Appendix B

I. Introduction

As described in comments, carbon capture and sequestration is adequately demonstrated and available at costs that are not exorbitant. In 2014, CATF submitted extensive comments on carbon capture and geologic sequestration, which we incorporate and attach here,[1] and this Appendix supplements those comments with information arising since that time.

II. Types of Capture Technology

a. CO_2 Capture has been Demonstrated at Commercial Scale for Decades.

Large scale CO_2 separation routinely occurs in gas processing and many other industrial applications.[2] Additionally, carbon dioxide capture from industrial air emissions streams, including from facilities burning coal, has occurred since the 1930s at a variety of industrial facilities, both in the U.S. and abroad, which need to remove CO_2 as a processing step.[3] Commercial scale capture projects in power generation have been established at Petra Nova W.A. Parish project and SaskPower's Boundary Dam 3 project.

There are three technically feasible technologies for capturing CO_2 from power generation, which are being demonstrated around the world: pre-combustion capture, post-combustion capture and oxyfuel capture. EPA has correctly recognized, each of these three carbon capture approaches is "technically feasible and available throughout most of the United States."[4] The selection of technology is specific to each facility and depends on considerations such as percentage capture, cost, plant locations, water requirements and availability as well as plant characteristics such as efficiency, capacity and space.

i. Pre-Combustion Systems are Demonstrated and Commercially Available at Large Scale.

Pre-combustion capture of CO_2 is the process by which CO_2 is removed from the syngas of a coal gasification plant so that the remainder is mostly hydrogen.[5] To accomplish the CO_2 removal, two steps are required in addition to the initial gasification: carbon monoxide in the syngas must be converted to CO_2 and hydrogen (in an operation called a 'water-gas shift reaction') and the CO_2

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[1] *See* Comment submitted by CATF & Partial Carbon Capture and Storage Retrofit Technical Appendix (Modified and Reconstructed Sources), Doc. No. EPA-HQ-OAR-2013-0603-0280 (Oct. 16, 2014) (Attach. H); Supplemental comment submitted by CATF & Technical Appendix (New Source Performance Standards) Doc. No. EPA-HQ-OAR-2013-0495-9664 (May 9, 2014) (Attach. I); Comment submitted by CATF (Clean Power Plan) & Attached Apps. and Exs., Doc. No. EPA-HQ-OAR-2013-0602-25574 (Attach. J).

[2] *See generally* Global CCS Institute, *The Global Status of CCS: 2017*, https://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/uploads/global-status/1-0_4529_CCS_Global_Status_Book_layout-WAW_spreads.pdf [hereinafter "*Global Status of CCS 2017*"].

[3] CPP RIA at 2-31.

[4] Abatement Measures TSD, ch. 7; CPP RIA at 2-29 – 2-39.

[5] *See generally*, Global CCS Institute, *Global Status of CCS 2013*, ch. 5 (Aug. 1, 2013) https://www.globalccsinstitute.com/publications/global-status-ccs-2013.

must be removed through an 'acid gas removal' step (AGR system). By varying the hydrogen to carbon monoxide ratio through the number of shift operations and AGR, the final concentration of CO_2 emitted after combusting the syngas can result in an overall 90 percent CO_2 reduction or in varying removal levels such as 65 percent, 30 percent or no removal at all.

A 2016 DOE database includes a total of 1.014 projects, consisting of 12,559 gasifiers (excluding spares), of which 356 projects with 863 gasifiers are active commercial operating projects.[6] All three of those processes (ammonia production, SNG, and liquid fuels production) entail significant amounts of syngas 'shift' and AGR. For many of these projects, the Rectisol® pre-combustion capture process of the German firms Linde or Lurgi is used (*e.g.*, Dakota Gasification in the United States[7] and Sasol in South Africa[8]); for others, UOP's Selexol™ process has been used (*e.g.*, the Coffeyville Syngas Plant in Kansas[9]). The total thermal capacity of these projects exceeds 20,000 MW, and some have been operating for decades.[10] CO_2 captured at the Dakota Gasification project is transported by pipeline to Canada, where it is used for EOR and sequestered. The CO_2 from the Coffeyville plant is transported by pipeline to Chaparral's oil fields at its North Burbank Unit in Osage County, Oklahoma for EOR where injection began on June 6, 2013.[11]

Additionally, pre-combustion capture systems have been commercially available for decades. The Rectisol® process uses methanol in subzero temperatures to remove CO_2 to a ppm level.[12] It has been available for decades, and over 50 Rectisol® units are in operation worldwide on gasifiers. [13] The Selexol™ process is offered by UOP, a Honeywell company.[14] The technology removes CO_2 using a physical solvent. Over 115 plants around the world have use the technology around the world.[15]

ii. Post-Combustion Systems are Demonstrated and Commercially Available at Large Scale

[6] Chris Higman, *State of the Gasification Industry: Worldwide Gasification and Syngas Databases: 2016 Update*, (Oct. 2016), *https://www.globalsyngas.org/uploads/downloads/2016-Wed-Higman.pdf*.

[7] *See* U.S. DOE, Office of Fossil Energy, *Practical Experience Gained During the First Twenty Years of Operation of the Great Plains Gasification Plant and Implications for Future Projects*, at 24 (2006), http://www.fossil.energy.gov/programs/powersystems/publications/Brochures/dg_knowledge_gained.pdf.

[8] *See* Koss, U., *State Of The Art Gas Technologies For Zero Emission IGCCs*, at 8 (2002), http://www.cooretec.de/lw_resource/datapool/Neuigkeiten/technologies_co2_separation.pdf.

[9] UOP, *UOP Selexol Technology for Acid Gas Removal*, at 23 (2009), http://www.uop.com/wp-content/uploads/2011/02/UOP-Selexol-Technology-for-Acid-Gas-Removal-tech-presentation.pdf.

[10] CATF analysis of U.S. DOE data. The U.S. DOE data is *available at*: http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasification-plant-databases/2010-archive.

[11] "Chaparral Energy Begins CO2 Injection at EOR Field in North Burbank," World Oil News (July 1, 2013), http://www.worldoil.com/Chaparral-Energy-begins-CO2-injection-at-EOR-project-in-North-Burbank-field.html.

[12] NETL, "Acid Gas Removal (AGR)," https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/rectisol.

[13] *See* HEI, L.L.C., *HECA Feasibility study*, Report #23 – AGR Licensor Evaluation, at 3-4 (Feb. 7, 2010), http://www.cpuc.ca.gov/NR/rdonlyres/538A0BA6-F6C9-495D-B13B-1399E446CDEC/0/23AGRLicensorEvaluation7Feb2010.pdf.

[14] UOP, *UOP Selexol Technology for Acid Gas Removal*, at 23 (2009) http://www.uop.com/wp-content/uploads/2011/02/UOP-Selexol-Technology-for-Acid-Gas-Removal-tech-presentation.pdf.

[15] Honeywell, UOP, "Technologies for Efficient Purification of Natural and Synthetic Gases," https://www.uop.com/technologies-for-efficient-purification-of-natural-and-synthetic-gases/.

Post-combustion capture systems describe a variety of approaches including chemical scrubbing with amines, membranes separation, adsorption onto structures such as metal-organic frameworks, and cryogenic separation. Chemical scrubbing with amines is the most widely used approach for removing CO_2 from coal-fired and gas-fired power plants. The flue gas contacts the amine in a tall vertical, packed tower called an absorber. The CO_2 binds to the amine and leaves the top of the absorber while the cleaned flue gas leaves the bottom. Next the amine-CO_2 liquid enters a stripper which uses heat to break the amine-CO_2 bond liberating the CO_2 for compression, transport and storage underground. The amine is recycled back to the absorber.[16] Amine scrubbing is used in both SaskPower and Petra Nova. Prior to application in the power sector, it has a long and successful history of application successfully to removing CO_2 from fossil fuel gases as shown in the table below:

Table 1 - Significant Post-Combustion CO_2 Capture Projects[17]

Vendor	Location	Exhaust Stream	CO_2 Use
ABB	Searles Valley, CA	Coal Boiler	Chemicals Industry
ABB	Warrior Run, MD	Coal Boiler	Food Industry
ABB	Shady Point, OK	Coal Boiler	Food Industry
TPRI	Shanghai, PRC	Coal Boiler	Food Industry
TPRI	Beijing, PRC	Coal Boiler	Demonstration, Food
MHI	Kedah Darul Aman, Malaysia	NG fired SR flue gas*	Urea production
MHI	Aonla, India	NG fired SR flue gas*	Urea Production
MHI	Phulpur, India	NG fired SR flue gas*	Urea Production
MHI	Kakinada, India	NG fired SR flue gas*	Urea Production
MHI	Vijaipur, India	NG fired SR flue gas*	Urea Production
MHI	Bahrain	NG fired SR flue gas*	Urea Production
MHI	Phu My, Vietnam	NG fired SR flue gas*	Urea Production
MHI	Fukuoka, Japan	NG fired SR flue gas*	General use
MHI	Abu Dhabi, UAE	NG fired SR flue gas*	Urea Production
MHI	District Ghotoki, Pakistan	NG fired SR flue gas*	Urea Production
MHI	Kedah Darul Aman, Malaysia	NG fired SR flue gas*	Urea production
MHI	Plant Barry, AL	Coal Boiler	Demo (amine)

[16] Howard Herzog, CARBON CAPTURE, 42-43, MIT Press Essential Knowledge Series, (2018) https://mitpress.mit.edu/books/carbon-capture.

[17] Unless otherwise indicated, the MHI project listed here are from https://www.mhi.com/products/environment/carbon_dioxide_recovery_process_commercial.html and Fluor projects listed here are from http://www.fluor.com/econamine/Pages/projectsites.aspx, ABB projects are from http://www.ieaghg.org/rdd/gmap/searchresultsgmap.php?keyword=Operational+Large+scale+Project. The Mongstad project is described in "Request for Interest: Carbon Capture Technology Tests at Available site, TCM DA, Mongstad, Norway, Cycle 1," App. 2 (Apr. 10, 2012) http://www.tcmda.com/Global/Dokumenter/RFI%20for%20utilisation%20of%20available%20site.pdf. The TPRI projects are described in IEA, *Facing China's Coal Future: Prospects and Challenges for Carbon Capture and Storage*, at tbls. 2 & 4, (2012), https://www.iea.org/publications/insights/insightpublications/facing-chinas-coal-future--prospects-and-challenges-for-carbon-capture-and-storage.html.

Fluor	Bellingham, MA	Gas Turbine Exhaust	Food Industry
Fluor	Lubbock, TX	Natural Gas	Enhanced Oil Recovery
Fluor	Carlsbad, NM	Natural Gas	Enhanced Oil Recovery
Fluor	Santa Domingo, DR	Light Fuel Oil	Enhanced Oil Recovery
Fluor	Barranquilla, Columbia	Natural Gas	Food Industry
Fluor	Quito, Ecuador	Light Fuel Oil	Food Industry
Fluor	Brazil	NG / Heavy Fuel Oil	Food Industry
Fluor	Rio de Janeiro, Brazil	Steam Reformer	Methanol Production
Fluor	Sao Paulo, Brazil	Gas Engine Exhaust	Food Production
Fluor	Argentina	Steam Reformer	Urea Plant Feed
Fluor	Spain	Gas Engine Exhaust	Food Industry
Fluor	Barcelona, Spain	Gas Engine Exhaust	Food Industry
Fluor	Bithor County, Romania	Heavy Fuel Oil	Food Industry
Fluor	Cairo, Egypt	Light Fuel Oil	Food Industry
Fluor	Israel	Heavy Oil Boiler	Food Industry
Fluor	Uttar Pradesh, India	NG Reformer Furnace	Urea Plant Feed
Fluor	Sechuan Province, PRC	NG Reformer Furnace	Urea Plant Feed
Fluor	Singapore	Steam Reformer	Food Industry
Fluor	San Fernando, Philippines	Light Fuel Oil	Food Industry
Fluor	Manila, Philippines	Light Fuel Oil	Food Industry
Fluor	Osaka, Japan	LPG	Demo Plant
Fluor	Chibu, Japan	Refinery Gas Mixture Heavy Fuel Industry	Food Industry
Fluor	Yokosuka, Japan	Coal/Heavy Fuel Oil	Demo Plant
Fluor	Botany Australia	Natural Gas	Food Industry
Fluor	Alton, Australia	Natural Gas	Food Industry
Alstom	New Haven, WV	Coal Boiler	Demo (ammonia)
Alstom	Mongstad, Norway	NG turbine/refinery	Demo (ammonia)
Aker	Mongstad, Norway	NG turbine/refinery	Demo (amine)

* MHI describes these as "post-combustion" capture projects, and the exhaust gas from which the CO_2 is separated is quite similar to conventional combustion gases (68% nitrogen, 8% CO_2, balance mostly water).[18]
+ Licensing of the PCC technology developed by Kerr-McGee[19] was transferred to ABB in 1990.

[18] Kamijo, *et al.*, *Recent technology development of KS-1 CO2 recovery process*, (May, 2004), http://www.netl.doe.gov/publications/proceedings/04/carbon-seq/038.pdf.
[19] Herzog, H. J., *The Economics of CO2 Separation and Capture*, tbl. 1, n. 1, http://www.me.unm.edu/~mammoli/ME561_stuff/economics_in_technology.pdf.

iii. Oxy-Combustion Capture Systems.

Oxy-combustion systems use high-purity O_2, rather than air, to combust coal and thereby produce a highly concentrated CO_2 stream.[20] The bulk of the nitrogen is removed from the air before combustion, resulting in CO_2 content up to 90 percent.[21] If regulations and geochemistry permit, the raw, dehydrated flue gas may be stored directly without further purification resulting in 100 percent capture.[22] This technology offers the lowest efficiency penalty and by its nature will be a "near zero" emitter of all criteria pollutants except, possibly, carbon monoxide.[23]

The most promising new oxyfuel technology under development is Net Power. Net Power believes their system will eventually rival the costs of electricity achieved by NGCC plants without carbon controls.[24] This gas-fired technology is in the demonstration stage at a 50 MW plant outside of Houston. This high pressure, oxy-combustion system uses supercritical CO_2 as the working fluid. CO_2 under these conditions offers thermodynamic efficiencies compared to steam-based systems. The inherent high pressure of the system reduces component size (reducing costs) and eliminates the costs of compression other systems incur to bring the CO_2 to pipeline or injection site pressures.[25] Plans for the technology also include a coal-based version that utilizes syngas derived from coal instead of methane.[26]

The Schwarze Pumpe oxyfuel pilot, southeast of Berlin in Germany, uses oxyfuel combustion and post-combustion to capture 75,000 tpa of CO_2.[27] The CO_2 was transported 400 km by road tanker, where it is injected into a depleted natural gas field.[28] The project consisted of a steam generator with a single 30 MW pulverized coal burner and the subsequent flue gas cleaning equipment.[29] The CO_2 purification and compression plant downstream produces liquid CO_2 and gaseous oxygen with a 99.5 percent purity.[30] The Schwarze Pumpe went into operation in 2008 and Vattenfall announced in November 2009 that it was achieving nearly 100 percent CO_2 capture.[31] The first test period of

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[20] *See generally*, Nicolas Perrin, *et al.*, *Oxycombustion for Carbon Capture on Coal Plants and Industrial Processes: Advantages, Innovative Solutions and Key Projects*, 37 Energy Procedia 1389-1404 (2013), http://www.sciencedirect.com/science/article/pii/S1876610213002580; Global CCS Institute, *CO_2 Capture Technologies: Oxy Combustion with CO_2 Capture*, at 3 (Jan. 2012), http://www.globalccsinstitute.com/publications/co2-capture-technologies-oxy-combustion-co2-capture/online/111741.
[21] *Id.*
[22] *Id.*
[23] *Id.*
[24] Bill Brown, "Demonstration and Commercialization of Net Power and Beyond," presented at 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, October 21-25, 2018 (photos of slides on file with CATF).
[25] Allam *et al.*, *High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide*, 37 Energy Procedia 1135 (2013), https://www.sciencedirect.com/science/article/pii/S187661021300221X.
[26] Xijia Lu, "Flexible Integration of the sCO2 Allam Cycle with Coal Gasification for Low-Cost, Emission-Free Electricity Generation," presented at 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, October 21-25, 2018 (Attach. K).
[27] MIT, "Schwarze Pumpe Fact Sheet," https://sequestration.mit.edu/tools/projects/vattenfall_oxyfuel.html; Vattenfall, "The Schwarze Pumpe Pilot Project," http://www.vattenfall.com/en/ccs/schwarze-pumpe.htm.
[28] *Id.*
[29] *Id.*
[30] *Id.*
[31] *Id.*

combustion with lignite ran from 2008 to 2011.[32] The second test period with bituminous coal began in 2012.[33] As of April 2011, the plant had accumulated 12,700 hours of operation.[34],[35] The pilot concluded operations in 2014.

The table below describes tests of other oxy-fired systems.

Table 2: Oxy-combustion Test Facilities and Pilot Projects[36]

Oxycombustion Test Facilities and Pilot Projects

Year Operational	Developer	Facility (Location)	Type	Size (MW)
2007	Babcock & Wilcox	CEDF (United States)	Test	30
2007	Jupiter Oxygen Corporation	Test Facility (United States)	Test	15
2008	Alstom*	Schwarze Pumpe (Germany)	Pilot	30
2008	ENEL/ITEA Isotherm	Test Facility (Italy)	Test	5
2009	Alstom	Lacq (France)	Pilot	35
2009	Doosan Babcock	Renfrew (Scotland)	Pilot	40
2009	Vattenfall*	Schwarze Pumpe (Germany)	Pilot	30
2010	Hitachi-Babcock*	Schwarze Pumpe (Germany)	Pilot	30
2011	Foster Wheeler	Compostilla	Pilot	30
2012	Petrobras	Paraná state, Brazil	Pilot	na
2013	IHI Corporation	Callide A (Australia)	Pilot	30

* —Schwarze Pumpe tests multiple technologies.
na —Not applicable, an industrial application, not power generation.

The ability of power systems to adopt CCS is due in large part from the experience of industrial projects that can be transferred to power applications. Listed below are key projects in the industrial sector that use CCS.

b. Examples of North American Integrated CO_2 Capture and Sequestration Projects in Other Industrial Applications.

1. Great Plains Synfuel Plant, North Dakota and Weyburn-Midale Project, Southeastern Saskatchewan, Canada (Synthetic Natural Gas):

The Great Plains Synfuel plant in North Dakota is a coal gasification facility that separates about 7,700 tpd of CO_2 for transportation by a pipeline crossing international borders, and injection for EOR into the Weyburn Field and sequestration in the Midale field in Saskatchewan, Canada.[37] EPA

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[32] MIT, "Schwarze Pumpe Fact Sheet," https://sequestration.mit.edu/tools/projects/vattenfall_oxyfuel.html; Vattenfall, "The Schwarze Pumpe Pilot Project", http://www.vattenfall.com/en/ccs/schwarze-pumpe.htm.
[33] *Id.*
[34] *Id.*
[35] Uwe Burchhardt, Göran Lindgre, Thomas Porsche, "Three years operational experiences with the Oxyfuel Pilot Plant of Vattenfall in Schwarze Pumpe," 2nd Oxyfuel Combustion Conference, https://ieaghg.org/docs/General_Docs/OCC2/Abstracts/Abstract/occ2Final00152.pdf
[36] IEA Greenhouse Gas R&D Programme, *Carbon Capture and Storage: Proven and it Works*, (Mar. 2014), http://www.ieaghg.org/docs/general_publications/CCS%20-%20Proven%20and%20it%20Works%20Update%20High%20Resolution.pdf.
[37] Global CCS Institute, "Great Plains Synfuel Plant and Weyburn-Midale Project," http://www.globalccsinstitute.com/project/great-plains-synfuel-plant-and-weyburn-midale-project; MIT, "Weyburn-

correctly noted that the plant is "functionally very similar to an electric power producing IGCC plant."[38] Over 20 Mt of CO_2 have been stored in these two fields since October 2000.[39] In addition to the purely commercial operation of this plant to produce synthetic natural gas and CO_2 for use in EOR, the project's sequestration operations are associated with a long-standing EOR monitoring and performance evaluation and research project, the IEAGHG Weyburn-Midale CO_2 Monitoring & Storage Project directed by the Petroleum Technology Research Centre.[40] Testing and evaluation of CO_2 sequestration monitoring methods include surface seismic, shallow groundwater, soil gas, and passive seismic techniques.[41] Covering more than 53,000 acres in southeast Saskatchewan, the area has undergone significant development of its oil and gas resources, notably water flooding and multi-leg horizontal well drilling.[42] In recent years, Cenovus has installed additional injection and production wells, pipelines for both oil production and injection of CO_2, as well as compression to increase the volume of CO_2 that is recycled.[43] The project and associated monitoring efforts demonstrate the permanence of CO_2 sequestration in developed oil fields.[44]

2. Air Products Steam Methane Reform Project (Hydrogen Production):

Air Products has built a state of the art system to capture CO_2 from two existing steam methane reformers located at the Valero Refinery in Port Arthur, Texas.[45] The CO_2 is captured by a pre-combustion system and delivered via a pipeline owned by Denbury Green Pipeline-Texas for injection into Denbury's Onshore EOR operations in Texas, in particular, its Hastings Field in Houston.[46] Approximately 1 Mtpa of CO_2 or 90 percent is recovered and purified at the plant.[47] The project started full-scale operations in April 2013.[48] DOE awarded the project $900,000 from the American Recovery and Reinvestment Act in October 2009 and an additional $253 million as part of DOE's CCS Program Phase 2 in January 2010, $368 million in private funding matched this

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Midale Fact Sheet," http://sequestration.mit.edu/tools/projects/weyburn.html; Petroleum Technology Research Centre, "Weyburn-Midale," http://ptrc.ca/projects/weyburn-midale.

38 EPA, "Technical Support Document: Effect of EPAct05 on BSER for New Fossil Fuel-fired Boilers and IGCCs," at 20 (Feb. 6, 2014), Docket ID No. EPA-HQ-OAR-2013-0495-187.

