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Carbon Capture and Sequestration (CCS) in the United States

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Summary

Carbon capture and sequestration (or storage)—known as CCS—is a process that involves capturing man-made carbon dioxide (CO_2) at its source and storing it permanently underground. (CCS is sometimes referred to as CCUS—carbon capture, utilization, and storage.) CCS could reduce the amount of CO_2—an important greenhouse gas—emitted to the atmosphere from the burning of fossil fuels at power plants and other large industrial facilities.

Globally, two fossil-fueled power plants currently generate electricity and capture CO_2 in large quantities: the Boundary Dam plant in Canada and the Petra Nova plant in Texas. Both plants retrofitted post-combustion capture technology to units of existing plants. A third fossil-fueled electricity-generating operation, the Kemper County Energy Facility in Mississippi, was scheduled to begin CCS operations by now, but cost overruns and delays in construction and operations led to the suspension of the plant's CCS component on June 28, 2017.

Each of the power plants using CCS systems may be referred to as a *demonstration project*, or a nearly first-of-its-kind venture using technologies developed at a pilot scale ramped up to commercial scale. Such projects move through many phases, from the initial research and development (R&D) phase through the final commercial deployment phase. It is not unusual for projects in the demonstration phase of this process to experience higher-than-anticipated costs, delays, and other challenges. Several other U.S. Department of Energy (DOE)-supported demonstration projects, such as FutureGen, the AEP Mountaineer project, and the Hydrogen Energy California Project, among others, faced challenges that led to their cancellation or suspension. Given the mixed success of large CCS projects in the United States, the economic viability of, and the commercial interest in, such projects remains uncertain.

The U.S. Department of Energy has long supported R&D on CCS within its Fossil Energy Research and Development (FER&D) portfolio. The Trump Administration proposed to cut FER&D funding substantially in its FY2018 budget request. The Trump Administration's proposal differs from the policy trends of the previous two Administrations, which supported R&D on CCS and emphasized the development of large-scale demonstration projects to evaluate how CCS might be deployed commercially. Some in Congress have signaled continued support for DOE's R&D efforts with respect to CCS. The House Energy and Water Development appropriations draft legislation would support CCS R&D at a level comparable to that in FY2017, for example. In addition, some Members of Congress have continued to introduce legislation in the 115th Congress intended to advance CCS. These bills include H.R. 2010, H.R. 2011, H.R. 2296, S. 843, S. 1068, and S. 1535.

The Obama Administration commissioned a CCS task force, which concluded in 2010 that the largest barrier to long-term demonstration and deployment of CCS technology is the absence of a federal policy to reduce greenhouse gas emissions. The task force further concluded that widespread deployment of CCS would occur only if the technology is commercially available at economically competitive prices. None of those factors appear to be in place currently, which may indicate that demonstration and deployment of industrial-scale CCS will be delayed compared to earlier projections, pending future policy, technological, and economic developments.

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Introduction

Carbon capture and sequestration (or storage)—known as CCS—is a process that involves capturing man-made carbon dioxide (CO_2) at its source and storing it to avoid its release to the atmosphere. (CCS is sometimes referred to as CCUS—carbon capture, utilization, and storage.) CCS could reduce the amount of CO_2 emitted to the atmosphere from the burning of fossil fuels at power plants and other large industrial facilities.[1] An integrated CCS system would include three main steps: (1) capturing and separating CO_2 from other gases; (2) purifying, compressing, and transporting the captured CO_2 to the sequestration site; and (3) injecting the CO_2 in underground geological reservoirs (the process is explained more fully below in "CCS Primer").

