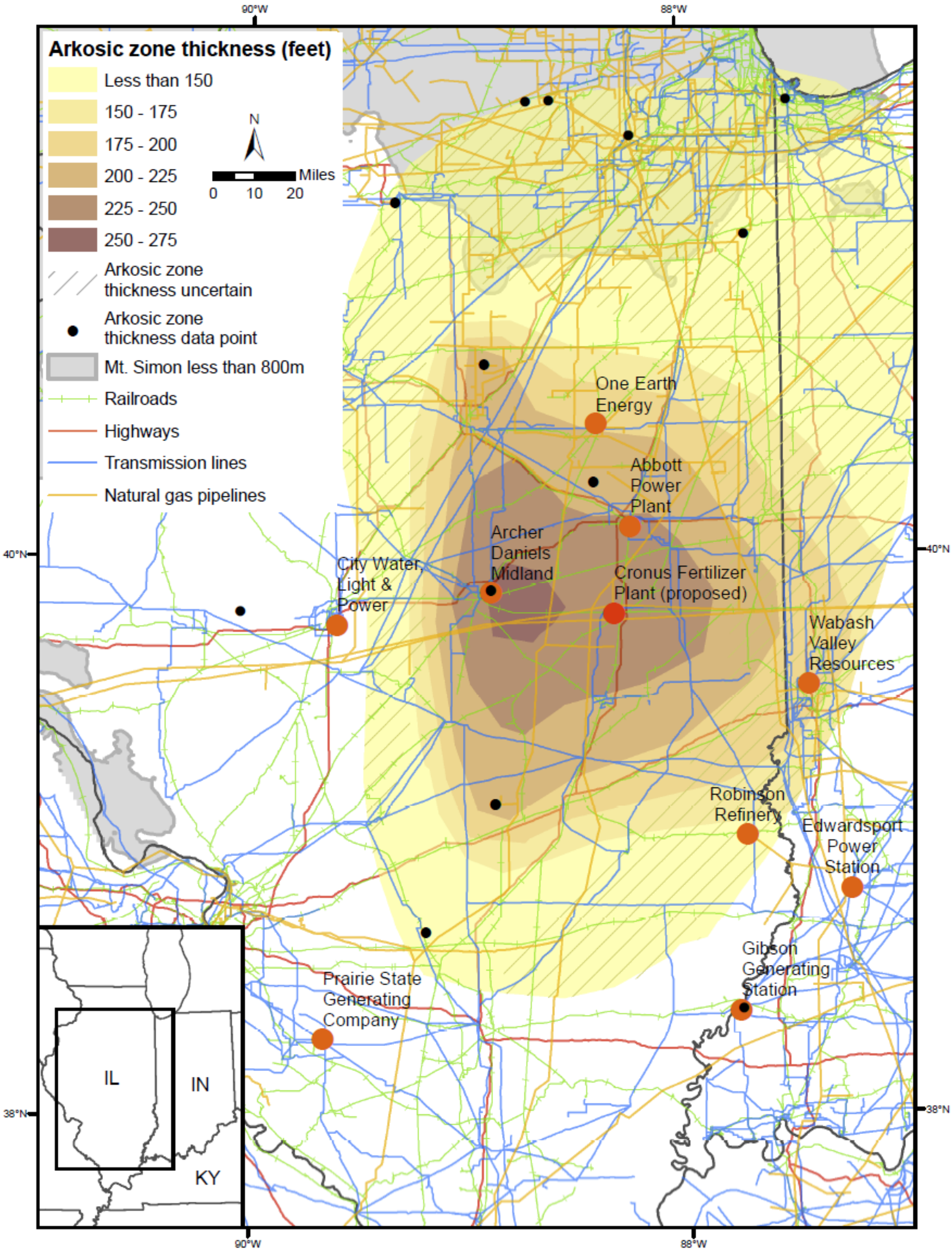

Figure 5. Map showing regional thickness of highly arkosic zone in the Lower Mt. Simon Sandstone, regional CO_2 sources considered in this study, and conceptual pipeline corridors based on existing rights-of-way (e.g. railroads, highways, transmission lines, and natural gas pipelines).

References

Bowersox, J. R. 2013. Evaluation of Phase 2 CO_2 injection testing in the deep saline Gunter Sandstone reservoir (Cambrian–Ordovician Knox Group), Marvin Blan No. 1 Well, Hancock County, Kentucky: Series 12, Contract Report 53. *Kentucky Geological Survey.*

Buschbach, T.C. 1975. Cambrian System. In: Willman, H.B., Atherton, E., Buschbach, T.C., Collinson, C., Frye, J.C., Hopkins, M.E., Lineback, J.A., Simon, J.A. (eds.), Handbook of Illinois Stratigraphy, p. 34-46.

Chessie-Seaboard Merger (CSX), 2019, Select Sites, available from: https://www.csx.com/index.cfm/customers/industrial-development/search-property-types/csx-select-sites/.

Damico, J.R., C.C. Monson**,** S. Frailey, Y. Lasemi, N.D. Webb, N. Grigsby, F. Yang, and P. Berger. 2014. Strategies for advancing CO_2 EOR in the Illinois Basin, USA. 12th International Conference on Greenhouse Gas Technologies (GHGT-12) Proceedings. *Energy Procedia* 63: 7694–7708.

Dipietro, P., Nichols, C., Eppink, J., Marquis, M. & Manfredo, L. 2009. Database and Model of Coalfired Power Plants in the United States for Examination of the Costs of Retrofitting with CO2 Capture Technology, DOE/NETL-402/030809.