39 Global CCS Institute, "Great Plains Synfuel Plant and Weyburn-Midale Project," http://www.globalccsinstitute.com/project/great-plains-synfuel-plant-and-weyburn-midale-project; MIT, "Weyburn-Midale Fact Sheet," http://sequestration.mit.edu/tools/projects/weyburn.html; Petroleum Technology Research Centre, "Weyburn-Midale," http://ptrc.ca/projects/weyburn-midale.

40 Petroleum Technology Research Centre, "Weyburn-Midale," http://ptrc.ca/projects/weyburn-midale. *See also*, Brian Hitchon (Ed.), BEST PRACTICES FOR VALIDATING CO_2 GEOLOGICAL STORAGE: OBSERVATIONS AND GUIDANCE FROM THE WEYBURN-MIDALE CO_2 STORAGE PROJECT (2012).

41 Global CCS Institute, "Great Plains Synfuel Plant and Weyburn-Midale Project," http://www.globalccsinstitute.com/project/great-plains-synfuel-plant-and-weyburn-midale-project.

42 *Id.*

43 *Id.*

44 *Id.*

45 Global CCS Institute, "Air Products Steam Methane Reformer EOR Project," http://www.globalccsinstitute.com/project/air-products-steam-methane-reformer-eor-project; MIT "Port Arthur Fact Sheet," https://sequestration.mit.edu/tools/projects/port_arthur.html.

46 Denbury Resources, "CO2 Sources and Pipelines – Gulf Coast Region," http://www.denbury.com/operations/gulf-coast-region/co2-sources-and-pipelines/default.aspx.

47 Global CCS Institute, "Air Products Steam Methane Reformer EOR Project," http://www.globalccsinstitute.com/project/air-products-steam-methane-reformer-eor-project; MIT "Port Arthur Fact Sheet," https://sequestration.mit.edu/tools/projects/port_arthur.html.

48 *Id.*

money.[49] The DOE called the project a "first-of-a-kind, breakthrough project advances carbon capture, utilization and storage technologies and demonstrates the potential to safely secure carbon dioxide pollution underground while providing an economic benefit and increasing our energy security."[50]

3. Century Plant (Natural Gas Processing):

Century, located in Pecos County, Texas, uses captures CO_2 from a natural gas processing plant in West Texas using Honeywell's UOP Selexol CO_2 pre-combustion capture technology.[51] The plant has an operational CO_2 capture capacity of 8.4 Mpta, making it the largest single industrial source CO_2 facility in North America.[52] The CO_2 captured at the plant is transported by pipeline for EOR in the Kinder Morgan Permian delivery system.[53] The first train of the plant has been in operation since 2010, with a second coming on line in 2012.[54]

4. Coffeyville Gasification Plant (Fertilizer Production):

Coffeyville Resources, a subsidiary of CVR Energy, operates a nitrogen fertilizer plant in Coffeyville, Kansas.[55] Chaparral Energy, an independent oil and natural gas production and exploration company, worked with Coffeyville Resources to build a CO_2 compression facility at the plant site.[56] The project utilizes industrial separation to capture the CO_2.[57] Approximately 650,000 to 770,000 tpa of CO_2 is captured through the fertilizer production process.[58] The plant converts petroleum petcoke to a hydrogen rich syngas used to make chemicals and nitrogen fertilizer.[59] In the process, the CO_2, which is typically vented, is captured during the process of fertilizer production and is being transported 69 miles by pipeline to Chaparral's oil fields at its North Burbank Unit in Osage County, Oklahoma for EOR. The project commenced operation in 2013.[60]

5. Enid Fertilizer CO_2-EOR Project (Fertilizer Production):

Around 680,000 tpa of CO_2, derived from the manufacture of fertilizer, are captured through industrial separation at Koch Nitrogen's Enid fertilizer plant in northern Oklahoma.[61] A 225 km

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49 *Id.*
50 U.S. DOE, "Breakthrough Industrial Carbon Capture, Utilization and Storage Project Begins Full Scale Operation," (May 10, 2013), *available at*: http://energy.gov/articles/breakthrough-industrial-carbon-capture-utilization-and-storage-project-begins-full-scale.
51 Global CCS Institute, "Century Plant," http://www.globalccsinstitute.com/project/century-plant; MIT, "Century Plant Fact Sheet," http://sequestration.mit.edu/tools/projects/century_plant.html.
52 *Id.*
53 *Id.*
54 *Id.*
55 Global CCS Institute, "Coffeyville Gasification Plant," http://www.globalccsinstitute.com/project/coffeyville-gasification-plant; MIT, "Coffeyville Fact Sheet," http://sequestration.mit.edu/tools/projects/coffeyville.html.
56 *Id.*
57 *Id.*
58 *Id.*
59 *Id.*
60 Global CCS Institute, "Coffeyville Gasification Plant," http://www.globalccsinstitute.com/project/coffeyville-gasification-plant; MIT, "Coffeyville Fact Sheet," http://sequestration.mit.edu/tools/projects/coffeyville.html.
61 Global CCS Institute, "Enid Fertilizer CO_2-EOR Project," http://www.globalccsinstitute.com/project/enid-fertilizer-co2-eor-project; MIT, "Enid Fertilizer Fact Sheet," http://sequestration.mit.edu/tools/projects/enid_fertilizer.html.

pipeline transports the CO_2 for use in EOR at the Northeast Purdy and the Brady Unit of the composite Golden Trend Field, as well as the Sko-Vel-Tum Field, both south of Oklahoma City. EOR at these fields commenced as early as 1982.[62] In early 2010, Koch Nitrogen completed upgrades and expansion of its Enid Oklahoma Plant, having purchased the plant in 2003.[63]

6. Lost Cabin Gas Plant (Natural Gas Processing):

This project uses pre-combustion capture technology at the existing Lost Cabin natural gas processing plant in Wyoming.[64] Approximately 1 Mtpa of CO_2 will be captured from the currently operating plant and transported via a 370 km pipeline to the Bell Creek oil field in Montana for EOR.[65] Construction of the CO_2 capture facilities started in 2011 and commenced operation in 2013.[66]

7. Core Energy/South Chester Gas Processing Plant (Natural Gas Processing):

CO2 is captured by Core Energy from natural gas processing for EOR in northern Michigan, with over 2 million MT captured to date. Operations began in 2003.

8. Antrim Gas Plant (Natural Gas Processing):

CO2 from a gas processing plant owned by DTE Energy is captured at a rate of approximately 1,000 tons per day since 2013 and injected into a nearby oil field operated by Core Energy in the Northern Reef Trend of the Michigan Basin.

9. Val Verde Natural Gas Plants (Natural Gas Processing):

These five separate gas-processing facilities in the Val Verde area of Texas, capture around 1.3 Mtpa of CO_2 for use in EOR operations at the Sharon Ridge oilfield.[67] The dehydrated and compressed gas is transported via the Val Verde and CRC pipelines.[68] The five facilities are the Mitchell, Gray Ranch, Puckett, Pikes Peak and Terrell gas plants.[69] EOR has been used at the Sharon Ridge field since 1972.[70]

10. Shute Creek Gas Processing (Natural Gas Processing):

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62 *Id.*
63 *Id.*
64 Global CCS Institute, "Lost Cabin Gas Plant," http://www.globalccsinstitute.com/project/lost-cabin-gas-plant; MIT, "Lost Cabin Fact Sheet," http://sequestration.mit.edu/tools/projects/lost_cabin.html.
65 *Id.*
66 *Id.*
67 Global CCS Institute, "Val Verde Natural Gas Plants," http://www.globalccsinstitute.com/project/val-verde-natural-gas-plants; MIT, "Val Verde Fact Sheet," http://sequestration.mit.edu/tools/projects/val_verde.html.
68 *Id.*
69 *Id.*
70 *Id.*

CO_2 injection in the Salt Creek oil field commenced in 2004. Five of the 18 phases of the Salt Creek EOR project have been completed, with closure planned by 2023.[71] It is regarded as one of the largest EOR projects in the United States.[72] A new 400 km pipeline to connect Exxon Mobil's Shute Creek gas plant in southwest Wyoming to Anadarko's Salt Creek oil field was completed in 2006.[73] Following an expansion in plant capacity in 2010, around 7 Mtpa of CO_2 are recovered from the gas processing facility using pre-combustion capture technology.[74] The Rangely Oil Field is one of the oldest and largest oil fields in the Rocky Mountain region.[75] The field has been producing since the 1940s, and has injected a total of approximately 23-25 Mt of CO_2 for EOR since 1986.[76]

11. **Chaparral/Conestoga Energy Partners' Arkalon Bioethanol plant (Chemical Production):**

Located in Kansas, this was the first ethanol plant to deploy carbon capture and supplies 170,000 tons of CO_2 per year to Chaparral Energy, which uses it for EOR in Texas oil fields.

12. **ADM Decatur CCS Project (Chemical Production):**

This project, which involves the compression and dehydration of CO_2, already separated in a corn-to-ethanol plant, and its storage in a deep saline aquifer adjacent to the producing plant, has progressed significantly through its construction activities.[77] The Illinois Industrial CCS Project will integrate its facilities with the existing 1,000 tpd of CO_2 facility under the Illinois Basin-Decatur Project to achieve a total CO_2 injection capacity of 3,000 tpd or approximately 1Mtpa of CO_2.[78] Construction of the surface facilities and the two monitoring wells has been completed.[79] EPA approved the a Class injection well VI permit for the project in September 2014.[80] The project began operations in April, 2017.[81]

13. **Shell Quest Facility (Hydrogen Production):**

In 2012, Shell announced that it would begin construction of a CCS facility at its Scotford Upgrader, capturing 1 Mtpa of CO_2 beginning in 2015 - a 35 percent reduction in direct CO_2 emissions from

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[71] Global CCS Institute, "Shute Creek Gas Processing Facility," http://www.globalccsinstitute.com/project/shute-creek-gas-processing-facility; MIT, "LaBarge Fact Sheet," https://sequestration.mit.edu/tools/projects/la_barge.html.
[72] *Id.*
[73] *Id.*
[74] *Id.*
[75] *Id.*
[76] Global CCS Institute, "Shute Creek Gas Processing Facility," http://www.globalccsinstitute.com/project/shute-creek-gas-processing-facility; MIT, "LaBarge Fact Sheet," https://sequestration.mit.edu/tools/projects/la_barge.html.
[77] *Global Status of CCS 2014* at 12; Global CCS Institute, "Illinois Industrial Carbon Capture and Storage Project, http://www.globalccsinstitute.com/project/illinois-industrial-carbon-capture-and-storage-project; MIT, "Decatur Fact Sheet," https://sequestration.mit.edu/tools/projects/decatur.html.
[78] *Id.*
[79] *Id.*
[80] *See* EPA, "U.S. EPA Approves Carbon Sequestration Permit in Decatur, Illinois," (Sept. 26, 2014), https://archive.epa.gov/epapages/newsroom_archive/newsreleases/afbc8abba5c91e3685257d5f0050ac84.html.
[81] *See* ADM, "ADM Begins Operations for Second Carbon Capture and Storage Project," (Apr. 7, 2017) https://www.adm.com/news/news-releases/adm-begins-operations-for-second-carbon-capture-and-storage-project-1.

the plant.[82] The Scotford Upgrader processes bitumen with hydrogen to produce oil.[83] An amine absorber captures CO_2 from the Upgrader's hydrogen plants.[84] The CO_2 is transported about 65 km by pipeline and injected into a saline formation.[85] In June 2018, Quest announced it had captured and stored three million tonnes of CO_2.[86]

c. Examples of Overseas Integrated CO_2 Capture and Sequestration Projects in Other Industrial Applications

1. In Salah, Algeria (Natural Gas Processing):

The currently suspended BP, Statoil, Sonatrach, DOE, EU Directorate of Research In Salah sequestration project is located in the Sahara Desert in Algeria.[87] Injections were suspended in 2011, but since it began operation in 2004, over 3.8 Mt of CO_2 were captured from an onsite BP natural gas processing plant and transported via pipeline, ultimately being injected in a saline field at a rate of up to 1.2 Mtpa.[88] The CO_2 is injected two km deep into the 20-meter thick Krechba Carboniferous sandstone formation via 3 horizontal wells.[89] The sandstone has 12 percent porosity and 10 mD permeability (a relatively tight formation but similar to many formations around the world).[90] A suite of monitoring tools, including satellite interferometry (INSAR) were tested and proven at the In Salah field. INSAR data documented unexpected vertical CO_2 migration along an unknown fracture or fault zone, however the CO_2 remained below its caprock and the integrity of the storage was not jeopardized.[91] This project demonstrates the successful injection, monitoring and sequestration of commercial volumes of CO_2 in saline reservoirs. This project demonstrated the successful injection of commercial volumes of CO_2.[92]

2. Sleipner, Norway, North Sea (Natural Gas Processing):

The Sleipner sequestration project is located 250 km offshore in the North Sea where CO_2 separated at an offshore natural gas processing platform has been injected at a rate of 1 Mtpa into the Utsira

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[82] Global CCS Institute, "Quest," http://www.globalccsinstitute.com/project/quest; MIT, "Quest Fact Sheet," http://sequestration.mit.edu/tools/projects/quest.html; OGJ Editors, *Shell okays Quest CCS Project in Alberta,* Oil & Gas J. (Sept. 5, 2012), *available at*: http://www.ogj.com/articles/2012/09/shell-okays-quest-ccs-project-in-alberta.html
[83] *Id.*
[84] *Id.*
[85] Shell, *Shell to Construct World's First Oil Sands Carbon Capture and Storage (CCS) Project*, (Sept. 5, 2012), http://www.shell.com/global/aboutshell/media/news-and-media-releases/2012/quest-first-oil-sands-ccs-project-05092012.html.
[86] Global CCS Institute, "Quest," https://www.globalccsinstitute.com/projects/quest.
[87] Global CCS Institute, "In Salah CO2 Storage," http://www.globalccsinstitute.com/project/salah-co2-storage; MIT, "In Salah Fact Sheet," https://sequestration.mit.edu/tools/projects/in_salah.html; *Global Status of CCS 2013* at 27, 29, 30, 42, 51, 126, 132, 164; P.S. Ringrose *et al.*, *The In Salah CO_2 Storage Project: Lessons Learned and Knowledge Transfer*, 37 Energy Procedia 6226 (2013), http://www.sciencedirect.com/science/article/pii/S1876610213007947.
[88] *Id.*
[89] *Id.*
[90] *Id.*
[91] *Id.*
[92] Global CCS Institute, "In Salah CO2 Storage," http://www.globalccsinstitute.com/project/salah-co2-storage; MIT, "In Salah Fact Sheet," https://sequestration.mit.edu/tools/projects/in_salah.html; *Global Status of CCS 2013* at 27, 29, 30, 42, 51, 126, 132, 164; P.S. Ringrose *et al.*, *The In Salah CO_2 Storage Project: Lessons Learned and Knowledge Transfer*, 37 Energy Procedia 6226 (2013), http://www.sciencedirect.com/science/article/pii/S1876610213007947.

Sandstone since 1996.[93] Approximately 18 Mt have been injected over the life of the project. The Utsira is a 200-250-meter-thick formation –with an overlying 800-meter-thick caprock formation that is predicted to be able to contain 600 billion tons of CO_2. Monitoring has verified that CO_2 is secure.[94] The Sleipner project demonstrates the successful long-term injection of commercial volumes of CO_2 into a deep offshore geologic saline reservoir.[95]

3. Snohvit, Norway, North Sea (Natural Gas Processing):

The Snohvit saline sequestration project is operated by Norwegian Statoil and has sequestered approximately 01.9 Mt of CO_2 separated from a natural gas, into the Tubaen sandstone Formation since 2008 at a subsea depth of about 2.5 km.[96] EU-financed monitoring accompanies this project.[97] The project is groundbreaking in that it is the first to operate without offshore installations.[98] The caprock that has kept the natural gas being produced in place for millennia is also expected to keep the CO_2 secure.[99]

4. Petrobras Lula Oil Field CCS Project, Brazil (Natural Gas Processing):

This facility is an offshore natural gas processing plant using pre-combustion technology to capture 700,000 tpa of CO_2. The CO_2 is directly injected via a 2 km injection riser to EOR at the Lula oil field located in the Santos Basin.[100] As part of developing the project, Petrobras conducted studies and determined that EOR provided a means to cost effectively recover hydrocarbon reserves instead of venting.[101] CO_2 injection commenced at pilot scale in 2011 and at commercial scale in June 2013.[102]

5. Abu Dhabi CCS Project (Iron & Steel):

The Abu Dhabi CCS project is the first ever CCS project in the iron and steel sector. The plant captures high purity CO2 produced by the direct reduced iron-making process at the Emirates Steel Industries factory in Mussafah.[103] Launched in November 2016, the compression facility has a

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93 *See* MIT "Sleipner Fact Sheet," http://sequestration.mit.edu/tools/projects/sleipner.html; Global CCS Institute, "Sleipner CO2 Injection," http://www.globalccsinstitute.com/project/sleipner%C2%A0co2-injection; *Global Status of CCS 2013* at 30, 42, 51, 126, 164, 181.
94 *Id.*
95 *Id.*
96 MIT, "Snohvit Fact Sheet," http://sequestration.mit.edu/tools/projects/snohvit.html; Global CCS Institute, "Snohvit CO2 Injection," http://www.globalccsinstitute.com/project/sn%C3%B8hvit-co2-injection.
97 *Id.*
98 *Id.*
99 *Id.*
100 Global CCS Institute, "Petrobas Lula Oil Field CCS Project", http://www.globalccsinstitute.com/project/petrobras-lula-oil-field-ccs-project; MIT, "Lula Fact Sheet," http://sequestration.mit.edu/tools/projects/lula.html; *Global Status of CCS 2013* at 31; Jorge Oscar de Sant' Anna Pizzaro, Celso Cesar Moreira Branco, *Planning and implementing an EOR project for the pre-salt Lula field*, World Oil (Aug. 2012), *available at*: http://www.worldoil.com/supplement-detail.aspx?supplementID=91087.
101 *Id.*
102 *Id.*
103 Global CCS Institute, "Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)", https://www.globalccsinstitute.com/projects/abu-dhabi-ccs-project-phase-1-being-emirates-steel-industries-esi-ccs-project.

capture capacity of 0.8 Mtpa. The captured CO2 is transported via approximately 50km pipeline to Abu Dhabi National Oil Company (ADNOC) oil reservoirs for enhanced oil recovery.[104]

6. **Yanchang Integrated Carbon Capture and Storage Demonstration Project, Phase 2, China (Chemical Production):**

A coal-to-chemicals plant in Yulin, Shanxi province captures 50,000 tpa of CO_2, which is then transported and injected into an oil field for EOR.[105] The second phase of the project will increase the captured CO_2 to 360,000 tpa and the estimated CO_2 captured during the life of the facility will be 6-8 Mt.[106]

7. **PetroChina Jilin Oil Field EOR Project, Phase 2 (Natural Gas Processing):**

PetroChina began injecting 200,000 tpa of trucked CO_2 from a natural gas processing plant in 2009. PetroChina will expand its injections to 800,000 to 1 Mt by 2015-2016 via a 150-200 km pipeline with an estimated total captured and stored CO_2 of 11- 20 Mt.[107]

III. Geologic CO_2 storage is a proven commercial technology and available to all section 111(d) affected sources.

As described in our main comments, geologic storage of CO_2 for power plants subject to ACE is widely available, and a vast network of pipeline infrastructure is in place to transport the CO_2 from the plant to storage.

REGULATIONS EXIST FOR STORING AND ACCOUNTING FOR STORED CO_2 VOLUMES

Carbon dioxide cannot be considered permanently stored without an accompanying monitoring, verification and accounting framework.[108] EPA has issued geologic storage regulations over the past decade to protect underground sources of drinking water and to gain accounting information on geologic carbon storage. Applicable regulations are the Underground Injection Control program (UIC) Class VI and the Greenhouse Gas Reporting Program Subpart RR for saline storage, while for oilfield storage UIC Class II plus Subpart RR.

Since the comment period for the Clean Power Plan, there have been several important regulatory developments in this area. For example, in December 2016, EPA published key guidance on post injection site care and site closure that describes how operators may develop an alternative post

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[104] MIT "ESI CCS Project Fact Sheet," https://sequestration.mit.edu/tools/projects/esi_ccs.html.

[105] Global CCS Institute, "Yanchang Integrated Carbon Capture and Storage Demonstration Project," http://www.globalccsinstitute.com/project/yanchang-integrated-carbon-capture-and-storage-demonstration-project.

[106] *Id.*

[107] Global CCS Institute, "PetroChina Jilin Oil Field EOR Project, Phase 2," http://www.globalccsinstitute.com/project/petrochina-jilin-oil-field-eor-project-phase-2.

[108] Susan D. Hovorka & Scott W. Tinker. *EOR as sequestration: Geoscience perspective* (2010), https://repositories.lib.utexas.edu/handle/2152/67533.

injection site care timeframe other than the UIC Class VI 50-year default.[109] In January 2018, EPA published a UIC Class VI (sequestration) implementation manual.[110] In addition, EPA has approved monitoring reporting and verification (MRV) plans for four projects opting into sequestration under GHGRP Subpart RR.[111] EPA also approved North Dakota's application for UIC Class VI primacy.[112] In addition, a number of states such as Texas have adopted state regulatory programs to verify CO_2 storage as highlighted in the table below.[113]

	Liability	Storage Fund	Pore space owner	CO_2 owner	Unitization	Primacy	Inter-state
Montana	X	X	X	X	X	X	
Wyoming		X	X	X	X	X	
North Dakota	X	X	X	X	X		
Oklahoma				X		X	
Kansas	X	X					
Illinois	X						
Louisiana	X	X		X			
Texas (onshore)		X		X		X	
Texas (offshore)	X	X					
West Virginia						X	X

Source: Holly Javedan, MIT, 2013.[114] Note: Missing 2017 UIC Class VI Primacy approval for ND.