The U.S. Department of Energy (DOE) has long supported research and development (R&D) on CCS within its Fossil Energy Research and Development portfolio (FER&D); however, the Trump Administration proposed to cut FER&D funding substantially in its FY2018 budget request. The Trump Administration's proposal differs from the policy trends of the previous two Administrations, which supported R&D on CCS and emphasized the development of large-scale demonstration projects—nearly first-of-their-kind ventures using technologies developed at a pilot or smaller scale that have been ramped up to commercial scale—to evaluate how CCS might be deployed commercially. The Trump Administration's proposal to curtail funding for CCS, coupled with the successful launch of one large CCS plant in January 2017 (the Petra Nova plant in Texas) and the suspension of another in June 2017 (the Kemper County Energy Facility in Mississippi), has contributed to uncertainty about the future of CCS. This report provides a summary and analysis of the current state of CCS in the United States.

Coal-Fired Power Plants with CCS

Globally, two fossil-fueled power plants currently generate electricity and capture CO_2 in large quantities: the Boundary Dam plant in Canada and the Petra Nova plant. Both plants retrofitted post-combustion capture technology to units of existing plants. (The different types of carbon capture technologies are discussed in "CCS Primer.") A third fossil-fueled electricity-generating operation, the Kemper County Energy Facility, was scheduled to begin CCS operations by now, but cost overruns and delays in construction and operations led to the suspension of the plant's CCS component on June 28, 2017.[2] Unlike the two retrofitted plants, Kemper was built from scratch with a precombustion integrated gasification combined cycle (IGCC) system. These three plants are discussed below.[3]

Petra Nova: The First (and Only) Large U.S. Power Plant with CCS

The Petra Nova–W.A. Parish Generating Station is the first industrial-scale coal-fired electricity-generating plant with CCS to operate in the United States. On January 10, 2017, the plant began capturing approximately 5,000 metric tons of CO_2 per day from its 240-megawatt-equivalent

[1] Carbon capture and sequestration (CCS) also could be used to capture carbon dioxide (CO_2) emissions from power plants that use bioenergy sources instead of fossil fuels.

[2] Mary Perez, "Mississippi Power Suspends Coal Portion of Kemper Plant," *Sun Herald*, June 28, 2017, at http://www.sunherald.com/news/business/article158675414.html.

[3] Some other types of plants use CO_2 capture technology as part of their industrial process, such as the Great Plains Synfuels Plant (discussed in "Precombustion Capture") or in some natural gas processing plants, which need to remove the CO_2 as an impurity from the natural gas prior to shipping.

slipstream using post-combustion capture technology.[4] The capture technology is approximately 90% efficient (i.e., it captures about 90% of the CO_2 in the exhaust gas after the coal is burned to generate electricity) and is projected to capture between 1.4 million and 1.6 million tons of CO_2 each year.[5] The captured CO_2 is transported via an 82-mile pipeline to the West Ranch oil field, where it is injected for enhanced oil recovery (EOR).[6] NRG Energy, Inc., and JX Nippon Oil & Gas Exploration Corporation, the joint owners of the Petra Nova project, together with Hilcorp Energy Company (which handles the injection and EOR), expect to increase West Ranch oil production from 300 barrels per day before EOR to 15,000 barrels per day after EOR.[7]

DOE provided Petra Nova with more than $160 million from its Clean Coal Power Initiative (CCPI) Round 3 funding, using funds appropriated under the American Recovery and Reinvestment Act of 2009 (Recovery Act; P.L. 111-5) together with other DOE FER&D funding for a total of more than $190 million of federal funds for the $1 billion retrofit project.[8] Petra Nova is the only CCPI Round 3 project that expended its Recovery Act funding and is currently operating.[9] The three other CCPI Round 3 demonstration projects funded using Recovery Act appropriations, (as well as the FutureGen project—slated to receive nearly $1 billion in Recovery Act appropriations) all have been canceled, have been suspended, or remain in development.[10]

The Petra Nova plant is projected to capture more CO_2 per year than the other currently operating power plant with CCS, Canada's Boundary Dam (which captures about 1 million tons per year; see "Boundary Dam: World's First Addition of CCS to a Large Power Plant," below). Petra Nova also generates more electricity than Boundary Dam, about 240 megawatts compared to Boundary Dam's 115 megawatts. Both projects retrofitted one unit of much larger multi-unit electricity-generating plants. The Petra Nova project retrofitted Unit 8 of the W.A. Parish power plant, which in total consists of four coal-fired units and six gas-fired units, comprising more than 3.7 gigawatts of gross capacity, making it one of the largest U.S. power plants.