Duke Energy, 2019, Compliance and Reporting, available from: https://www.duke-energy.com/our-company/environment/compliance-and-reporting/ccr-rule-compliance-data.

Ellett, K. M., R. S. Middleton, P. H. Stauffer, J. A. Rupp, Facilitating CCS Business Planning by Extending the Functionality of the SimCCS Integrated System Model, Energy Procedia, Volume 114, 2017, Pages 6526-6535.

Finley, R. 2005. An Assessment of Geological Carbon Sequestration Options in the Illinois Basin, Final Report for U.S. DOE Contract: DE-FC26-03NT41994. *U.S. Department of Energy.*

Freiburg, J. T., Ritzi, R. W., and Kehoe, K. S. (2016). Depositional and diagenetic controls on anomalously high porosity within a deeply buried CO_2 storage reservoir—The Cambrian Mt. Simon Sandstone, Illinois Basin, USA. *International Journal of Greenhouse Gas Control*, *55*, 42-54.

Freiburg, J. T. and Leetaru, H. E. Controls on porosity development and the potential for CO_2 sequestration or waste water disposal in the Cambrian Potosi Dolomite (Knox Group): Illinois Basin. In 41st Annual Eastern Section AAPG Meeting. Program Abstracts, 2012.

Knepp, R., Frailey, S., Grube, J., Seyler, B., Garner, D., Korose, C., Huff, B., Damico, J. and Rittenhouse, S. 2009. CO_2 sequestration and enhanced oil recovery potential in Illinois Basin oil reservoirs. *In: Carbon dioxide sequestration in geological media—State of the science: Studies in Geology, AAPG.*

Lasemi, Y. and Khorasgani, Z. 2014. Stratigraphy of the Cambro-Ordovician Succession in Illinois: Topical Report DE-FE0002068. *U.S. Department of Energy.*

Leetaru, H. E. 2014a. An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins, Final Report DE-FE0002068. *U.S. Department of Energy*.

Leetaru, H. E. and McBride, J. H. (2009). Reservoir uncertainty, Precambrian topography, and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin. *Environmental Geosciences*, *16*(4), 235-243.

Medina, C. R. and Rupp, J. A. 2012. Reservoir characterization and lithostratigraphic division of the Mount Simon Sandstone (Cambrian): Implications for estimations of geologic sequestration storage capacity. *Environmental Geosciences,* 19, 1–15.

Mehnert, E., J. Damico, S. Frailey, H. Leetaru, R. Okwen, B. Storsved, and Valocchi, A. (2014). Basin-scale modeling for CO_2 sequestration in the basal sandstone reservoir of the Illinois Basin—Improving the geologic model: *Energy Procedia*, v. 63, p. 2949–2960.

Monson, C. C., C. P. Korose, and S. M. Frailey, Screening methodology for regional scale CO_2 EOR and storage using economic criteria, Energy Procedia, Vol. 63, 2014, p. 7796-7808.

Morse, D. G. and Leetaru, H. E. 2005. Reservoir characterization and three dimensional models of Mt. Simon gas storage fields in the Illinois Basin. *Illinois State Geological Survey Circular 567.*
Sexton, A., and McKaskle, R., 2018. Transportation and Infrastructure Assessment Subtask 5.2, Topical Report: DOE/ FE0029445-3. U.S. Department of Energy.

Society of Petroleum Engineers (SPE), 2016, CO_2 Storage Resources Management System, available from: https://www.spe.org/industry/CO2-storage-resources-management-system.php.

Trimeric. 2018. Memorandum to Steven Whittaker, ISGS: "High-Level Cost Estimate for CO_2 Capture and Transportation Costs: CarbonSAFE Phase2 Illinois – Christian County, Rev. 1" (November 2018).

Udegbunam, E. O., Beaty, D. S. and Fagan, J. P. 1993. Strategies for improved oil recovery from Aux Vases reservoirs in McCreery and McCullum waterflood units, Dale Consolidated Field, Franklin County, Illinois: Champaign, IL. *Illinois State Geological Survey*, 39.

United States Department of Energy (US DOE), (2015). Carbon Storage Atlas: 5th edition: Washington, D.C., U.S. Department of Energy, 113 p.

Vinodkumar, P., O'Brien, K., and Korose, C., 2018. An assessment of potential CO_2 Sources throughout the Illinois Basin Subtask 5.1 – CO_2 Source Assessment, Topical Report: DOE/ FE0029445-2. U.S Department of Energy.

Wang, S., K. M. Ellett, A. M. Ardekani, Assessing the Utility of High-level CO2 Storage and Utilization Resource Estimates for CCS System Modelling, Energy Procedia, Volume 114, 2017, p. 4658-4665.

Webb, N. D., and N. P. Grigsby, *in press*, Assessing the Cypress Sandstone for CO_2-Enhanced Oil Recovery and Carbon Storage: Part I - Reservoir Characterization of Noble Oil Field, Western Richland County, Illinois: Urbana, IL, Illinois State Geological Survey, 59 p.

Webb, N. D., N. P. Grigsby, J. J. Arneson, L. G. Giannetta, and S. M. Frailey, 2016, The Mississippian Thick Cypress Sandstone: A Nonconventional CO_2-EOR Target in the Illinois Basin, American Association of Petroleum Geologists Annual Convention and Exhibition

Will, R., Smith, V. and Leetaru, H. E. 2014. Utilization of the St. Peter Sandstone in the Illinois Basin for CO_2 Sequestration, Topical Report DOE/FE0002068-7. *U.S. Department of Energy*, 54.