GEOLOGIC SEQUESTRATION CAPACITY ASSESSMENTS HAVE BEEN EXPANDED AND REFINED

DOE's National Energy Technology Laboratory (NETL) has issued a national carbon atlas, and revisions since the previous decade. The most recent reassessment of the NATCARB Atlas (version V, published in 2015) demonstrates additional storage capacity compared to the previous version

[109] EPA, *Geologic Sequestration of Carbon Dioxide, Underground Injection Control (UIC) Program Class VI Well Plugging, Post-Injection Site Care, and Site Closure Guidance* (2016), https://www.epa.gov/sites/production/files/2016-12/documents/uic_program_class_vi_well_plugging_post-injection_site_care_and_site_closure_guidance.pdf.
[110] U.S. Environmental Protection Agency, *Geologic Sequestration of Carbon Dioxide—Underground Injection Control Program Class VI Implementation Manual for UIC Program Directors* (2018), https://www.epa.gov/sites/production/files/2018-01/documents/implementation_manual_508_010318.pdf.
[111] U.S. Environmental Protection Agency, Subpart RR – Geologic Sequestration of Carbon Dioxide, https://www.epa.gov/ghgreporting/subpart-rr-geologic-sequestration-carbon-dioxide (MRV plan final decision documents).
[112] 40 C.F.R. § 147 (2018).
[113] 16 Tex. Admin. Code § 5.101 (2010).
[114] Holly Javedan, *Regulations for Underground Storage of CO_2 Passed by U.S. States* (2013), https://sequestration.mit.edu/pdf/US_State_Regulations_Underground_CO2_Storage.pdf

cited in the CPP RIA.[115] [116] [117] According to the Atlas, the low, medium, and high estimates of geologic sequestration capacity are, respectively, 2.4 trillion metric tons, 8.3 trillion metric tonnes and, 22 trillion metric tonnes. This is enough capacity for hundreds, if not thousands of years of coal plant CO_2 emissions. (For reference, the United States' energy sector CO_2 emissions totaled 5.1 billion metric tonnes in 2017.[118])

Worldwide saline projects, such as Norway's Sleipner and Snohvit sites, Canada's Aquistore project, SECARB's Cranfield project, and the Illinois Basin project in Decatur IL, have demonstrated the ability to sequester millions of tonnes of CO_2 that has been verified by sophisticated monitoring methods.[119] [120] [121] [122] NETL Research Carbon Sequestration Partnerships (RCSPs) have delineated carbon storage reservoirs across North America and, in the process, developed protocols and experience in site characterization, monitoring, verification and accounting (MVA) to ensure that injected CO_2 remains confined in the subsurface and does not migrate and threaten aquifers or escape into the atmosphere.[123] There have been important learning and results from the regional partnerships discussed in our 2014 comments. For example, the Plains CO_2 Reduction Partnership (PCOR), in 2016, released the 5th edition of their storage Atlas which covers nine U.S. states in the northern Rocky Mountains, Great Plains and adjacent Alberta and Saskatchewan Canada. The Atlas suggests a regional storage capacity of 330 Gt of CO_2 (about 150 years of U.S. EGU-related emissions) and that CO_2-EOR in the region's depleted oil fields could store an additional 3.2 Gt of CO_2 while producing 7 billion barrels of oil.[124]

As a part of NETL's efforts, the American Recovery and Reinvestment Act of 2009 (ARRA) provided $100 million for nine specific geologic storage projects, as summarized in the NETL 2016 Site Characterization Accomplishments final report.[125] The ARRA-funded projects cut broadly

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115 National Energy Technology Laboratory, U.S. Department of Energy, *NETL's 2015 Carbon Storage Atlas Shows Increase in U.S. CO2 Storage Potential* (2015), https://www.energy.gov/fe/articles/netl-s-2015-carbon-storage-atlas-shows-increase-us-co2-storage-potential.

116 National Energy Technology Laboratory, U.S. Department of Energy, *Carbon Storage Atlas* 111 (5th ed. 2015), https://www.netl.doe.gov/research/coal/carbon-storage-1/atlasv.

117 U.S. Environmental Protection Agency, *Regulatory Impact Analysis for the Clean Power Plan Final Rule*, at 2-33 (2015), https://www3.epa.gov/ttnecas1/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf.

118 U.S. Energy Information Administration, *U.S. energy-related CO2 emissions fell slightly in 2017* (2018), https://www.eia.gov/todayinenergy/detail.php?id=36953.

119 CCP, "Key Large-scale CO_2 capture and storage (CCS) Projects," https://www.co2captureproject.org/ccs_in_action.html

120 CCS Network, "Sleipner CO_2 Storage Project," https://ccsnetwork.eu/projects/sleipner-co2-injection.

121 Aquistore "Aquistore Project: Annual Report," (2016) http://aquistore.ca/+pub/AQ%20Annual%20Report%202016%20Final.pdf.

122 Greenberg, S. *et al.*, *Geologic carbon storage at a one million tonne demonstration project: Lessons learned from the Illinois Basin-Decatur Project*, 114 Energy Procedia 5529 (2017) https://ac.els-cdn.com/S1876610217321215/1-s2.0-S1876610217321215-main.pdf?_tid=e6afd238-2357-44b2-8bc0-2ac7220667e0&acdnat=1540985984_04496614dc1c6e844f809b8ae19cb690.

123 For example, Gulf Coast Carbon Center geologic storage technical library contains over a decade of technical papers on geologic storage. *See* http://www.beg.utexas.edu/gccc/forum/codexhome.php; National Energy Technology Laboratory, U.S. Department of Energy, *Monitoring, Verification and Accounting of CO_2 Stored in Deep Geologic Formations*, (2nd ed. 2012), http://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/MVA_Document.pdf.

124 *See* Plains CO_2 Reduction Partnership, *Regional Storage Potential*, https://www.undeerc.org/pcor/region/

125 *See* National Energy Technology Laboratory, U.S. Department of Energy, NETL's ARRA Site Characterization

across the U.S.: Los Angeles basin/California offshore; Newark Basin/New Jersey, Pennsylvania, New York; South Georgia Rift Basin/South Carolina, Georgia; Illinois and Michigan Basins/Illinois, Indiana, Kentucky, Michigan; Black Warrior Basin/Alabama; Ozark Plateau Aquifer/Kansas; Miocene Texas offshore; Rocky Mountains/Colorado, Utah, Arizona, New Mexico; Rock Springs uplift and Moxa Arch/Wyoming.

These ARRA projects have demonstrated improved geologic storage assessment and monitoring best practices and have resulted in storage capacity estimates ranging from 160 billion metric tonnes to upwards of 640 billion metric tonnes (76-305 times today's power sector emissions) in the assessed geologic formations alone. Moreover, these ARRA projects have supported development and improvement of computational models used to develop regional storage capacity estimates including providing new data on subsurface formation porosity, permeability, injectivity. NETL has been winding down these regional carbon sequestration partnerships and has been transitioning to its new CarbonSAFE program since 2016.[126]

In addition, the U.S. Geological Survey has independently studied some sedimentary basins with deep, secure subsurface formations and estimates there is the capacity to sequester over 500 years of today's U.S. energy emissions in the formations assessed to date only.[127] Additional capacity lies in the basins not yet assessed by USGS.

VERY LARGE EASTERN U.S. AND GULF COAST OFFSHORE GEOLOGIC STORAGE COULD STORE TRILLIONS OF TONNES OF CO_2

Offshore storage holds promise to receive large quantities of captured CO_2 for EOR and saline storage. It can be envisioned that a network of pipelines leading to a trunk line to the Gulf could store CO_2 from a wide region in the United States. Offshore storage offers several important advantages:

- Offshore formations are thicker, and more ductile, less prone to fracture and more likely to accommodate CO_2;
- Storage sites are distant from populated areas;
- Offshore geologic resource leasing is less complex;
- Pipelines will be easier to route;
- There are no underground sources of drinking water (USDWs) in the offshore, and, moreover, leakage of CO_2 and brine (concentrated seawater) in to the ocean may pose lesser environmental risk (if unaccompanied by hydrocarbons); and
- Softer sedimentary rocks on the continental shelf minimizes risk of damaging induced seismicity.

Initiative: Accomplishments (2016), https://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/infrastructure/ARRA-Site-Characterization-Accomplishments-2016.pdf.

126 *See* National Energy Technology Laboratory, U.S. Department of Energy, *RCSP Geologic Characterization Efforts*, https://www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-infrastructure/rcsp-geologic-characterization (describing NETL's Regional Carbon Sequestration Partnerships).

127 U.S. Geological Survey, National Assessment of Geologic Carbon Dioxide Storage Resources (2013), https://pubs.er.usgs.gov/publication/fs20133020.

In 2012, ICF International, for the BOEM Outer Continental Shelf Study, analyzed U.S. offshore storage options in the U.S. Outer Continental Shelf, where there very large carbon storage resources, an estimated 3.6 trillion metric tonnes. The report includes costs for construction of pipelines and provides estimates for several example cases.[128] The study concluded that there would be $16.9B benefit to the U.S. economy for storing CO_2 on the Outer continental shelf.

According to a 2014 assessment by ARI for NETL, 310 Mt to 3.9 Gt of CO_2 could be utilized and stored at a low cost in the process of EOR in the offshore Gulf of Mexico, one of the world's largest and thickest porous sedimentary sequences. [129] [130]

The Gulf Coast Carbon Center at the University of Texas, Austin, also a recipient of funding has recently mapped and begun the process of estimating the magnitude of large geologic carbon storage formations in the offshore saline formations and gas fields of the Gulf of Mexico. In 2018, the Center released an atlas of storage opportunities in Miocene age strata of the Gulf Coast and concluded that hundreds of millions of tonnes could be sequestered in those thick sandstone sequences alone. [131]

Modeled offshore pipeline buildout scenarios demonstrate that the Gulf Coast could serve as a hub for storing CO_2 from energy and industrial production in the United States.[132] The analysis concluded that for a total capital cost of $6 billion dollars, there is a potential to store 40 Mtpa in 52 oil fields in the shallow Gulf of Mexico through a three pipeline system, and store 57 Mtpa in 63 large oil fields also connected by a three pipeline system in the deep Gulf of Mexico.

Battelle Memorial Institute received a $4.7 million grant in 2015 to lead a consortium to investigate geologic storage opportunities in the Northeast United States including the Baltimore Canyon Trough and the George's Banks Basin.[133] The results of this investigation are particularly important given the limited opportunities that exist in the Northeast United States for deep geologic carbon storage onshore. The effort includes mapping the geologic formations in the subsurface using existing well logs and seismic methods, investigating the hydrogeology by testing existing geologic cores. The results suggest that three deep saline reservoir formations, representing thousands of feet of thickness, such as the Mississauga Formation, exist in the offshore overlain by thick mud caprock that, combined, may be able to store large quantities of CO_2, providing a permanent geologic sink for the hundreds of millions to billions of tonnes of CO_2 generated by coal plants in the Northeast

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128 Harry Vidas, Bob Hugman, Ananth Chikkatur, Boddu Venkatesh, ICF International (2012). *Analysis of the Costs and Benefits of CO_2 Sequestration on the U.S. Outer Continental Shelf*, https://www.boem.gov/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Energy_Economics/External_Studies/OCS%20Sequestration%20Report.pdf.

129 National Energy Technology Laboratory, U.S. Department of Energy, *CO_2 – EOR Offshore Resource Assessment* (2014), https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=626.

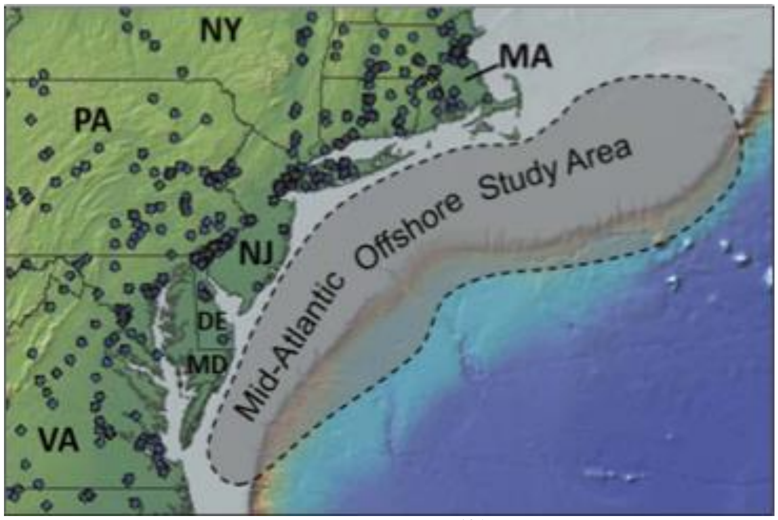
130 Ramon Trevino & Tip Meckel, *Geological CO_2 Sequestration Atlas of Miocene Strata, Offshore Texas State Waters* (2017), https://store.beg.utexas.edu/reports-of-investigations/3415-ri0283-atlas.html?search_query=RI0283&results=2.

131 *Id.*

132 Vello Kuuskraa, Advanced Resources International, Inc., *Establishing CO_2 Utilization, Storage and Pipeline Systems for Oil Fields in Shallow and Deep Waters of the Gulf of Mexico* (2017), https://www.osti.gov/servlets/purl/1469161.

133 National Energy Technology Laboratory, U.S. Department of Energy, *Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment Project*, https://www.netl.doe.gov/research/coal/project-information/fe0026087?k=FE0026087.

region.[134] Initial results of the study suggest that these formations have the capacity, permeability, porosity, and requisite depth for commercial scale geologic carbon storage.



Battelle Mid-Atlantic offshore carbon resources assessment region.[135]

ADDITIONAL PROGRESS HAS BEEN MADE IN GEOLOGIC CARBON SEQUESTRATION RESEARCH

Substantial new research in the field of geologic sequestration has taken place since the end of the comment period for the Clean Power Plan in late 2014, which has deepened our understanding of geologic carbon storage technologies and delineated it in more detail. In the U.S., this includes a deeper understanding of options for geologic CO_2 storage in onshore and offshore regions.[136] Globally, recently published studies include global and regional storage capacity assessments, as well as field and laboratory research efforts that provide additional confidence in geologic carbon storage as a critical technology for reducing emissions from the power sector.[137] Further development of computational models has also improved scientists' abilities to assess subsurface formations and

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134 *See* Neeraj Gupta, *Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment* (2017), https://www.netl.doe.gov/File%20Library/Events/2017/carbon-storage-oil-and-natural-gas/tues/Gupta-P2-FY17_MidAtlanticProjectTeam_DOE_FINAL.pdf.

135 *Id.*

136 For example, a research effort supported by the U.S. Department of Energy National Energy Technology Lab (NETL), has resulted in major advances in the understanding of offshore storage reservoirs in the Gulf Coast as part of the NETL CarbonSAFE program. *See* National Energy Technology Laboratory, U.S. Department of Energy, *Regional Carbon Sequestration Partnerships (RCSP) Initiative*, https://www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-infrastructure/rcsp; National Energy Technology Laboratory, U.S. Department of Energy, *CarbonSAFE*, https://www.netl.doe.gov/research/coal/carbon-storage-1/storage-infrastructure/carbonsafe.

137 *See, e.g.*, IEA Greenhouse Gas R&D Programme, International Energy Agency, IEAGHG Technical Report 2017-01: Case Studies of CO_2 Storage in Depleted Oil and Gas Fields, IEA-GHG R&D (2017), https://ieaghg.org/docs/General_Docs/Reports/2017-01.pdf; International Energy Agency, 2015, *Carbon Capture and Storage: The Solution for Deep Emissions Reductions*, https://www.iea.org/publications/freepublications/publication/CarbonCaptureandStorageThesolutionfordeepemissionsreductions.pdf; Society of Petroleum Engineers, 2017, *CO_2 Storage Resources Management System*, https://www.spe.org/industry/docs/SRMS.pdf.

estimate their storage capacities, thereby enhancing the tools available to identify and select secure CO_2 storage sites.

More specifically, studies have advanced storage practices and technologies in several key areas: 1) improvement of the quantitative ability to estimate volumetric storage capacities using data on CO_2 storage efficiencies and storage rates;[138] 2) improvement of the available methods for the identification of robust storage sites;[139] 3) better management of subsurface CO_2 including reservoir pressure response and build up in saline reservoirs;[140] 4) assessment of new storage resources such as in the offshore, depleted gas reservoirs and residual oil zones.[141]

Atlas V CO_2 Storage Resource Estimates			
	Low	**Medium**	**High**
Oil and Natural Gas Reservoirs	186	205	232
Unmineable Coal	54	80	113
Saline Formations	2,379	8,328	21,633
Total	**2,618**	**8,613**	**21,978**

**Data current as of November 2014. Estimates in billion metric tons.*

Summary of North American Storage Resources. Table from NETL (2015).[142]

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[138] *See, e.g.*, Nicholas W. Bosshart *et al.*, *Quantifying the effects of depositional environment on deep saline formation CO_2 storage efficiency and rate*, 69 Int. J. Greenhouse Gas Control 8 (2018), https://doi.org/10.1016/j.ijggc.2017.12.006; Reza Ganjdanesh & Seyyed A. Hosseini, *Development of an analytical simulation tool for storage capacity estimation of saline aquifers*, 74 Int. J. Greenhouse Gas Control 142 (2018), https://doi.org/10.1016/j.ijggc.2018.04.017; Angela Goodman, Sean Sanguinito, and Jonathan S. Levine, *Prospective CO_2 saline resource estimation: Refinement of existing US-DOE-NETL methods based on data availability*, 54 Int. J. Greenhouse Gas Control 242 (2016), http://dx.doi.org/10.1016/j.ijggc.2016.09.009.

[139] *See, e.g.*, Rebecca Allen *et al.*, 2017, *Ranking and categorizing large-scale saline aquifer formations based on optimized CO_2 storage potentials and economic factors*, 65 Int. J. of Greenhouse Gas Control 182, http://dx.doi.org/10.1016/j.ijggc.2017.07.023; Stefan Iglauer, *Optimum storage depths for structural CO_2 trapping*, 77 Int. J. Greenhouse Gas Control 82 (2018), https://doi.org/10.1016/j.ijggc.2018.07.009.

[140] Jens T. Birkholzer, Curtis M. Oldenburg, & Quanlin Zhou, *CO_2 migration and pressure evolution in deep saline aquifers*, 40 Int. J. Greenhouse Gas Control 203 (2015), http://dx.doi.org/10.1016/j.ijggc.2015.03.022.

[141] *See, e.g.*, Stefan Bachu, *Review of CO_2 storage efficiency in deep saline aquifers*, 40 Int. J. of Greenhouse Gas Control 188 (2015), http://dx.doi.org/10.1016/j.ijggc.2015.01.007; Amy L. Clarke *et al.*, Application of material balance methods to CO_2 storage capacity estimation within selected depleted gas reservoirs, 23 Petroleum Geoscience 339 (2017), https://doi.org/10.1144/petgeo2016-052, (Attach. L); David L. Carr *et al.*, CO_2 Sequestration Capacity Sectors in Miocene Strata of the Offshore Texas State Waters, 5 Gulf Coast Association of Geological Societies Journal 130 (2016) (Attach. M); IEA Greenhouse Gas R&D Programme, International Energy Agency, IEAGHG Technical Report 2017-01: Case Studies of CO2 Storage in Depleted Oil and Gas Fields, IEA-GHG R&D (2017), https://ieaghg.org/docs/General_Docs/Reports/2017-01.pdf.

[142] National Energy Technology Laboratory, U.S. Department of Energy, Carbon Storage Atlas 3 (5th ed. 2015), https://www.netl.doe.gov/research/coal/carbon-storage-1/atlasv.

2016 DECADE-LONG NETL CARBONSAFE INITIATIVE WILL ASSIST IN DEVELOPING LARGE ONSHORE AND OFFSHORE CARBON STORAGE RESOURCES

In late 2016, DOE, following the end of its successful decade-long Regional Carbon Storage Partnerships (RCSP) effort, initiated a new phase of its efforts to advance carbon storage technology. In November 2016, DOE launched the "CarbonSAFE" program by awarding $44 MM to support and promote the development of carbon storage sites with the potential to store over 50 Mt of CO_2 by 2026, building on learning from its RCSP program.[143] [144] There are 16 CarbonSAFE storage projects currently receiving federal funding as illustrated in the table below.

CarbonSAFE map shows locations of projects in table below.[145]

	Pre-Feasibility Project Title	Project Number
1	Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study	FE0029186
2	Integrated Pre-Feasibility Study for CO_2 Geological Storage In The Cascadia Basin, Offshore Washington State And British Columbia	FE0029219
3	Integrated Mid-Continent Stacked Carbon Storage Hub	FE0029264
4	Integrated Carbon Capture and Storage in The Louisiana Chemical Corridor	FE0029274
5	Northern Michigan Basin CarbonSAFE Integrated Pre-Feasibility Project	FE0029276
6	CarbonSAFE Rocky Mountain Phase I: Ensuring Safe Subsurface Storage Of Carbon Dioxide In The Intermountain West	FE0029280
7	Integrated Pre-Feasibility Study of A Commercial-Scale Commercial Carbon Capture Project In Formations Of The Rock Springs Uplift, Wyoming	FE0029302
8	Integrated Commercial Carbon Capture and Storage Prefeasibility Study At Dry Fork Station, Wyoming	FE0029375
9	CarbonSAFE Illinois East Sub-Basin	FE0029445
10	CAB-CS: Central Appalachian Basin CarbonSAFE Integrated Pre-Feasibility Project	FE0029466
11	Integrated Carbon Capture and Storage in Kansas	FE0029474
12	Integrated CCS Pre-Feasibility in The Northwest Gulf Of Mexico	FE0029487
13	California CO_2 Storage Assurance Facility Enterprise (C2SAFE)	FE0029489
	Feasibility Project Title	**Project Number**
14	CarbonSAFE Illinois Macon County	FE0029381
15	Establishing An Early Carbon Dioxide Storage (ECO_2s) Complex In Kemper County, Mississippi: Project ECO_2S	FE0029465
16	North Dakota Integrated Carbon Storage Complex Feasibility Study	FE0029488

List of NETL CarbonSAFE Projects as of September 2018.[146] *CarbonSAFE is an extension of the research efforts initiated in the regional sequestration partnerships.*

There are two phases of funded CarbonSAFE projects: Phase I: Pre-Feasibility studies in Wyoming, Illinois, Texas Gulf Coast, Utah, Nebraska, Kansas, Rocky Mountains, Washington State (onshore

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[143] *See* National Energy Technology Laboratory, U.S. Department of Energy, *CarbonSAFE*, https://www.netl.doe.gov/research/coal/carbon-storage-1/storage-infrastructure/carbonsafe.
[144] *See* National Energy Technology Laboratory, U.S. Department of Energy, *Energy Department Announces more than $44 Million for CO2 Storage Projects* (2016), https://netl.doe.gov/newsroom/news-releases/news-details?id=8dc33ed0-b938-442b-812e-9c4d453f58fe.
[145] National Energy Technology Laboratory, *supra* note 143.
[146] *See id.*

and offshore) Central Appalachian Basin, California, North Dakota, and Louisiana, and, Phase II: Storage complex feasibility studies in Mississippi, North Dakota, and the Illinois Basin.