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[4] In this report, the amount of CO_2 is stated in metric tons, or 1,000 kilograms, which is approximately 2,200 pounds. Hereinafter, the unit *tons* means metric tons. Slipstream refers to the exhaust gases emitted from the power plant. NRG News Release, "NRG Energy, JX Nippon Complete World's Largest Post-Combustion Carbon Capture Facility On-Budget and On-Schedule," January 10, 2017, at http://investors.nrg.com/phoenix.zhtml?c=121544&p=irol-newsArticle&ID=2236424.

[5] Global CCS Institute, Projects Database, "Petra Nova Carbon Capture," at http://www.globalccsinstitute.com/projects/petra-nova-carbon-capture-project; and Christa Marshal and Edward Klump, "Carbon Capture Takes a 'Huge Step' with First U.S. Plant," *Energy Wire*, January 10, 2017, at https://www.eenews.net/energywire/stories/1060048090/search?keyword=petra+nova.

[6] Injecting CO_2 into an oil reservoir often increases or enhances production by lowering the viscosity of the oil, which allows it to be pumped more easily from the formation. The process is sometimes referred to as *tertiary recovery* or *enhanced oil recovery* (EOR).

[7] NRG News Release, "NRG Energy, JX Nippon Complete World's Largest Post-Combustion Carbon Capture Facility On-Budget and On-Schedule," January 10, 2017, at http://investors.nrg.com/phoenix.zhtml?c=121544&p=irol-newsArticle&ID=2236424.

[8] U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL), "Recovery Act: Petra Nova Parish Holdings: W.A. Parish Post-Combustion CO2 Capture and Sequestration Project," at https://www.netl.doe.gov/research/coal/project-information/fe0003311.

[9] For an analysis of carbon capture and sequestration (CCS) projects funded by the American Recovery and Reinvestment Act (P.L. 111-5), see CRS Report R44387, *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*, by Peter Folger.

[10] FutureGen is discussed in more detail in CRS Report R44387, *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*, by Peter Folger.

In 2015, the entire W.A. Parish complex emitted nearly 15 million tons of CO_2 from all of its generating units.[11] The Petra Nova project reduces CO_2 emissions overall from the entire complex by about 11%. By comparison, in 2015, total U.S. CO_2 emissions from the electricity-generating sector were about 1.9 billion tons.[12] The Petra Nova project would reduce that total by a small percentage (about 0.08%). However, according to DOE, a purpose of Petra Nova was to demonstrate that post-combustion capture and reuse can be done economically for existing plants when there is an opportunity to recover oil from nearby oilfields. DOE also has stated that the success of Petra Nova has the potential to enhance the long-term viability and sustainability of coal-fueled power plants across the United States and throughout the world.[13]

Kemper: Next in Line for the United States, Now in Doubt?

On June 28, 2017, Southern Company and its subsidiary Mississippi Power announced they were suspending the start-up of the coal gasification component of their Kemper County Energy Facility,[14] a precombustion technology that would combine IGCC with CCS to capture CO_2 and transport the gas for EOR at a nearby oilfield. The suspension of operations comes after several years of cost overruns and delays; total costs escalated to more than $7 billion from approximately $2.67 billion, and the original target start-up date was 2014.[15] The plant will continue to generate electricity from burning natural gas, according to Southern Company, pending a decision from the Mississippi Public Service Commission on future operations.[16]

DOE supported the Kemper County plant with a $270 million award for the development and deployment of a gasification technology called Transport Integrated Gasification (TRIG™), under a cooperative agreement as part of the CCPI Round 2 program. The $270 million award represented approximately 10% of what DOE had reported as the overall cost to build the plant, approximately $2 billion.[17] At the time of the award, the plant was expected to have an estimated peak net output capability of 582 megawatts and was designed to capture 65% of the total CO_2 emissions released.[18] According to DOE, that would have made the CO_2 emissions from the Kemper project comparable to emissions from a natural gas-fired combined cycle power plant. The estimated 3 million tons of CO_2 captured each year from the plant were to be transported via pipeline for use in EOR operations at nearby depleted oil fields in Mississippi.