One important Phase II CarbonSAFE project is already showing promise as an option to be a major hub for geologic sequestration in the southeast U.S. Southern States Energy Board and Southern Company Kemper County Mississippi's ECO_2S project (number 15 on the map above). The ECO_2S project is a delineated and studied 30,000-acre area near the Kemper County energy facility.[147] The consortium, formed in 2016, has, so far, drilled four wells into the Tuscaloosa Group, Washita-Fredricksburg Interval, and Paluxy Formation, which, together, show great promise to store large volumes of CO_2 in its thick, stacked Cretaceous-age sandstones which lie beneath a thick mudstone caprock. These low cost ($2-$4 per metric tonne) highly porous and permeable saline reservoirs (e.g. 30% porosity and Darcy-class permeability in the Paluxy) may be able to accommodate large commercial CO_2 volumes, and has potential to provide a regional storage hub for Mississippi and other Southeast states.

CO_2 SEQUESTRATION IN OIL FIELDS

CO_2 injected for EOR does not simply produce oil but can be sequestered in the process. CO_2-EOR provides revenue to offset the added costs of carbon sequestration. The term "incidental" or "associated" storage is used to describe CO_2 that is trapped in the process of producing oil with CO_2 flooding. In addition to proving storage through monitoring and verification, storage in EOR settings requires CO_2 separation and recycling facilities to recapture CO_2 from the produced oil for reinjection such that the CO_2 does not return to the atmosphere. Several studies have assessed the ability of CO_2-EOR to sequester carbon dioxide and/or reduce the carbon intensity of oil production.[148]

EOR storage offers some advantages over storage in saline formations: 1) the EOR industry possess long experience in managing, injecting and tracking injected CO_2, and possess the know-how to manage CO_2 projects; 2) depleted oil fields with long operating histories offer known reservoir capacities, injectivities and other characteristics, can *today* accept large volumes of CO_2 for tertiary oil production and subsequent storage; 3) EOR fields are generally equipped with the facilities to manage and inject CO_2; 4) oil fields are proven geologic traps by nature, known for their ability to hold oil and gas for millions of years; 5) multiple injection and production wells offer the potential to manage the subsurface CO_2 plume; 6) the opportunity for stacked storage in associated saline water-bearing formations in the EOR fields enhances local storage capacity and storage options; and 7) the added revenues from EOR can drive investment in CO_2 capture, transportation, injection, and monitoring infrastructure, which can be transferred to saline sequestration at a potentially lower cost than in greenfield saline sequestration.[149]

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[147] Southern States Energy Board, *CarbonSAFE: Establishing an early CO_2 storage complex in Kemper County, Mississippi: Project ECO_2S* (2018), https://www.netl.doe.gov/File%20Library/Events/2018/mastering/monday/D-Riestenberg-CarbonSAFE-Project-ECO2S.pdf.

[148] *See, e.g.,* International Energy Agency, *Storing CO_2 through Enhanced Oil Recovery* (2015), https://www.iea.org/publications/insights/insightpublications/Storing_CO2_through_Enhanced_Oil_Recovery.pdf.

[149] Bruce Hill *et al.*, *Geologic Carbon Storage Through Enhanced Oil Recovery*, 37 Energy Procedia 6808, 6811 (2013), https://www.sciencedirect.com/science/article/pii/S1876610213008576.

In 2014, the last year for which data is available, there were approximately 134 CO_2-EOR projects actively injecting CO_2 in the deep subsurface.[150] DOE has estimated that there are over 1,600 oilfields, with a total of 146 billion barrels of oil in place where CO_2-EOR could be applied.[151] Advanced Resources International estimates that next generation EOR combined with current estimates of residual oil zones, could produce a demand for approximately 33 billion metric tons of CO_2.[152] Currently there is an estimated 2 to 3 billion metric tons of naturally occurring CO_2 available to meet this demand.[153] The remaining demand must be made up by captured sources of CO_2.

So-called "next-generation+" techniques would take EOR to the next level, with the advantage of monitoring and surveillance technology, improving the ability to utilize CO_2 for producing oil along with increasing the potential to utilize and store much greater volumes of CO_2 in oilfields while utilizing the same subsurface methods to monitor and ensure storage of the injected CO_2.[154] [155]

Residual oil zones (ROZs), a recently commercialized next-generation EOR strategy, are increasing the demand for CO_2.[156] ROZs are naturally artesian water-flushed oil reservoirs where residual oil can be produced utilizing CO_2 whether a there is a conventional production zone overlying the ROZ or not.[157] Commercial-scale ROZs have been proven in West Texas (e.g. Kinder Morgan's Tall Cotton field) and identified elsewhere such as in Wyoming. Shell first identified and produced ROZs in its West Texas Wasson field, which was later taken over by Occidental.[158] Now a half-dozen or more companies including Hess, Kinder Morgan, Occidental, XTO, Chevron and several others, are currently applying or planning to apply CO_2-EOR technologies to ROZ.[159] Another early player, Hess, launched its ROZ plays in 1996 and expanded those operations in 2004 and 2007.[160]

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150 Kuuskraa & Wallace, *CO_2-EOR Set for Growth as New CO_2 Supplies Emerge*, 112 OIL & GAS J. 66 (2014), https://www.ogj.com/articles/print/volume-112/issue-4/special-report-eor-heavy-oil-survey/co-sub-2-sub-eor-set-for-growth-as-new-co-sub-2-sub-supplies-emerge.html.

151 *See* National Energy Technology Laboratory, U.S. Department of Energy, *Development of Novel Methods for CO2 Flood Monitoring*, E&P Focus, Spring 2012, https://www.netl.doe.gov/file%20library/research/oil-gas/epnews-2012-spring.pdf.

152 Vello Kuuskraa, *Using the Economic Value of CO2 EOR to Accelerate the Deployment of CO_2 Capture, Utilization and Storage (CCUS)* (2012), https://hub.globalccsinstitute.com/publications/proceedings-2012-ccs-cost-workshop/using-economic-value-co2-eor-accelerate-deployment-co2-capture-utilization-and-storage-ccus.

153 Vello A. Kuuskraa, Tyler Van Leeuwen, Matt Wallace, U.S. Department of Energy, Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2 – Enhanced Oil Recovery (CO_2–EOR) (2011), https://www.netl.doe.gov/energy-analyses/temp/FY11_ImprovingDomesticEnergySecurityLoweringCO2EmissionsNextGenCO2EOR_060111.pdf.

154 Vello A. Kuuskraa *et al.*, *The Synergistic Pursuit of Advances in MMV Technologies for CO_2 – Enhanced Recovery and CO_2 Storage*, 37 Energy Procedia 4099 (2013) (discussing "five case studies of using MMV technology and smart wells to monitor and manage CO_2 storage and CO_2-EOR operation"), https://www.sciencedirect.com/science/article/pii/S1876610213005547.

155 Wallace *et al.*, U.S. Department of Energy, *An In-Depth Look at "Next Generation" CO_2-EOR Technology* (2013), https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Disag-Next-Gen-CO2-EOR_full_v6.pdf.

156 *See* ROZ Study Group, *Reference Material: Worldwide ROZs*, http://residualoilzones.com/reference-material-worldwide-rozs/.

157 Vello A. Kuuskraa *et al.*, *CO_2 Utilization from "Next Generation" CO_2 Enhanced Oil Recovery Technology*, 37 Energy Procedia 6854 (2013), http://www.elsevier.com/__data/assets/pdf_file/0006/179214/CO2- Utilization-from-Next-Generation-CO2-Enhanced-Oil.pdf.

158 Vello Kuuskraa & Matt Wallace, *supra* note 150.

159 *See* Vello Kuuskraa, *QC Updates Carbon Dioxide Projects in OGJ's Enhanced Oil Recovery Survey*, 110 Oil & Gas J. 72 (2012), https://www.ogj.com/articles/print/vol-110/issue-07/drilling-production/qc-updates-carbon-dioxide-projects.html.

160 Vello Kuuskraa & Matt Wallace, *supra* note 150.

In summary, the long commercial experience with deep geologic CO_2 injection, the continuously expanding infrastructure that accompanies CO_2-EOR, accompanied by the rising demand for CO_2, renders oilfields a viable option for sequestering CO_2 captured from EGUs in the U.S.

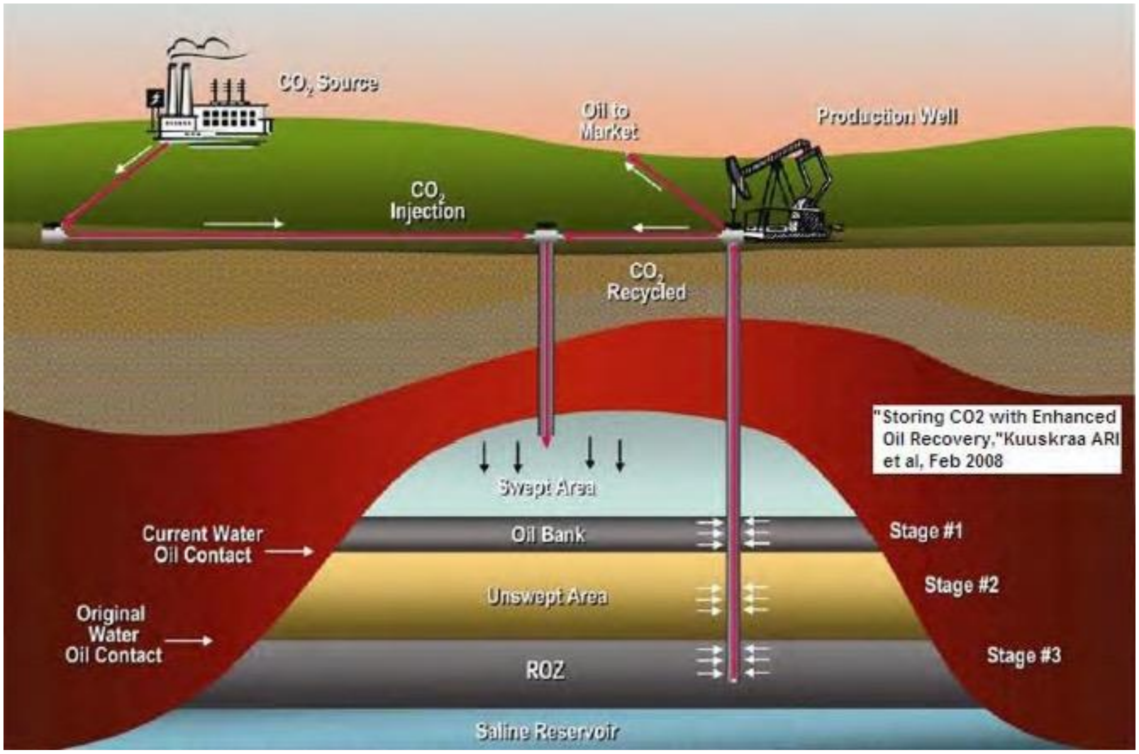
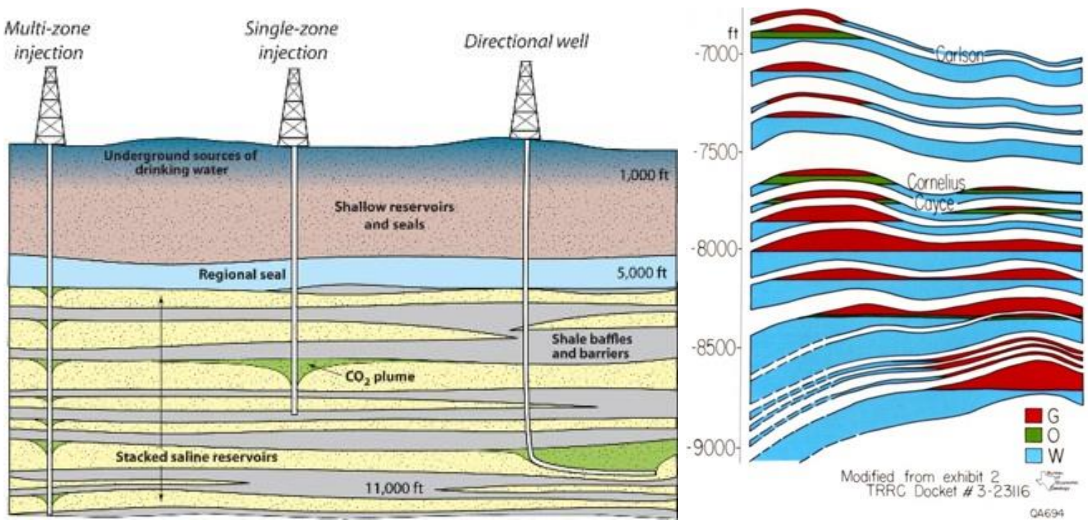


Illustration showing residual oil zones (ROZ) below existing oilfields. Residual oil zones may also exist where there is no conventional production interval. Source: Advanced Resources International.[161]

STACKED SALINE STORAGE IN OILFIELDS

Another potential storage opportunity takes advantage of existing infrastructure for EOR to store CO_2 in geologic formations that are associated with producing formations. This is called stacked saline storage. In oilfields, the characteristic sedimentary sequences often include repeating layers of interbedded sandstone and mudstone that represent opportunities for storing CO_2. Stacked storage takes advantage of these repeating sequences of geology to build storage capacity vertically. *See* illustration below. Utilizing multiple formation sections for storage is advantageous because injected CO_2 may be spread out throughout the geologic section instead of creating one large single CO_2 plume. Also, commercial pipelines and injection facilities used for EOR may now be repurposed for saline storage within the EOR fields. Stacked geologic carbon storage may be an opportunity to store CO_2 at a lower cost because of the existing facilities which could reduce cost at the outset.

[161] Kuuskraa *et al.*, *supra* note 157 at 6862.



Illustrations above-- Left: J.C. Pashin et al., Southeastern Regional Carbon Sequestration Partnership (SECARB) Phase III: Final Report prepared for Advanced Resources International, at 57 (2008) (illustration of stacked saline storage). Right: Susan Hovorka, TX BEG modified from Noel Tyler and William A. Ambros, Facies architecture and production characteristics of strand plain reservoirs in North Markham – North Bay City Field, Frio Formation, Texas, 70 AAPG BULL. 809-829 (July 1986) (illustration of layered oil, gas and saline formations (and intervening caprock in white) at the SECARB Frio project, Texas that could be accessed in stacked storage).

TODAY'S SUPERCRITICAL CO_2 PIPELINE SYSTEM DEMONSTRATES THE COMMERICAL AVAILABILITY OF CO_2 PIPELINES

Pipeline networks will play an important role in providing storage opportunities for CO_2 storage from coal plants not located above or adjacent to a storage basin. Pipelines are a mature and safe CO_2 commercial transport method that have been proven by decades of use as evidenced by the >4,500 miles of CO_2 pipelines in the United States today. In total this pipeline system, which spans a dozen states and neighboring Canada, carries about 68 million tons per year of natural and anthropogenic CO_2 and has continued to grow to meet demand from the EOR industry.[162] At this time, about 20% of the CO_2 is from captured sources, and the remainder is naturally sourced CO_2. However, according to NETL in a 2015 report, EOR alone could absorb 400 MT of CO_2 per year, 85% of which would be from captured sources.[163]

NRG Petra Nova's W.A. Parish Plant in Thompsons, Texas, is America's first commercial scale full-chain post combustion capture CCUS project and demonstrates the ability to capture and transport CO_2 for geologic storage.[164] 1.4 Mt of supercritical CO_2 per year is delivered from the Parish plant to the West Ranch Field through a newly-constructed 12-inch diameter supercritical pipeline 82 miles

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[162] National Energy Technology Laboratory, U.S. Department of Energy, *A Review of the CO2 Pipeline Infrastructure in the U.S.* (2015), https://www.energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20A%20Review%20of%20the%20CO2%20Pipeline%20Infrastructure%20in%20the%20U.S_0.pdf

[163] *Id.*

[164] National Energy Technology Laboratory, U.S. Department of Energy, *Recovery Act: Petra Nova Parish Holdings: W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project*, https://www.netl.doe.gov/research/coal/project-information/fe0003311.

to the south. The project is on track to deliver CO_2 to the EOR site for 20 years.[165] The project has been operating successfully for several years, starting December 2016 and reported capturing and transporting 1 Mt of CO_2 in the first 10 months of operations and boosting oil production 1300%.[166] The plant is designed to capture the 1.4 Mtpa of CO_2 from a 240 MWe slipstream from boiler #8 and transporting the 99% purity CO_2 to the Hilcorp West Ranch Field for EOR. A storage monitoring plan for the project was designed by Texas Bureau of Economic Geology.

Air Products' CO_2, captured from two existing steam methane reformers at the Valero Refinery in Port Arthur, Texas, was connected by a spur to Denbury's Green Pipeline in 2013.[167] The captured CO_2 is delivered for injection into Denbury's Onshore EOR operations at Hastings Field in Houston.[168] Approximately 1 Mtpa of CO_2 or 90 percent is recovered and purified at the plant and transported by pipeline.[169] The project started full-scale operations in April 2013 and is still successfully operating today.

MODELING STUDIES DEMONSTRATE HOW PIPELINE NETWORKS CAN BE BUILT TO TRANSPORT CAPTURED CO_2 TO SEQUESTRATION SITES.

Numerous studies over the past decade have examined the potential for a nationwide network of pipelines for CO_2 transport. Different methods and considerations were used in each case to connect sources to suitable storage sites, with some using direct point-to-point routes, and others considering aggregating emission from multiple sources into a trunk line. The results of those analyses demonstrate the necessity for, and viability of a network of U.S. CO_2 pipelines to transport large volumes of CO_2 necessary to meet climate objectives.

In one of the most comprehensive studies NETL (2011) looked at the 388 large coal plants existing nearly a decade ago, and found that 84% of them were within 25 miles of storage, 97% were within 100 miles of storage – 322 of the 323 GW examined were within 150 miles of storage.[170] NETL found that "both transport and storage requirements for retrofits at a significant number of sites have a good chance of being met. The report also details expansions of the pipeline system that were planned at the time of the report and modeled EIA-NEMS analysis to investigate a range of pipeline expansion scenarios. A modeled 2030 case projected 56 new pipeline segments and 11,000 miles of new pipelines, primarily from electric power plants to EOR projects and saline storage sites, based on a tripling of carbon capture in the U.S, with 99% coming from electric utilities. Pipelines were built at an average cost of $562,000 per mile with 323 million per mile for interstate pipelines and $624 million per mile for intrastate pipelines. Note that pipeline transportation costs are difficult to predict in general because they are dependent upon volume of CO_2 moved through them, terrain,

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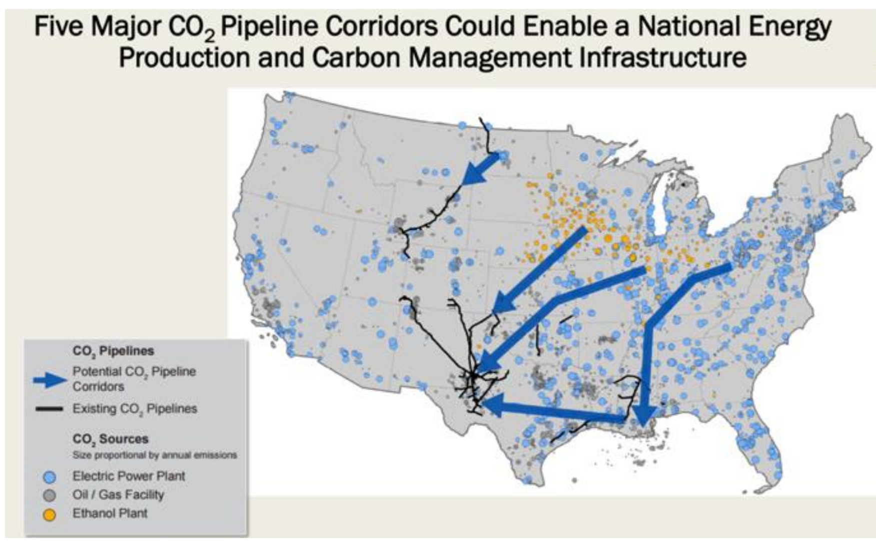
[165] Wikipedia, the Free Encyclopedia, *Petra Nova*, https://en.wikipedia.org/wiki/Petra_Nova.
[166] *See* NRG Energy, Inc., *Carbon capture and the future of coal power*, https://www.nrg.com/case-studies/petra-nova.html.
[167] Global CCS Institute, *Air Products Steam Methane Reformer EOR Project* (2017), http://www.globalccsinstitute.com/project/air-products-steam-methane-reformer-eor-project; MIT, *Port Arthur Fact Sheet: Carbon Dioxide Capture and Storage Project*, https://sequestration.mit.edu/tools/projects/port_arthur.html.
[168] Denbury Resources, *Naturally Occurring CO_2 Sources*, http://www.denbury.com/operations/gulf-coast-region/co2-sources-and-pipelines/default.aspx.
[169] *See supra* note 167.
[170] National Energy Technology Laboratory, U.S. Department of Energy, *Coal-Fired Power Plants in the United States: Examinations of the Costs of Retrofitting with CO_2 Capture Technologies, Revision 3* (2011), https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/GIS_CCS_retrofit.pdf.

and population restrictions. Additional NETL pipeline analysis published in 2015 found that if a CO_2 emissions cap was imposed of 40% of 2005 levels by 2030 and 80% by 2050, 15,194 miles (24,452 km) of pipeline would exist by 2040, with 79% of this being direct source-sink.[171]
A 2010 DOE/NETL study examined transportation from plants to storage basins estimated transport costs to be $3.65 per tonne.

Other studies demonstrating CO_2 pipeline feasibility include:

- A 2009 study modeled potential pipeline buildout scenarios for CO_2 pipelines.[172] The study showed that to limit the atmospheric CO_2 levels to 450 ppm and 550 ppm, 23,000 miles (37,014 km) or 11,000 miles (17,702 km) respectively would be needed - and could be built - by 2050. The study concluded that the need to increase the size of existing dedicated CO_2 pipeline system should not be seen as a major obstacle for the commercial deployment of CCS technologies in the United States.

- In 2017, the State CO_2-EOR Working Group illustrated the ability of five pipeline corridors (map below), at a cost of $15 billion, to transport CO_2 from areas of high industrial activity, including coal plants, to depleted oilfields for EOR.



2017 Policy study illustration of potential pipeline corridors (illustrative, not modeled)[173]

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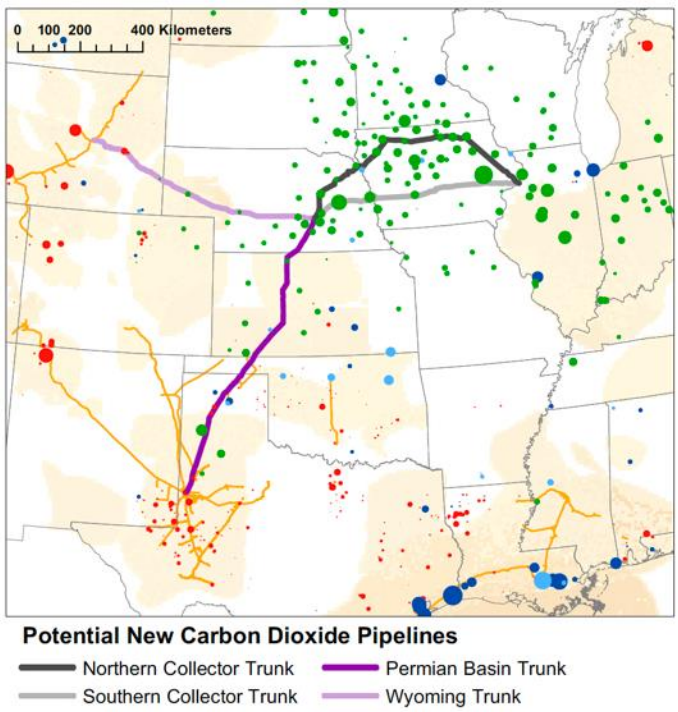
[171] National Energy Technology Laboratory, *supra* note 162.
[172] JJ Dooley *et al.*, *Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks*, 1 Energy Procedia 1595 (2009), http://ac.els-cdn.com/S1876610209002100/1-s2.0-S1876610209002100-main.pdf?_tid=68c9643a-798e-11e4-ab93-00000aacb362&acdnat=1417461507_82ec94a603dee8e29cf213349b3f313b.
[173] *See* State CO_2-EOR Deployment Working Group, *21st Century Energy Infrastructure: Policy Recommendations for Development of American CO_2 Pipeline Networks* (2017), http://www.betterenergy.org/wp-content/uploads/2018/02/White_Paper_21st_Century_Infrastructure_CO2_Pipelines_0.pdf; CO2 EOR State Deployment Work Group, *Infrastructure for Carbon Capture: Technology, Policy and Economics* (2017), https://www.naruc.org/default/assets/File/GPI%20NARUC%20webinar%20slides.pdf.

- Zelek, *et al*., (2012) NEMS-CCUS model results found that captured emissions were stored, in general, within 100 miles of the source via direct pipelines.[174]

- A 2018 Princeton study demonstrates the feasibility of linking Midwest CO_2 sources by pipeline, proposing several pipeline corridors (*see* figure below) that could provide a capacity of 19-30 million tonnes per year linking low cost CO_2 sources from ethanol refineries in the Midwest to dedicated geological storage resources in West Texas and the Permian Basin or Wyoming.[175]



Map of modeled potential carbon dioxide pipelines from Edwards and Celia (2018).[176]

A 2014 NETL publication describes DOE's transport cost model designed to estimate the price of CO_2 transported, broken out by region, covering all costs, including a return on investment on 12, 16 and 20-inch diameter pipelines.[177] The report also cites a variety of previous estimates of cost including, for example, Kinder Morgan's pipeline cost metrics, shown in the table below.

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174 Charles A. Zelek *et al*., *NEMS-CCUS: A Model and Framework for Comprehensive Assessment of CCUS and Infrastructure* (2012), https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/CMTC150377-NEMS_CCUS.pdf.

175 Ryan Edwards & Michael Celia, Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States, 115 Proceedings of the National Academy of Sciences of the United States of America E8815 (2018), www.pnas.org/cgi/doi/10.1073/pnas.1806504115.

176 *Id.*

177 National Energy Technology Laboratory, U.S. Department of Energy, *FE/NETL CO_2 Transport Cost Model: Description and User's Manual* (2014), https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/co2-transp-cost-model-desc-user-man-v1-2014-07-11.pdf.

Terrain	Capital Cost ($/inch-diameter/mile)
Flat, Dry	$50,000
Mountainous	$85,000
Marsh, Wetland	$100,000
River	$300,000
High Population	$100,000
Offshore (150'-200' depth)	$700,000

NEW SOURCE-SINK ANALYSIS INDICATES THAT ALL AFFECTED SOURCES ARE WITHIN A REASONABLE DISTANCE OF A STORAGE BASIN.

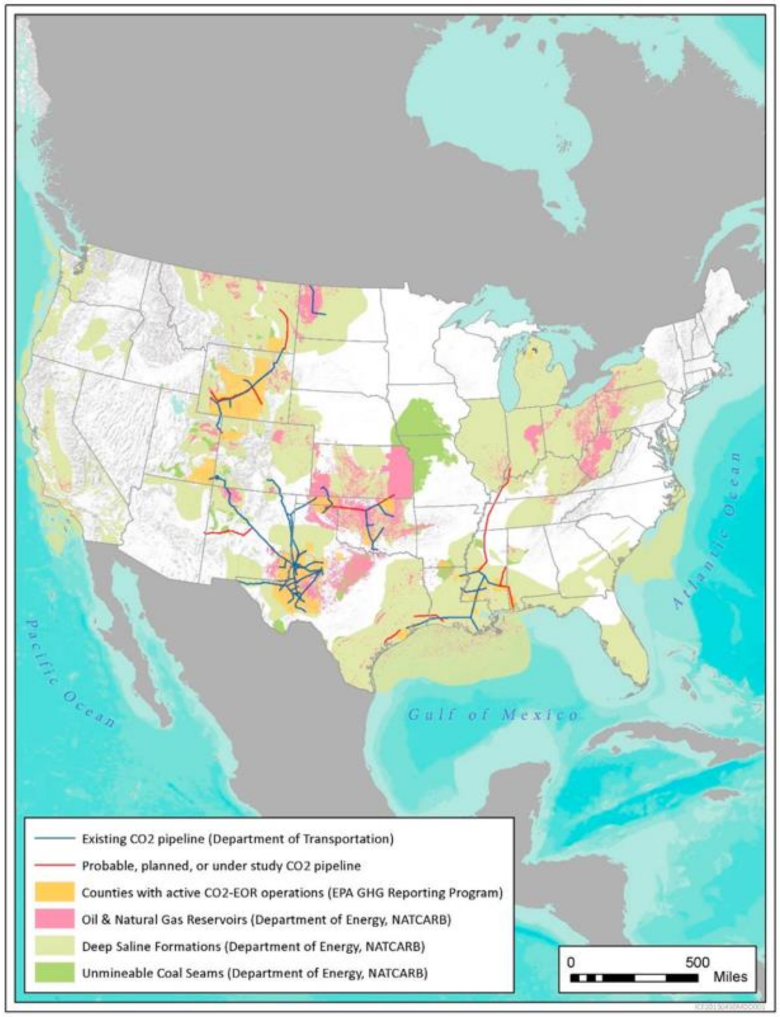
In the proposed Affordable Clean Energy Plan (ACE), states are expected to evaluate the "candidate technologies" in establishing a standard of performance for each particular source and may take into consideration the individual characteristics of that source. As we have argued previously in these comments, the ACE rule failed to analyze CCS technology as a BSER and did not include it in the candidate technologies. This failure included considering the availability of geologic carbon storage for the affected sources.

Despite determining that the building block approach was the BSER under the Clean Power Plan, EPA analyzed saline and EOR-based sequestration capacity in the U.S. and existing sources. In the CPP RIA EPA provided a simple map of available sequestration opportunities and pipelines, concluding that:[178]

> "*Geologic sequestration (GS) (i.e., long-term containment of a CO2 stream in subsurface geologic formations) is technically feasible and available throughout* ***most*** *of the United States.* (emphasis added).

Clean Air Task Force commissioned a study which built on this map to illustrate the availability of geologic storage for affected plants. The study demonstrates each source can be matched to a reasonable storage site, further supporting inclusion of CCS in the BSER.

[178] CPP RIA at 2-34.



EPA Figure 2-21 from the Clean Power Plan RIA suggesting a lack of storage resources in wide swaths of the U.S. A new analysis provided in these comments link all affected sources with a storage basin. [179]

A University of Texas Gulf Coast Carbon Center source-sink analysis was commissioned by Clean Air Task Force with the objective to identify the closest geologic storage opportunities for each of the power plant affected by the proposed ACE rule. Results demonstrate that captured CO_2 from *every one of the affected coal plants* can be pipelined a reasonable distance to a storage basin in the United States. The results, illustrated in the map above, showing the applicable sources, and paired storage location. An estimate of the total distance required to link the emissions source to storage sites is included in tabular form as an appendix. [180]

The source-sink analysis suggests that source-sink distances for coal plants are well within the range of existing U.S. pipelines identified in NETL's 2015 report.[181] The analysis found:

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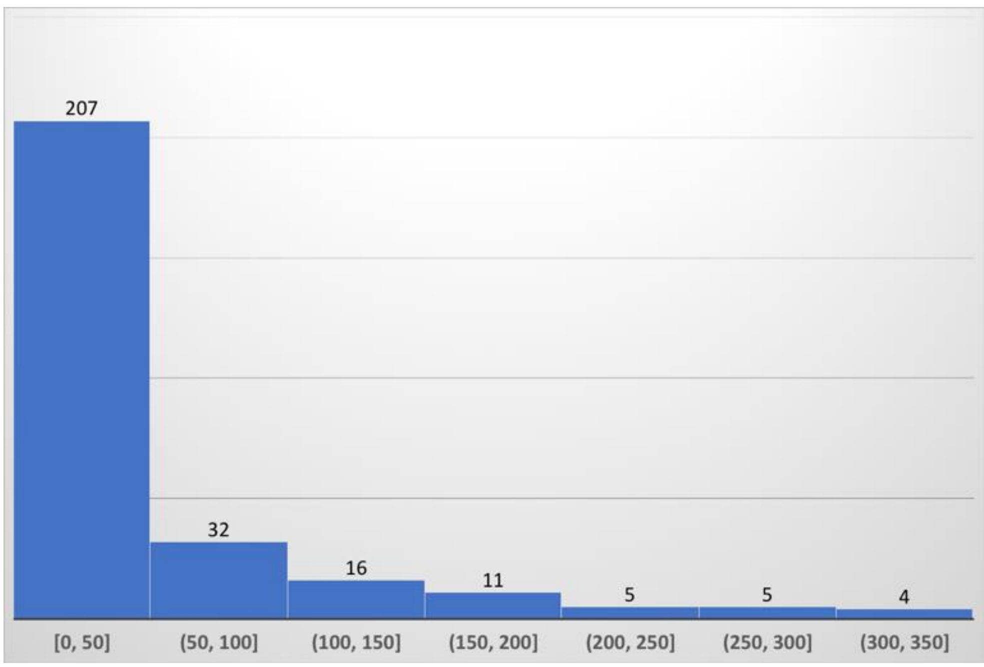
[179] *Id.*
[180] Peter Tutton, *Matching 111d Affected Sources to Storage Locations in the US for Carbon Capture and Sequestration* (2018) (attached).
[181] National Energy Technology Laboratory, *supra* note 162 at 4-14.

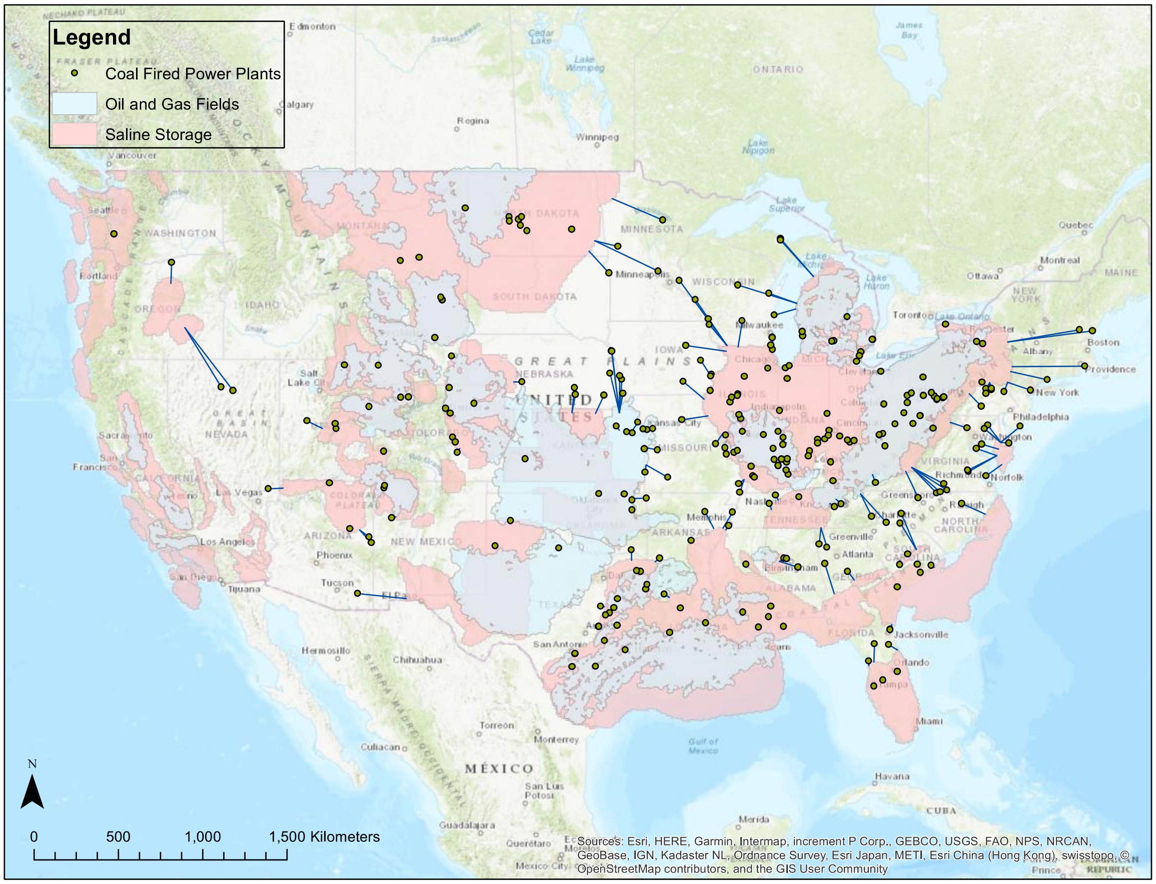
- 25% of plants are less than 50 km (31) miles from a potential geologic storage basin.
- 50% the plants are within a distance of 12 km (8 miles) (median value).
- 95% of the plants are within 200 km (125 miles) or less from a geologic sink.
- Only 14 of the 286 plants exceed a 200 km (124 mile) distance, ranging from 201 km (125 mi) to 349 km (216 miles). Of those, only 5 plants exceed 300 km (186 mi).

For comparison:

- The CO_2 pipeline from the commercially successful post combustion capture at the Petra Nova power plant extends 82 miles south to the West Ranch Field.
- The CO_2 pipeline from Dakota gasification to Weyburn field is 329 km (204 miles) a distance at which only 3 plants subject to the rule exceed.
- In the West Texas Permian Basin, trunk lines range from 183 km (113 mi) to 810 km (502 mi).
- Distribution lines in the Permian range from 6 km (4 mi) to 23 km (14 mi).
- In the Rocky Mountains CO_2 pipelines range from 48 km (30 mi) to 371 km. (230 mi).
- In the Gulf Coast pipelines range from 81 km (50 mi) to 550 km (314 mi).



Above: Histogram displaying numbers of sources in 50 km (31 mi) increments from source to sink analysis. For example, the (0, 50) bins are all plants that are 0-50 km from a storage basin, of which there are 209 sources of 286 total sources (73%). Source: P. Tutton for CATF analysis.



Map illustrates applicable coal fired power plant sources capturing CO_2 (green dots) and paired geologic storage basins for ACE -applicable sources. Sedimentary basins with saline storage capacity are shaded tan and oil and gas fields in light blue. Where green source dots overlay storage basins, pipeline distances are too small to be shown in the continental-scale map. See accompanying table in appendix. Prepared by Peter Tutton, University of Texas Austin, for Clean Air Task Force.

CONCLUSION

Today's commercial CO_2 management know-how, combined with centuries of sequestration capacity in deep geologic formations and reasonable distances to transport captured CO_2 by pipeline to storage sites, means that carbon capture and storage should be a core BSER strategy to provide deep reductions in emissions from the affected sources under the Clean Air Act section 111(d).

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Matching 111d Affected Sources to Geologic Storage Locations in the U.S. for Carbon Capture and Sequestration

30 October 2018

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Introduction

The availability of geologic storage to existing U.S. coal plants that would be subject to review as part of the proposed Affordable Clean Energy rule, was investigated using a source-sink matching approach. The method employed spatial data, along with 2017 emissions and storage information to link coal fired power plants to geologic storage locations, in onshore U.S. saline brine reservoirs or depleted oil fields. The study aimed to illustrate the potential distances carbon dioxide would have to be transported, from each source, for it to be stored in basins with adequate capacity. As described below, the study mapped straight- line distances and therefore the results serve as a simple indicator of geologic storage availability to potential carbon capture facilities.

Prior Literature

A review of the previous literature shows that numerous studies have investigated incorporating point sources into a nationwide CO_2 pipeline network for CCS. A variety of methods and assumptions were used in each case to connect sources to suitable geologic storage sites, with some using direct point-to-point routes, and others considering aggregating emission from multiple sources into a trunk line. In the simplest case the State CO_2-EOR Working Group (2017) illustrates how five pipeline corridors, at a cost of $15 billion, could transport CO_2 from areas of high industrial activity, to sites for enhanced oil recovery (EOR). Zelek et al. (2012) used the DOE NEMS-CCUS model, considering several climate mitigation pathways, and associated policies. The results showed that the emissions were generally stored within 100 miles of the source, and the optimal solutions typically used direct pipelines for CO_2 transportation. The NETL (2015a) investigation demonstrated if a U.S. emissions cap was imposed representing reductions of 40% of 2005 CO_2 emissions levels by 2030 and 80% reductions by 2050, 15,194 miles (24,452 km) of pipeline would exist by 2040, with 79% of this being direct The IEAGHG (2010) employed a similar scenario in which global emissions were halved by 2050 compared to 2005 levels, 22,227 km of direct pipelines would be needed in the U.S., or 17,992 km if clusters are used. Finally, Dooley et al. (2009) showed that to limit the atmospheric CO_2 levels to 450 ppm and 550 ppm, 23,000 miles (37,014 km) or 11,000 miles (17,702 km) of pipeline in the U.S., respectively, would be needed by 2050.

Method: Estimating Point to Point Distances

To understand the potential magnitude of implementing CCS on coal fired power plants, the present study considered the direct, or point to point, distances from each source to a suitable injection site with no limit to the distance between source and sink. Previous studies limited the pipeline distance to find a suitable storage sites, e.g. 10 miles in Dahowski and Dooley (2008) and up to 25 miles in the case of Dooley (2008).

In this investigation, ArcGIS 10.6 was used to perform a spatial analysis on the distance of coal fired power plants from sites of potential geologic CO_2 storage. For this analysis, MSB Energy Associates assembled a database of U.S. EPA (2017) continuous emissions monitoring data (CEMs), for coal-fired power plants in the U.S., meeting the definition of affected source under the proposed Affordable Clean Energy rule (ACE) (EPA, 2018). Sources with zero emissions for 2017 were then cross-checked with a database of operating data and removed from the analysis, as the EIA's report 860M, Monthly Update to Annual Electric Generator Report (EIA, 2018), showed them either to be retired or not expected to return to service within the next year as shown in Table 1. This resulted in a net 286 power plants, emitting a total of 1,213 million metric tons of CO_2 annually which were then matched to suitable storage sites using a method developed by Tutton (2018).

Table 1. The coal fired power plants removed from the data set due to having zero emissions in 2017. The EIA report 860M (EIA, 2018) was used to determine the status of each plant.