The Mississippi Public Service Commission approved the project, subject to a cap on total costs of $2.9 billion.[19] Construction began in 2010.[20] Some observers attribute the cost escalation and

[11] U.S. Environmental Protection Agency, "2015 Greenhouse Gas Emissions from Large Facilities, W.A. Parish," at https://ghgdata.epa.gov/ghgp/service/facilityDetail/2015?id=1006868&ds=E&et=FC_CL&popup=true.

[12] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*, EPA 430-P-17-001, April 15, 2017, Table ES-2, at https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf.

[13] DOE, NETL, "Recovery Act: Petra Nova Parish Holdings: W.A. Parish Post-Combustion CO2 Capture and Sequestration Project," at https://www.netl.doe.gov/research/coal/project-information/fe0003311.

[14] Southern Company, "Southern Company and Mississippi Power Announce Suspension of Gasification Operations," news release, June 28, 2017, at http://www.southerncompany.com/newsroom/news-releases.html.

[15] Mary Perez, "Mississippi Power Suspends Coal Portion of Kemper Plant," *Sun Herald*, June 28, 2017.

[16] Southern Company, "Southern Company and Mississippi Power Announce Suspension of Gasification Operations." news release, June 28, 2017, at http://www.southerncompany.com/newsroom/news-releases.html.

[17] DOE, Office of Fossil Energy, "CCPI Round 2 Selections," at http://energy.gov/fe/ccpi-round-2-selections.

[18] DOE, NETL, CCS Demonstrations, CCPI Initiative, "Demonstration of a Coal-Based Transport Gasifier," at http://netl.doe.gov/research/proj?k=FC26-06NT42391.

[19] Excluding costs of the lignite mine, CO_2 pipeline, financing, and other costs.

project delays to a combination of increased piping, materials, and labor costs due to resizing and re-scoping of the original design of the CCS component.[21] In addition, Kemper's status as a first-of-its kind facility likely contributed to cost overruns and construction delays.

Suspension of the Kemper County plant increases uncertainty about the future of large CCS projects at coal-fired power plants in the United States and, by extension, into the future of coal. Kemper is not the first large, DOE-supported CCS demonstration project to hit roadblocks leading to delay and even cancellation.[22] The Trump Administration has signaled that it will not support large CCS demonstration projects in its FY2018 budget request, proposing to substantially reduce CCS funding and refocus its entire FER&D portfolio on "early-stage" research.[23] The House Appropriations Committee's FY2018 bill funding DOE disagrees with the Administration budget request and would fund CCS activities at roughly FY2017 levels. However, suspension of the Kemper County Energy Facility might affect budget negotiations if, as some CCS critics suggest, it signals a deeper problem with the viability of CCS at fossil-fuel-burning power plants generally.[24]

Boundary Dam: World's First Addition of CCS to a Large Power Plant

The Boundary Dam project was the first commercial-scale power plant with CCS in the world to begin operations. Boundary Dam, a Canadian venture operated by SaskPower,[25] cost approximately $1.3 billion according to one source.[26] Of that amount, $800 million was for building the CCS process and the remaining $500 million was for retrofitting the Boundary Dam Unit 3 coal-fired generating unit. The project also received $240 million from the Canadian federal government. Boundary Dam started operating in October 2014, after a 4-year construction and retrofit of the 150-megawatt generating unit. The final project was smaller than earlier plans to build a 300-megawatt CCS plant, but that original idea may have cost as much as $3.8 billion. The larger-scale project was discontinued because of the escalating costs.[27]

(...continued)

[20] Global CCS Institute, Projects Database, "Kemper County Energy Facility," at http://www.globalccsinstitute.com/projects/kemper-county-energy-facility.