State	**County**	**Plant**	**ORIS-ID**	**CO_2 Emissions, metric tons**	**Status Current to July 2018**
CO	Prowers County	Lamar	508	0	(OS) Out of service and NOT expected to return to service in next calendar year
KY	Hancock County	Coleman	1381	0	(OS) Out of service and NOT expected to return to service in next calendar year
KY	Webster County	Robert Reid	1383	0	(OS) Out of service and NOT expected to return to service in next calendar year
MO	Boone County	Columbia	2123	0	(OP) Operating
NJ	Mercer County	Mercer Generating Station	2408	0	Retired
WV	Kanawha County	Kanawha River	3936	0	Retired
MI	Hillsdale County	Michigan Hub, LLC	4259	0	Retired
MN	Cook County	Taconite Harbor Energy Center	10075	0	2 Units Operating and 1 Retired
NC	Bladen County	NC Renewable Power - Elizabethtown	10380	0	(OS) Out of service and NOT expected to return to service in next calendar year

In order to identify geologic basins with adequate capacity to store CO_2, this analysis utilized the DOE NatCarb database (NETL, 2015 b, c) which provides information for both saline formations, as well as oil and gas fields. NETL estimated the storage capacity of saline formations using a calculated volumetric capacity approach combining formation thickness and rock properties, whereas the capacity for oil and gas fields was estimated with the benefit of prior production data. The NETL database provided the potential magnitude, and locations, of storage in the U.S. The 50th percentile (median) capacity factor (based on porosity/thickness/area/storage efficiency) was selected from the NETL database for the storage capacity of each basin. GIS was used to combine the areal extent of overlapping geologic resources in order to further delineate storage basins (see map, Figure 6, below). The 50th percentile (median) geologic storage capacity value of all the cells, were then summed for each basin.

Delineating oil and gas basins required an alternate approach to aggregate oilfields, represented by 68,684 separate features in the dataset, into a workable oil and gas storage basin database. To do this, depleted oil and gas fields within 10 km of each other were identified and combined into basins, for the purposes of this analysis, and a basin outline was then drawn around all selected fields. The 50th percentile (median) capacity estimate for each field within the aggregated basin was then summed to give the overall basin capacity estimate, similar to the NETL basins and capacities for saline storage.

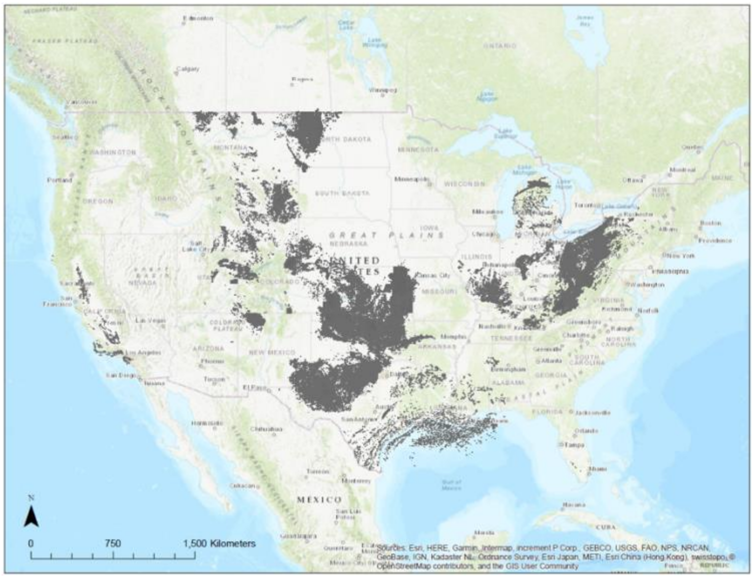
In order to subdivide basins into potential injection sites, large basins were broken up into grid cell-based features, each representing 300 million metric tons of storage, with a point placed at the center (centroid point) of each cell as described below. This was achieved be rasterizing each basin with a cell size calculated using the following equation (with the 300 representing the 300 million metric tons per cell):

$$Cell\ Size = \sqrt{Basin\ Area \cdot \frac{300}{Basin\ Capacity}}$$

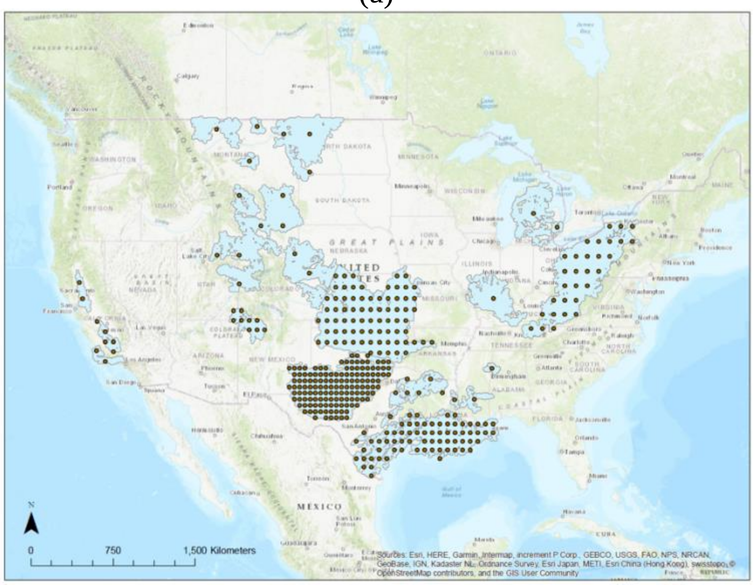
Once the feature had been rasterized it was converted to a point feature, resulting in a point at the centroid of each raster cell, Figure 1. GIS was then used to match each coal fired power plant to the nearest basin center of sufficient storage capacity to sequester the plant's emissions. The model was run based on a 40-year injection period as a conservative proxy for the remaining lifetime emissions of each plant.

All the basins with storage greater than the expected project emissions were selected, and the distance to the closest potential injection site (centroid point) contained within one of these basins was then output. This rule applied to sources located within basins too. The distance to the closest centroid, with sufficient capacity, was calculated, and as such sources weren't allowed to inject on site.

Figure 3 shows source and sink couples. Due to the magnitude of storage estimates, over 8,000 billion metric tons (NETL, 2015 b, c), some basins have closely spaced centroids giving the appearance of pipelines terminating at a basin's border. The expanded map, Figure 4, provides a more detailed view, and shows that in each case they end at a centroid. Table 2 gives the distance to the centroid within the basin.



(a)



(b)

Figure 1. NatCarb oil and gas data (NETL, 2015c) were converted into centroids as a proxy for potential injection sites. A similar exercise was done for saline storage basins.

Findings

The results show that there is sufficient storage capacity within the United States to store centuries of CO_2 captured from applicable coal fired power plants. Additionally, the majority of the plants are located within a reasonable distance of a storage site, with 73% of sources located under 50 km away, and 95% located under 200 km away. In total, 13,183 km of pipeline would be needed to individually link each emission source to the closest injection point.

It is important to note that the results are a simple representation of source to sink matching based on lifetime plant emissions, 50th percentile (median) storage efficiency factor, and a straight-line distance to the closest centroid within a basin that has adequate capacity. The analysis does not consider routing factors and obstacles, or long interstate regional trunk-lines (like the 232-mile Denbury Greencore Pipeline or the 273 -mile long Denbury Green pipeline from Jackson MS to Houston, TX). Features such as trunk-lines may serve to increase the efficiency of carbon dioxide transport.

Table 2. Percentile of emissions within a given distance of a suitable storage site, considering a 40-year injection period.

Percentile of Sources, %	Distance, km
5	2.3
50	12.3
95	199.4

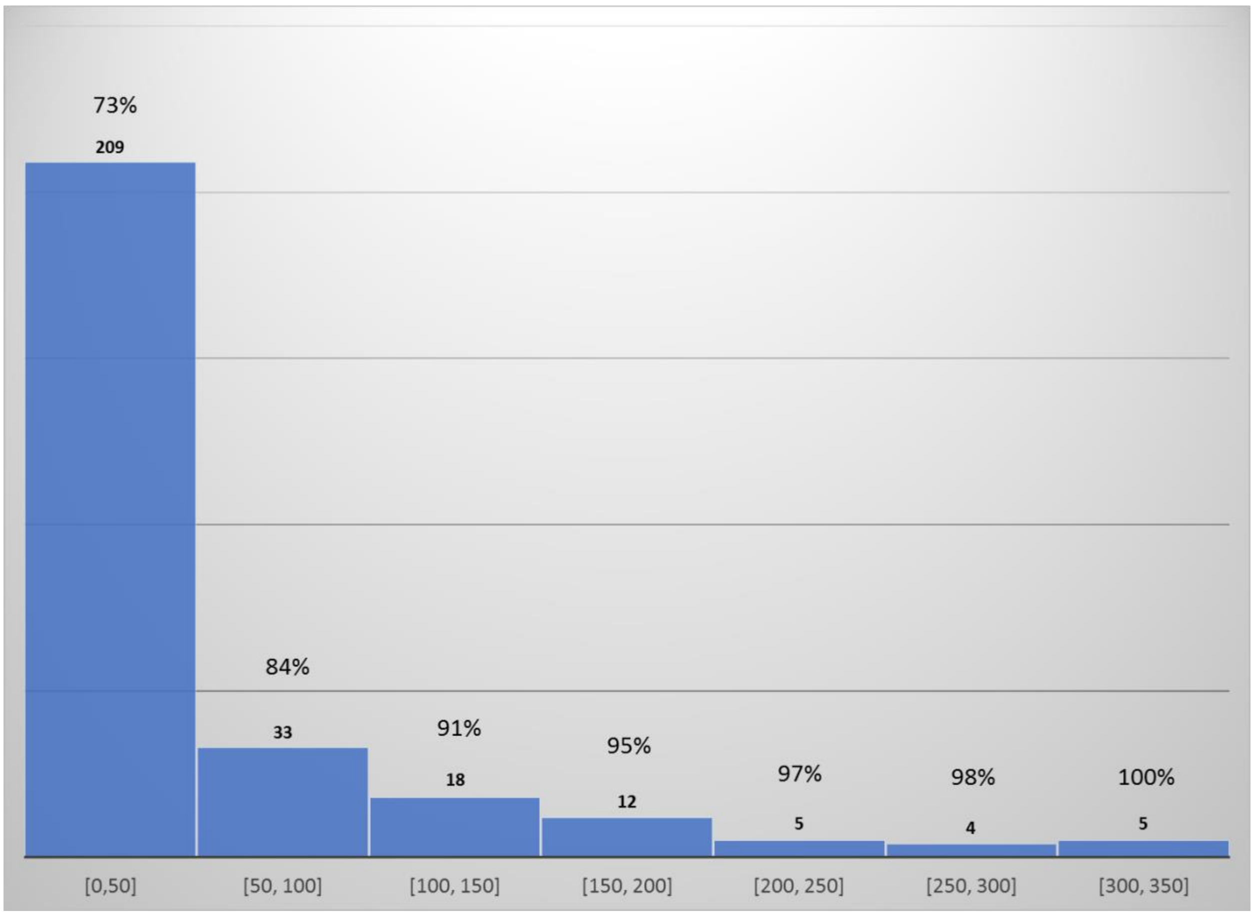


Figure 2. Histogram displaying numbers of sources in 50 km (31 mi) increments from source to sink analysis. For example, the (0, 50) bins are all plants that are 0-50 km from a storage basin, of which there are 209 sources of 286 total sources (73%). This only considered CEMS from plants with non-zero emissions for 2017. Those with zero emission were removed as EIA 860M (EIA, 2018) showed that these were either retired or unlikely to return to service within the next year. The cumulative percentage of sources are shown above each bar.

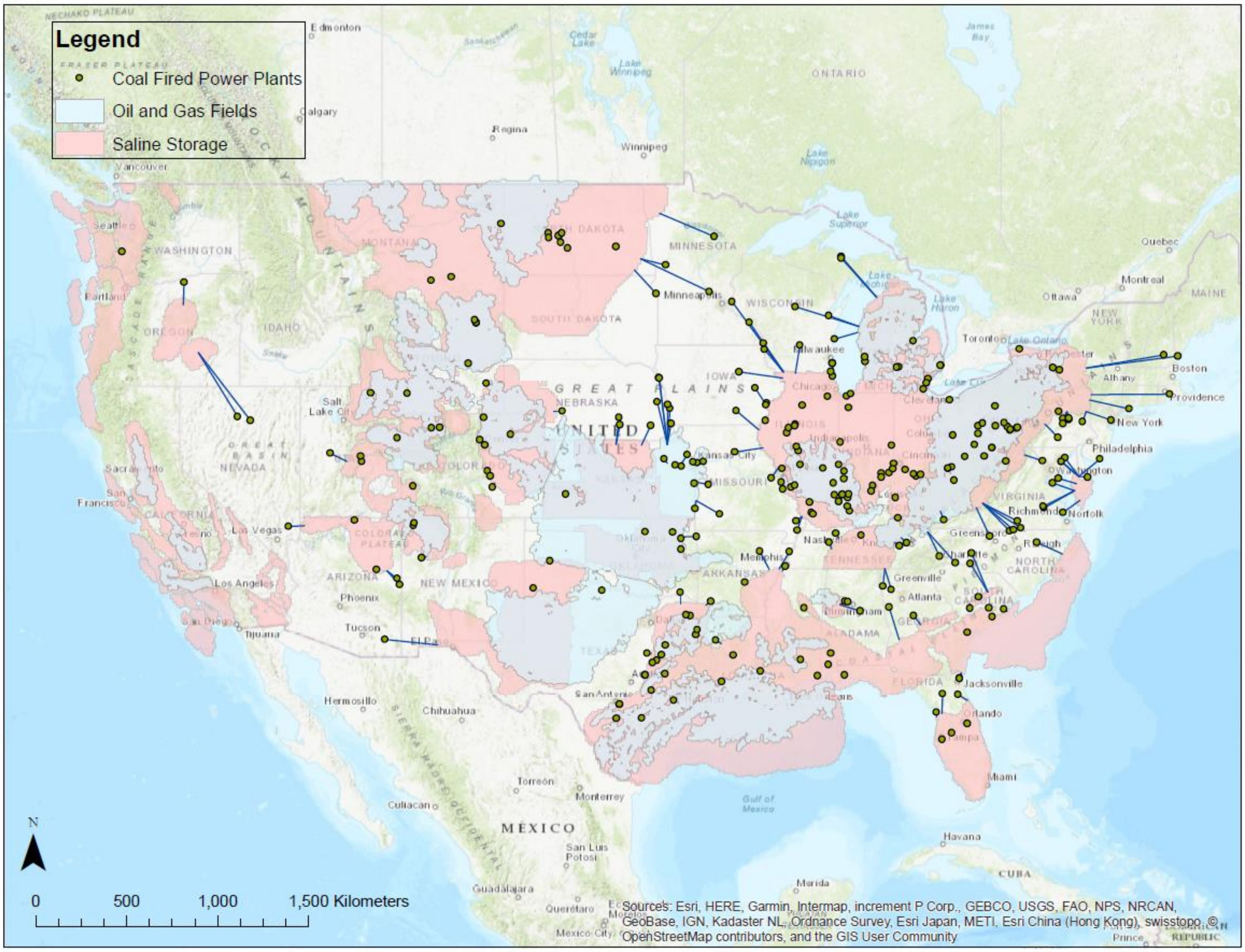


Figure 3. A map of the point to point routes between coal fired power plants and storage sites, considering both saline storage, and oil and gas fields. The map shown is for the 50th percentile (median) scenario. Note that, although it appears that pipelines terminate at the basin edge, the expanded map Figure 4, show that in each case they terminate at a centroid. Table 2 gives the distance to the centroid within the basin.

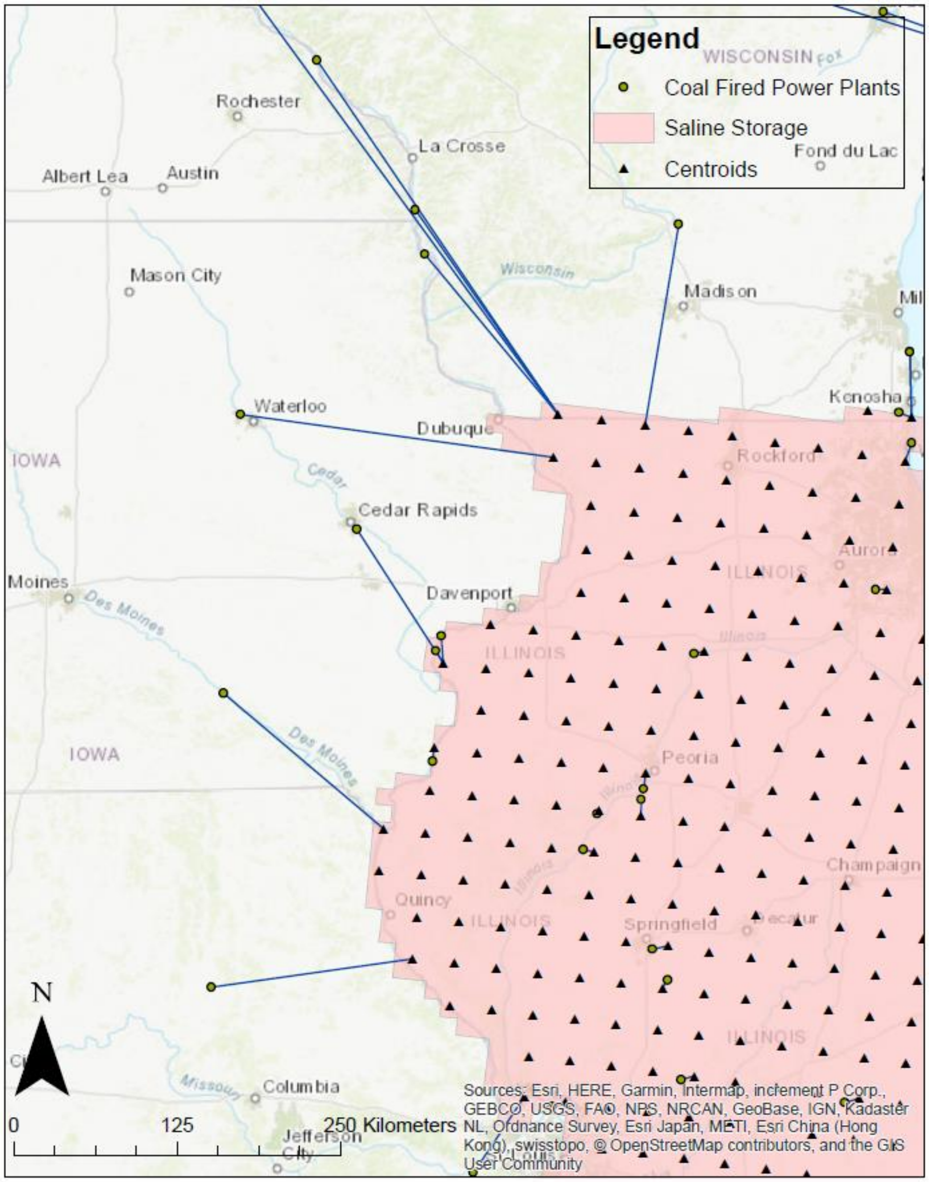
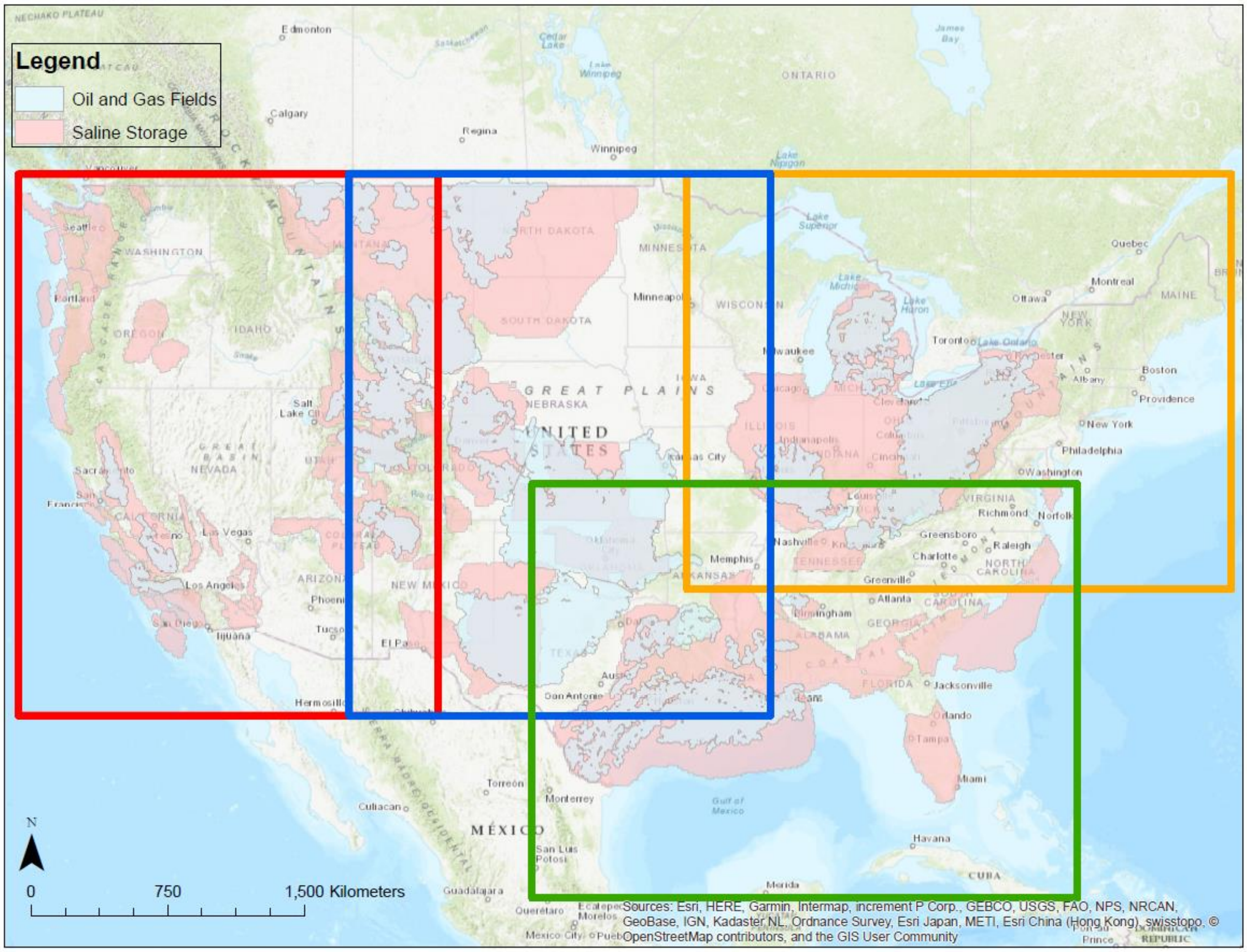
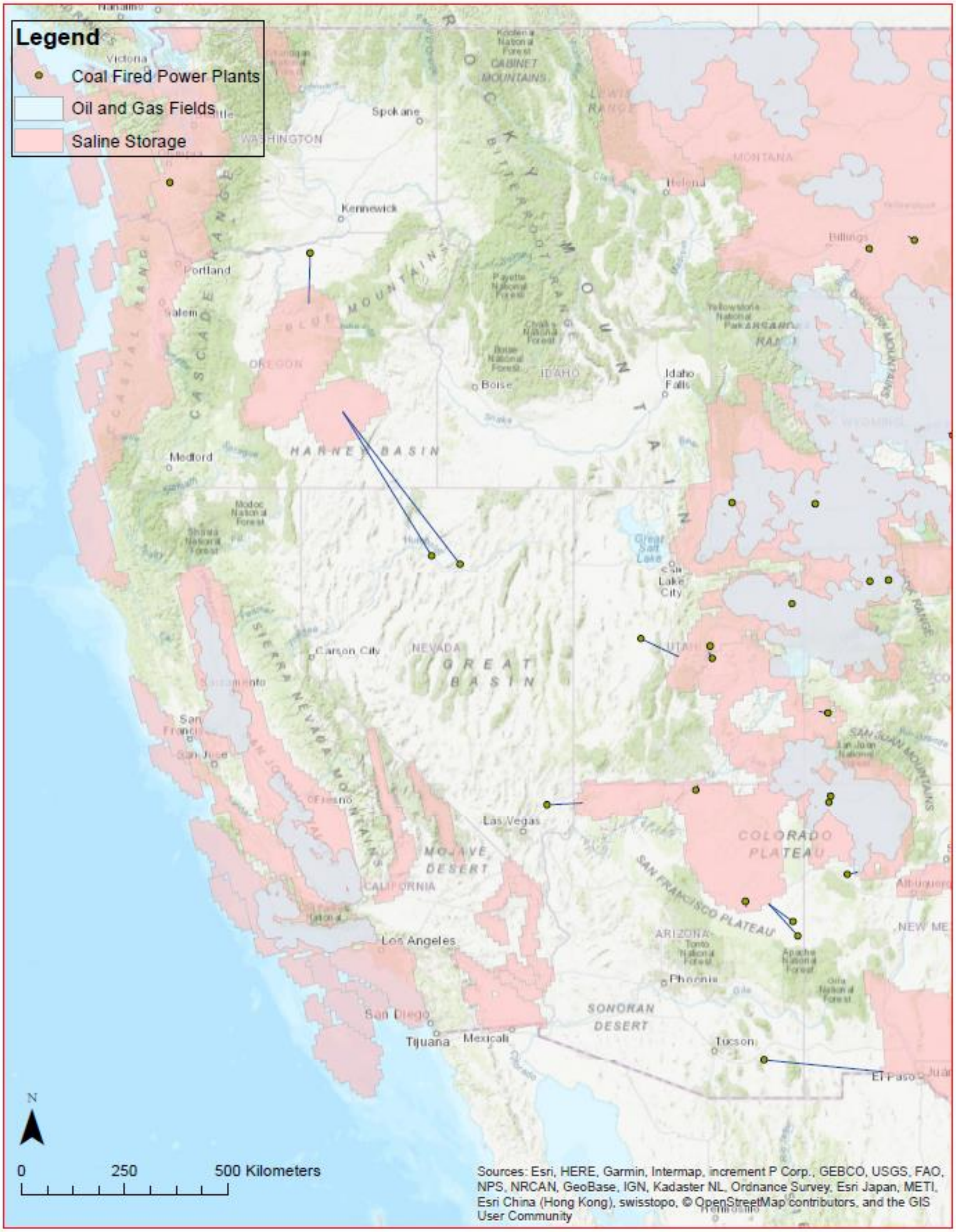


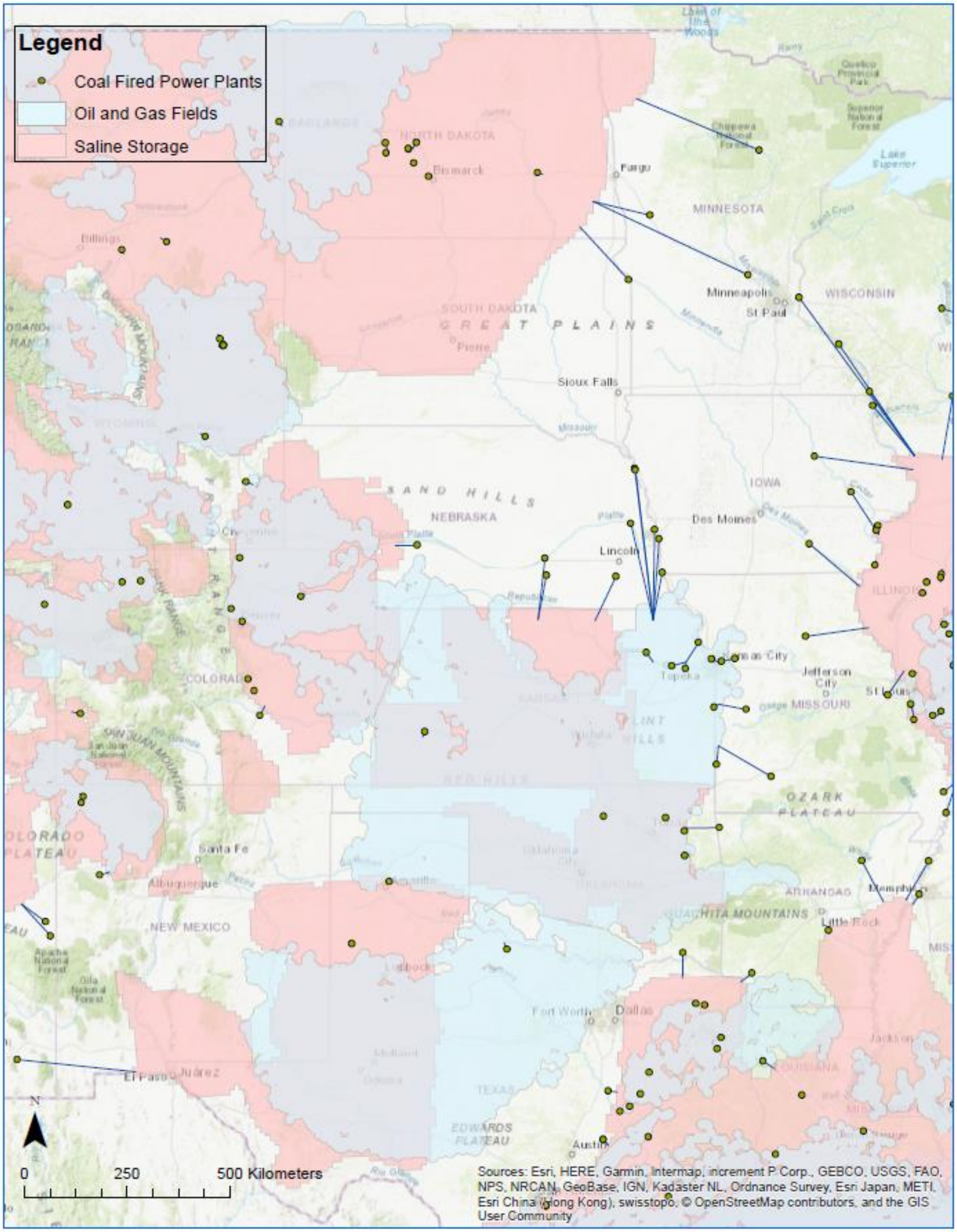
Figure 4. A map showing how a basin is split up into centroids, which act as a proxy for a suitable injection site. Each centroid is within a parcel of land, calculated by dividing the basin into areas equating to 300 million metric tons of estimated CO_2 storage capacity. Some of these centroids appear near the boundary of basin, giving the appearance of transporting to the basin edge. Additionally, it can be seen that the sources which are located within the basin also transport to the nearest centroid.


Legend
Oil and Gas Fields
Saline Storage
0
750
1,500 Kilometers
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

(a)

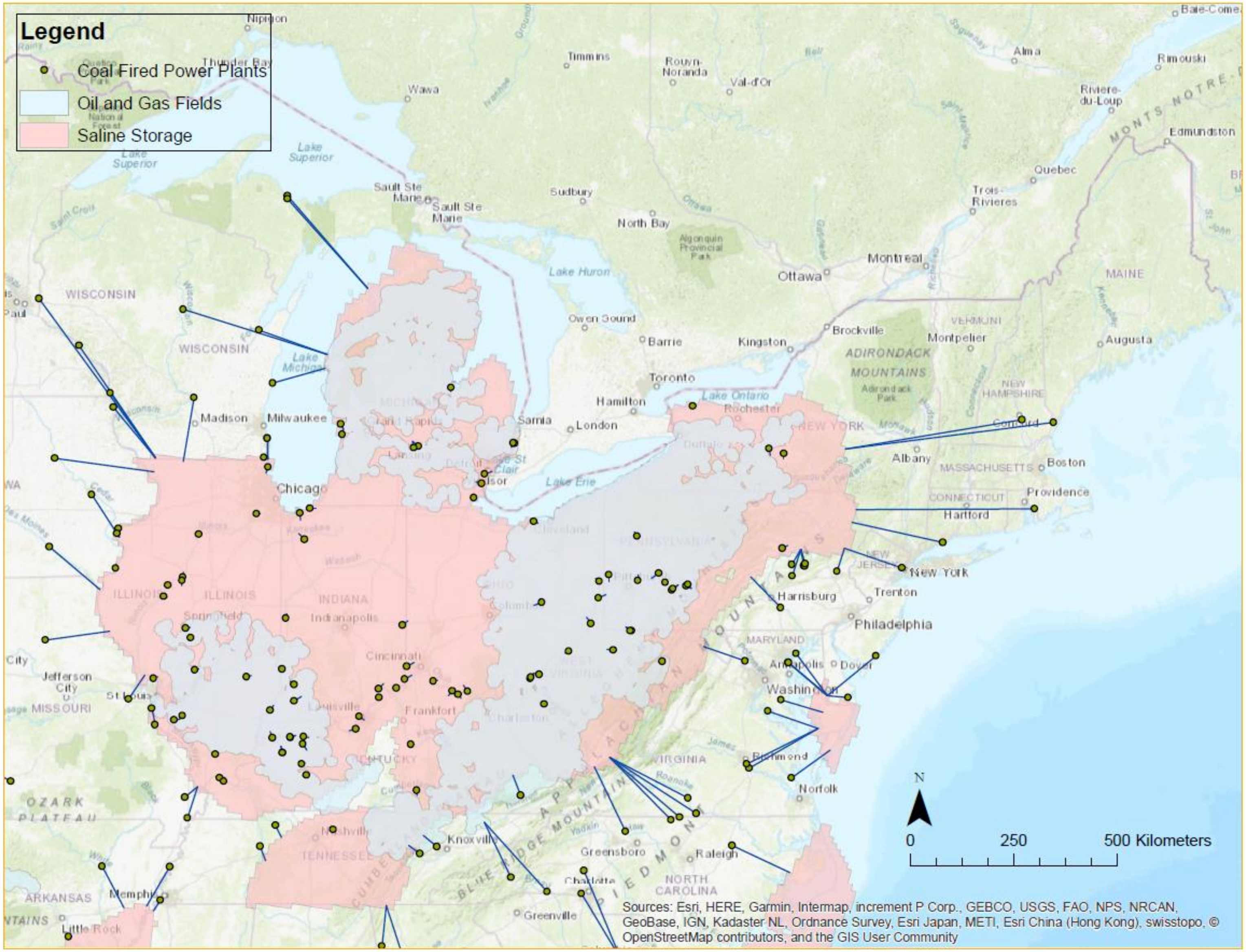

Legend
Coal Fired Power Plants
Oil and Gas Fields
Saline Storage
N
0
250
500 Kilometers
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

(b)

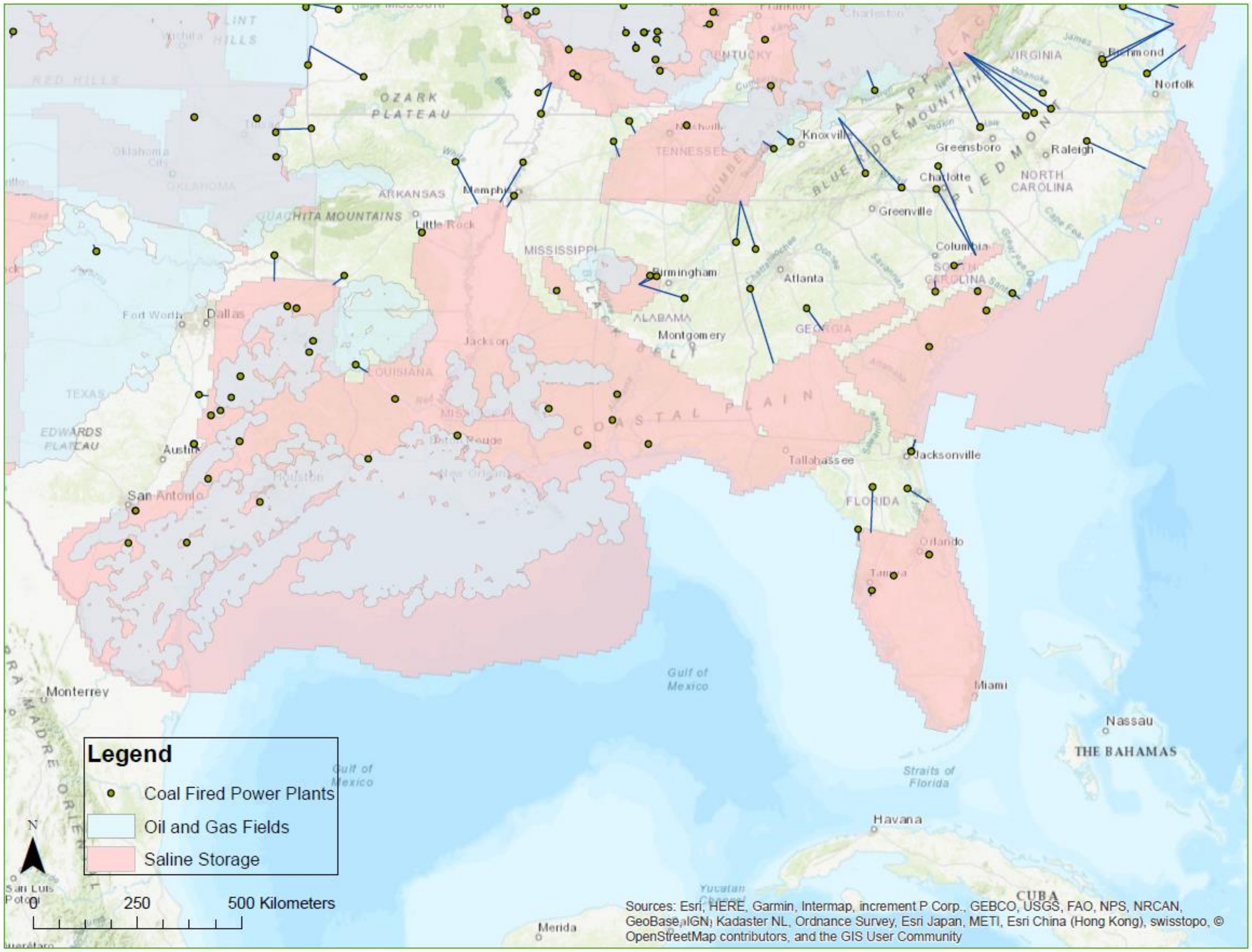


Legend
Coal Fired Power Plants
Oil and Gas Fields
Saline Storage
NORTH DAKOTA
Bismarck
Fargo
MINNESOTA
Minneapolis
St Paul
WISCONSIN
SOUTH DAKOTA
GREAT PLAINS
Pierre
Sioux Falls
SAND HILLS
NEBRASKA
Lincoln
IOWA
Des Moines
Billings
COLORADO
Topeka
Jefferson City
MISSOURI
St Louis
OZARK PLATEAU
Santa Fe
Albuquerque
NEW MEXICO
ARKANSAS
Memphis
Little Rock
OUACHITA MOUNTAINS
Fort Worth
Dallas
El Paso
Juárez
TEXAS
EDWARDS PLATEAU
Austin
0 250 500 Kilometers
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

(c)


Legend
Coal Fired Power Plants
Oil and Gas Fields
Saline Storage
0
250
500 Kilometers
N
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

(d)



(e)

Figure 5. a) Showing the extent of each of the four separate maps. b) to e) Showing more detailed regional maps of source sink matching.

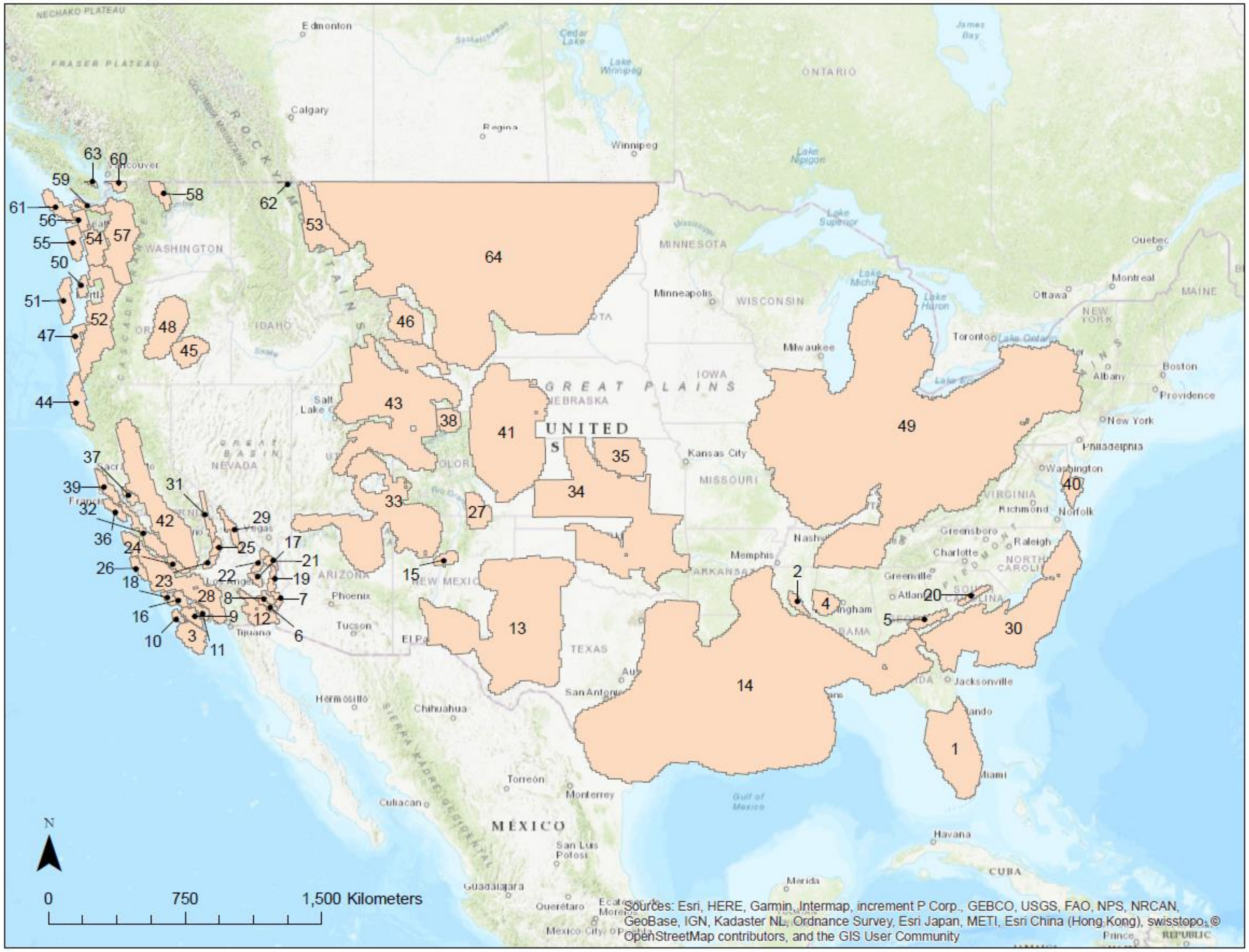


Figure 6. A map showing the basin numbers for saline storage, with delineations taken from NETL (2015b).

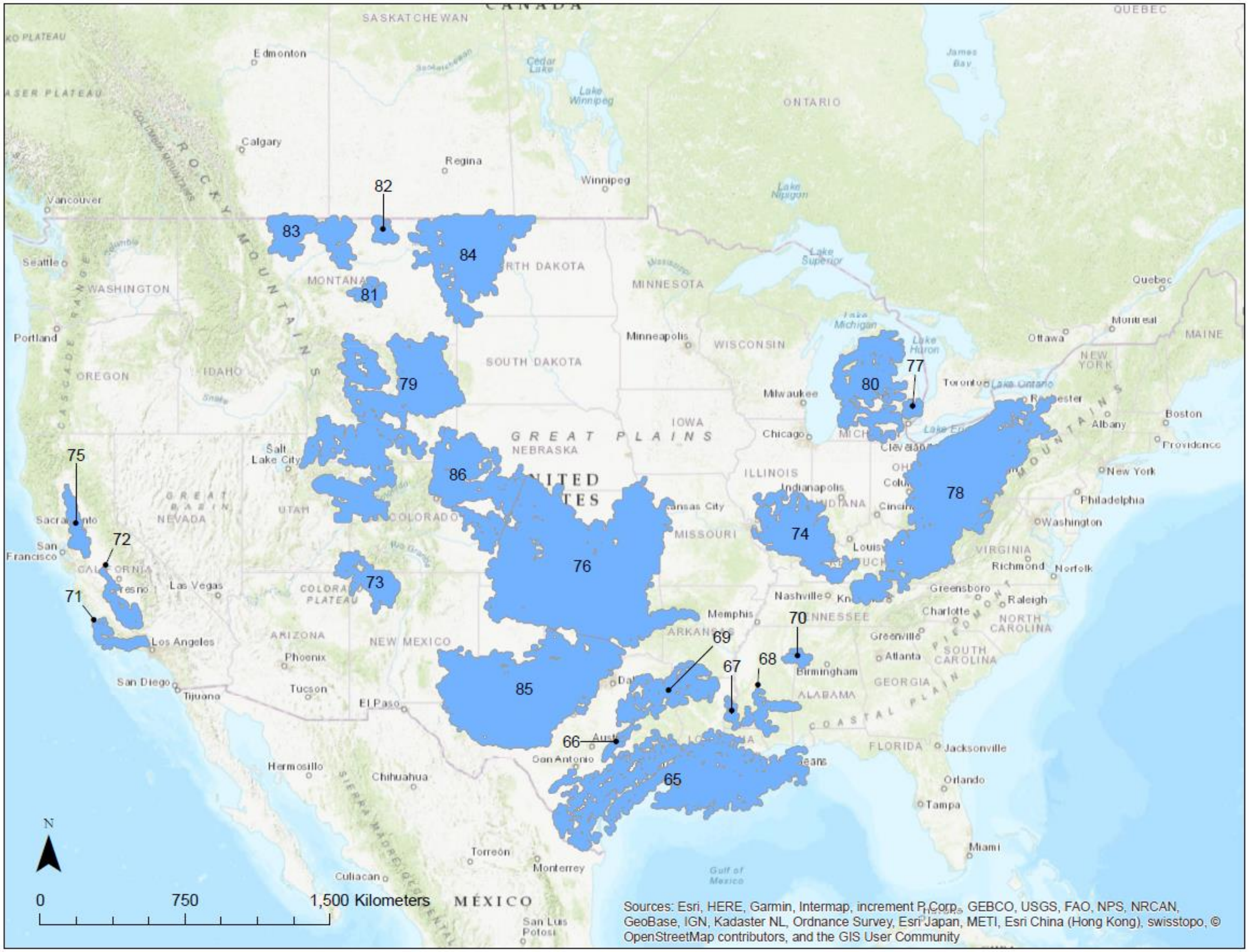


Figure 7. A map showing basin numbers for depleted oil and gas fields, with delineations adapted from NETL (2015c).

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Table 3. Showing the distances to the closest available storage site, considering both saline formations, and oil and gas fields. A map of these point to point routes is shown in Figures 3 and 5. The highlighted cell represent scenarios under which a certain power plant stores its emissions within an oil or gas field. See Figures 6 and 7 for basin numbering. This only considered CEMS from plants with non-zero emissions for 2017. Those with zero emission were removed as EIA 860M (EIA, 2018) showed that these were either retired or unlikely to return to service within the next year.

ORIS-ID	County	Plant	CO_2 Emissions, million metric tons	Distance to sink (km)	Basin Number
3	Mobile County	Barry	3.4	2.2	14
8	Walker County	Gorgas	4.6	27.0	14
26	Shelby County	E C Gaston	4.0	91.4	4
51	De Soto Parish	Dolet Hills Power Station	2.0	27.7	14
56	Washington County	Charles R Lowman	1.6	4.8	14
59	Hall County	Platte	0.4	113.2	34
60	Adams County	Gerald Whelan Energy Center	1.3	83.6	35
87	McKinley County	Escalante	1.1	19.1	33
108	Finney County	Holcomb	1.1	11.5	34
113	Navajo County	Cholla	4.3	10.7	33
127	Wilbarger County	Oklaunion Power Station	1.7	14.8	85
130	Berkeley County	Cross	8.5	6.0	30
136	Putnam County	Seminole (136)	7.2	51.3	1
160	Cochise County	Apache Station	1.7	234.8	13
165	Mayes County	Grand River Dam Authority	0.8	6.7	76
207	Duval County	St. Johns River Power	5.3	25.0	30
298	Limestone County	Limestone	9.6	3.3	14
469	Adams County	Cherokee	1.4	7.4	41
470	Pueblo County	Comanche (470)	8.9	19.9	41
477	Boulder County	Valmont	0.2	2.5	41
492	El Paso County	Martin Drake	1.3	5.5	41
525	Routt County	Hayden	2.8	0.4	43
527	Montrose County	Nucla	0.1	16.1	33
564	Orange County	Curtis H. Stanton Energy Center	4.6	2.1	1

568	Fairfield County	Bridgeport Harbor Station	0.2	158.7	49
594	Sussex County	Indian River	0.4	37.1	40
602	Anne Arundel County	Brandon Shores	4.1	93.3	40
628	Citrus County	Crystal River	9.6	22.6	1
641	Escambia County	Crist Electric Generating Plant	3.4	1.7	14
645	Hillsborough County	Big Bend	5.9	10.7	1
663	Alachua County	Deerhaven	0.5	94.1	1
667	Duval County	Northside	1.8	26.6	30
676	Polk County	C D McIntosh Jr Power Plant	1.5	7.8	1
703	Bartow County	Bowen	13.8	98.8	49
708	Floyd County	Hammond	0.6	80.7	49
856	Peoria County	E D Edwards	2.9	9.6	49
861	Montgomery County	Coffeen	5.6	7.4	49
876	Christian County	Kincaid Generating Station	4.7	5.5	49
879	Tazewell County	Powerton	5.9	8.9	49
883	Lake County	Waukegan	2.0	10.6	49
884	Will County	Will County	0.4	5.7	49
887	Massac County	Joppa Steam	4.1	9.2	49
889	Randolph County	Baldwin Energy Complex	7.5	10.2	49
891	Mason County	Havana	2.9	5.9	49
892	Putnam County	Hennepin Power Station	1.8	5.5	49
963	Sangamon County	Dallman	2.6	8.5	49
976	Williamson County	Marion	2.1	8.2	49
983	Jefferson County	Clifty Creek	6.2	13.0	49
994	Pike County	IPL - Petersburg Generating Station	9.8	15.9	49
995	Porter County	Bailly Generating Station	1.9	12.3	49
997	LaPorte County	Michigan City Generating Station	1.3	11.2	49
1001	Vermillion County	Cayuga	5.4	7.9	49
1004	Knox County	Edwardsport Generating Station	3.4	9.1	49

1008	Floyd County	R Gallagher	0.2	11.0	49
1012	Warrick County	F B Culley Generating Station	2.2	10.2	49
1040	Wayne County	Whitewater Valley	0.0	12.3	49
1047	Allamakee County	Lansing	1.1	113.7	49
1073	Linn County	Prairie Creek	0.6	89.6	49
1082	Pottawattamie County	Walter Scott Jr. Energy Center	8.1	149.8	76
1091	Woodbury County	George Neal North	2.3	278.4	76
1104	Des Moines County	Burlington (IA)	1.2	7.8	49
1131	Black Hawk County	Streeter Station	0.0	168.1	49
1167	Muscatine County	Muscatine	1.1	15.3	49
1241	Linn County	La Cygne	4.2	9.8	76
1250	Douglas County	Lawrence Energy Center	2.7	12.2	76
1252	Shawnee County	Tecumseh Energy Center	0.4	26.0	76
1355	Mercer County	E W Brown	1.6	6.1	49
1356	Carroll County	Ghent	10.9	3.9	49
1364	Jefferson County	Mill Creek	8.5	12.4	49
1374	Daviess County	Elmer Smith	1.9	13.6	49
1378	Muhlenberg County	Paradise	2.8	6.5	49
1379	McCracken County	Shawnee	7.1	8.1	49
1382	Henderson County	HMP&L Station 2	1.3	12.6	49
1384	Pulaski County	John S. Cooper	0.5	9.8	49
1393	Calcasieu Parish	R S Nelson	3.0	1.9	14
1552	Baltimore County	C P Crane	0.3	96.1	40
1554	Anne Arundel County	Herbert A Wagner	0.2	92.6	40
1571	Prince George's County	Chalk Point	0.5	77.3	40
1572	Montgomery County	Dickerson	0.2	77.2	49
1573	Charles County	Morgantown	2.4	95.8	40
1619	Bristol County	Brayton Point	1.1	302.7	49
1702	Bay County	Dan E Karn	2.8	6.5	49
1710	Ottawa County	J H Campbell	7.7	9.7	49

1733	Monroe County	Monroe	15.4	4.5	49
1740	Wayne County	River Rouge	1.0	13.3	49
1743	St. Clair County	St. Clair	3.7	8.1	49
1745	Wayne County	Trenton Channel	2.0	10.3	49
1769	Marquette County	Presque Isle	1.8	200.9	49
1825	Ottawa County	J B Sims	0.3	9.5	49
1831	Ingham County	Eckert Station	0.5	12.9	49
1832	Eaton County	Erickson	1.2	12.0	49
1843	Marquette County	Shiras	0.3	196.7	49
1893	Itasca County	Boswell Energy Center	7.7	208.7	64
1915	Washington County	Allen S King	2.9	337.0	64
1943	Otter Tail County	Hoot Lake	0.3	93.0	64
2076	Jasper County	Asbury	1.1	36.0	76
2079	Jackson County	Hawthorn	2.8	5.5	76
2080	Henry County	Montrose	0.4	51.1	76
2094	Jackson County	Sibley	1.5	29.7	76
2103	Franklin County	Labadie	15.1	53.5	49
2104	St. Louis County	Meramec	1.2	14.5	49
2107	St. Charles County	Sioux	5.1	7.8	49
2167	New Madrid County	New Madrid Power Plant	6.4	63.3	49
2168	Randolph County	Thomas Hill Energy Center	8.0	113.1	49
2240	Dodge County	Lon D Wright Power Plant	0.4	181.0	76
2277	Lancaster County	Sheldon	0.8	90.6	35
2291	Douglas County	North Omaha Station	2.0	166.0	76
2324	Clark County	Reid Gardner	0.3	64.8	33
2364	Merrimack County	Merrimack	0.3	297.8	49
2367	Rockingham County	Schiller	0.1	349.1	49
2378	Cape May County	B L England	0.0	113.5	40
2403	Hudson County	Hudson Generating Station	0.0	105.2	49
2442	San Juan County	Four Corners Steam Elec Station	6.0	5.0	33

2451	San Juan County	San Juan	12.2	9.3	33
2527	Yates County	Greenidge Generation LLC	0.1	11.4	49
2535	Tompkins County	Cayuga Operating Company, LLC	0.2	9.8	49
2706	Buncombe County	Asheville	1.3	118.7	78
2712	Person County	Roxboro	5.8	164.4	49
2718	Gaston County	G G Allen	1.0	149.3	20
2721	Cleveland County	Cliffside	5.0	179.0	78
2727	Catawba County	Marshall	8.5	188.4	49
2790	Morton County	R M Heskett	0.5	6.4	64
2817	Mercer County	Leland Olds	4.2	6.7	64
2823	Oliver County	Milton R Young	5.9	4.2	64
2824	Mercer County	Stanton	0.2	7.5	64
2828	Jefferson County	Cardinal	9.9	14.3	49
2832	Hamilton County	Miami Fort Power Station	6.1	14.7	49
2836	Lorain County	Avon Lake Power Plant	0.5	7.2	49
2840	Coshocton County	Conesville	3.9	14.3	49
2850	Adams County	J M Stuart	6.8	8.8	49
2866	Jefferson County	W H Sammis	6.4	8.4	49
2876	Gallia County	Kyger Creek	5.9	11.0	49
2952	Muskogee County	Muskogee	7.0	8.2	34
2963	Rogers County	Northeastern	2.3	2.9	34
3118	Indiana County	Conemaugh	10.6	14.4	49
3122	Indiana County	Homer City	5.1	2.2	49
3130	Indiana County	Seward	2.5	11.0	49
3136	Armstrong County	Keystone	11.1	15.2	49
3140	York County	Brunner Island, LLC	2.4	77.1	49
3149	Montour County	Montour, LLC	2.6	10.8	49
3297	Richland County	Wateree	3.1	15.1	20
3298	Berkeley County	Williams	2.3	5.2	30
3393	Shelby County	Allen	3.6	24.8	14

3396	Anderson County	Bull Run	2.7	32.4	49
3399	Stewart County	Cumberland	9.5	25.7	49
3403	Sumner County	Gallatin	5.5	5.8	49
3406	Humphreys County	Johnsonville	2.2	30.1	49
3407	Roane County	Kingston	5.2	25.5	49
3470	Fort Bend County	W A Parish	14.4	2.6	14
3497	Freestone County	Big Brown	8.3	1.9	14
3797	Chesterfield County	Chesterfield Power Station	3.3	145.2	40
3809	York County	Yorktown Power Station	0.1	87.6	30
3845	Lewis County	Centralia	6.0	1.2	57
3935	Putnam County	John E Amos	13.4	7.5	49
3943	Monongalia County	Fort Martin Power Station	5.6	12.5	49
3944	Harrison County	Harrison Power Station	12.3	10.9	49
3948	Marshall County	Mitchell (WV)	7.5	13.6	49
3954	Grant County	Mount Storm Power Station	6.8	6.3	49
4041	Milwaukee County	South Oak Creek	5.2	36.9	49
4050	Sheboygan County	Edgewater (4050)	4.0	88.9	49
4072	Brown County	Pulliam	0.5	118.1	49
4078	Marathon County	Weston	3.8	245.8	49
4143	Vernon County	Genoa	1.5	136.7	49
4158	Converse County	Dave Johnston	5.0	10.0	64
4162	Lincoln County	Naughton	5.0	2.0	43
4271	Buffalo County	J P Madgett	1.8	233.9	49
4941	Coconino County	Navajo Generating Station	14.4	10.0	33
6002	Jefferson County	James H Miller Jr	20.6	36.9	14
6004	Pleasants County	Pleasants Power Station	7.2	7.3	49
6009	Jefferson County	White Bluff	8.3	6.1	14
6016	Fulton County	Duck Creek	1.9	2.6	49
6017	Jasper County	Newton	3.2	8.3	49
6018	Boone County	East Bend	4.4	14.1	49

6019	Clermont County	W H Zimmer Generating Station	7.2	7.7	49
6021	Moffat County	Craig	8.0	3.9	43
6030	McLean County	Coal Creek	8.1	10.2	64
6031	Adams County	Killen Station	4.2	13.7	49
6034	St. Clair County	Belle River	7.0	8.3	49
6041	Mason County	H L Spurlock	6.3	11.5	49
6052	Heard County	Wansley (6052)	3.8	155.8	14
6055	Pointe Coupee Parish	Big Cajun 2	5.6	2.5	14
6061	Lamar County	R D Morrow Senior Generating Plant	0.1	0.6	14
6064	Wyandotte County	Nearman Creek	1.1	13.9	76
6065	Platte County	Iatan	9.9	43.1	76
6068	Pottawatomie County	Jeffrey Energy Center	11.4	21.5	76
6071	Trimble County	Trimble County	7.0	4.9	49
6073	Jackson County	Daniel Electric Generating Plant	2.7	2.5	14
6076	Rosebud County	Colstrip	13.8	12.5	64
6077	Lincoln County	Gerald Gentleman Station	7.5	36.4	41
6082	Niagara County	Somerset Operating Company (Kintigh)	0.3	5.1	49
6085	Jasper County	R M Schahfer Generating Station	5.8	14.6	49
6089	Richland County	Lewis & Clark	0.3	7.8	64
6090	Sherburne County	Sherburne County	12.5	277.0	64
6094	Beaver County	Bruce Mansfield	7.5	11.8	49
6095	Noble County	Sooner	3.7	6.3	34
6096	Otoe County	Nebraska City Station	8.5	88.8	76
6098	Grant County	Big Stone	2.3	119.8	64
6101	Campbell County	Wyodak	3.1	7.5	64
6106	Morrow County	Boardman	1.7	85.9	57
6113	Gibson County	Gibson	16.3	10.8	49

6124	Effingham County	McIntosh (6124)	0.0	6.1	30
6136	Grimes County	Gibbons Creek Steam Electric Station	1.7	2.6	14
6137	Posey County	A B Brown Generating Station	2.1	12.7	49
6138	Benton County	Flint Creek Power Plant	2.8	62.4	76
6139	Titus County	Welsh Power Plant	5.8	3.4	14
6146	Rusk County	Martin Lake	13.8	3.6	14
6147	Titus County	Monticello	10.0	2.2	14
6155	Jefferson County	Rush Island	8.2	16.3	49
6165	Emery County	Hunter	8.2	12.8	33
6166	Spencer County	Rockport	10.4	8.7	49
6170	Kenosha County	Pleasant Prairie	6.0	7.1	49
6177	Apache County	Coronado Generating Station	4.6	57.3	33
6178	Goliad County	Coleto Creek	3.9	2.5	14
6179	Fayette County	Sam Seymour	11.8	1.3	14
6180	Robertson County	Oak Grove	13.3	1.9	14
6181	Bexar County	J T Deely	4.2	4.7	14
6183	Atascosa County	San Miguel	3.5	4.5	14
6190	Rapides Parish	Brame Energy Center	2.0	2.1	14
6193	Potter County	Harrington Station	4.7	2.5	13
6194	Lamb County	Tolk Station	4.9	5.6	13
6195	Greene County	John Twitty Energy Center	2.0	112.8	76
6204	Platte County	Laramie River	11.2	12.5	41
6213	Sullivan County	Merom	4.8	7.2	49
6248	Morgan County	Pawnee	4.0	8.0	41
6249	Georgetown County	Winyah	1.3	17.2	30
6250	Person County	Mayo	1.5	171.7	49
6254	Wapello County	Ottumwa	4.4	117.2	49
6257	Monroe County	Scherer	15.2	52.4	14
6264	Mason County	Mountaineer (1301)	6.7	10.2	49
6469	Mercer County	Antelope Valley	6.7	9.5	64

6481	Millard County	Intermountain	7.6	73.5	43
6639	Webster County	R D Green	2.6	12.7	49
6641	Independence County	Independence	7.2	90.5	14
6648	Milam County	Sandow	4.4	15.8	14
6664	Louisa County	Louisa	3.5	7.8	49
6705	Warrick County	Alcoa Allowance Management Inc	3.2	10.5	49
6761	Larimer County	Rawhide Energy Station	2.1	5.1	41
6768	Scott County	Sikeston	1.7	31.0	49
6772	Choctaw County	Hugo	2.8	51.0	14
6823	Ohio County	D B Wilson	3.0	5.9	49
7030	Robertson County	Twin Oaks	2.8	2.9	14
7097	Bexar County	J K Spruce	5.9	4.7	14
7210	Orangeburg County	Cope Station	1.9	21.3	30
7213	Halifax County	Clover Power Station	3.4	162.2	49
7343	Woodbury County	George Neal South	2.3	275.7	76
7504	Campbell County	Neil Simpson II	0.7	7.4	64
7790	Uintah County	Bonanza	3.7	3.3	43
7902	Harrison County	H W Pirkey Power Plant	4.5	4.3	14
8023	Columbia County	Columbia	7.0	113.6	49
8042	Stokes County	Belews Creek	8.4	137.1	49
8066	Sweetwater County	Jim Bridger	11.8	4.9	43
8069	Emery County	Huntington	5.1	4.2	43
8102	Gallia County	Gen J M Gavin	14.0	8.7	49
8219	El Paso County	Ray D Nixon	1.4	4.7	41
8222	Mercer County	Coyote	2.9	7.7	64
8223	Apache County	Springerville Generating Station	8.2	84.1	33
8224	Humboldt County	North Valmy	0.7	300.2	45
8226	Allegheny County	Cheswick	1.4	10.9	49
10113	Schuylkill County	Gilberton Power Company	0.9	29.9	49
10343	Northumberland County	Mt. Carmel Cogeneration	0.5	31.3	49
10384	Edgecombe County	Edgecombe Genco, LLC	0.1	119.2	30

10603	Cambria County	Ebensburg Power Company	0.4	9.6	49
10641	Cambria County	Cambria Cogen	0.9	8.3	49
50611	Schuylkill County	WPS Westwood Generation, LLC	0.0	50.7	49
50879	Schuylkill County	Wheelabrator - Frackville	0.6	31.1	49
50888	Northampton County	Northampton Generating Plant	0.3	44.0	49
50974	Venango County	Scrubgrass Generating Plant	0.7	8.6	49
52007	Mecklenburg County	Mecklenburg Power Station	0.2	190.5	30
52071	Milam County	Sandow Station	4.5	16.0	14
54081	Richmond city	Spruance Genco, LLC	0.8	144.6	40
54634	Schuylkill County	St. Nicholas Cogeneration Project	1.1	26.8	49
55076	Choctaw County	Red Hills Generation Facility	2.7	8.1	2
55479	Campbell County	Wygen I	0.9	7.4	64
55749	Big Horn County	Hardin Generating Station	0.2	6.9	64
55856	Washington County	Prairie State Generating Station	10.9	8.4	49
56068	Milwaukee County	Elm Road Generating Station	7.4	36.7	49
56224	Eureka County	TS Power Plant	1.0	339.6	45
56319	Campbell County	Wygen II	0.9	7.8	64
56456	Mississippi County	Plum Point Energy Station	3.6	88.5	14
56564	Hempstead County	John W. Turk Jr. Power Plant	4.0	28.0	14
56596	Campbell County	Wygen III	0.9	7.9	64
56609	Campbell County	Dry Fork Station	3.3	8.4	64
56611	McLennan County	Sandy Creek Energy Station	6.1	17.4	14
56671	Monongalia County	Longview Power	4.2	10.8	49
56786	Stutsman County	Spiritwood Station	0.5	7.8	64
56808	Wise County	Virginia City Hybrid Energy Center	3.2	40.8	49