[21] Ibid.

[22] Others include, for example, FutureGen, the AEP Mountaineer Project, the Hydrogen Energy California Project, and others. See CRS Report R44387, *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*, by Peter Folger, for additional information and analysis.

[23] For more information, see CRS In Focus IF10589, *DOE Fossil Energy Research & Development: Funding for CCS*, by Peter Folger.

[24] See, for example, Gordon Hughes, *The Bottomless Pit: the Economics of Carbon Capture and Storage*, Global Warming Policy Foundation (GWPF), GWPF Report 24, 2017, at https://www.thegwpf.org/content/uploads/2017/06/CCS-Report.pdf; Sandy Buchanan, "Mississippi's Kemper County Experiment Proves Clean Coal Is a Myth," *The Hill*, June 24, 2017, at http://thehill.com/blogs/pundits-blog/energy-environment/339191-mississippis-kemper-county-experiment-proves-clean-coal; Nicolas D. Loris, *The Many Problems of the EPA's Clean Power Plan and Climate Regulations: A Primer*, Heritage Foundation, Backgrounder, July 7, 2015, pp. 7-8, at http://thf_media.s3.amazonaws.com/2015/pdf/BG3025.pdf.

[25] SaskPower is the principal electric utility in Saskatchewan, Canada.

[26] MIT Carbon Capture & Sequestration Technologies, CCS Project Database, "Boundary Dam Fact Sheet: Carbon Capture and Storage Project," at http://sequestration.mit.edu/tools/projects/boundary_dam.html.

[27] MIT Carbon Capture & Sequestration Technologies, CCS Project Database, "Boundary Dam Fact Sheet: Carbon Capture and Storage Project."

Similar to the Petra Nova project discussed above, Boundary Dam captures, transports, and sells most of its CO_2 for enhanced oil recovery, shipping 90% of the captured CO_2 via a 41-mile pipeline to the Weyburn Field. CO_2 not sold for EOR is injected and stored about 2.1 miles underground in a deep saline aquifer at a nearby experimental injection site. By March 2017, the plant had captured almost 1.5 million metric tons of CO_2 since full-time operations began in October 2014.[28] The 115-megawatt (net) plant plans to capture at least 1 million tons of CO_2 per year.[29]

Some observers contend that Boundary Dam has yet to meet its expectations for capture efficiency, cost, and availability.[30] Some technical and operational issues that reduced the amount of CO_2 captured after start-up were reported in 2016, and these issues led to shortfalls in delivery of CO_2 to the utility using the gas for EOR.[31] Some reports also indicated that the CCS system consumed approximately 45 megawatts to capture and compress the CO_2,[32] out of a total capacity of 150 megawatts (approximately 30% reduction, also known as the *energy penalty* or *parasitic load*).

Lessons Learned

Each of the projects discussed above is a demonstration project. Projects move through many phases, from the initial R&D phase through the demonstration phase to the final commercial deployment phase. It is not unusual for projects in the demonstration phase of this process to experience higher-than-anticipated costs, delays, and other challenges, although deploying technologies such as CCS at a commercial scale should provide cost estimates closer to operational conditions than projects at the research or pilot scale. **Figure 1** shows a typical cost trend for new technology as it develops from R&D to commercial deployment. It could be argued that the high costs and project delays apparent for the Kemper and Boundary Dam projects reflect the fact that these projects' stage in the process corresponds to the peak of the cost curve in **Figure 1**.

[28] Global CCS Institute, Projects Database, "Boundary Dam Carbon Capture and Storage," at http://www.globalccsinstitute.com/projects/boundary-dam-carbon-capture-and-storage-project.

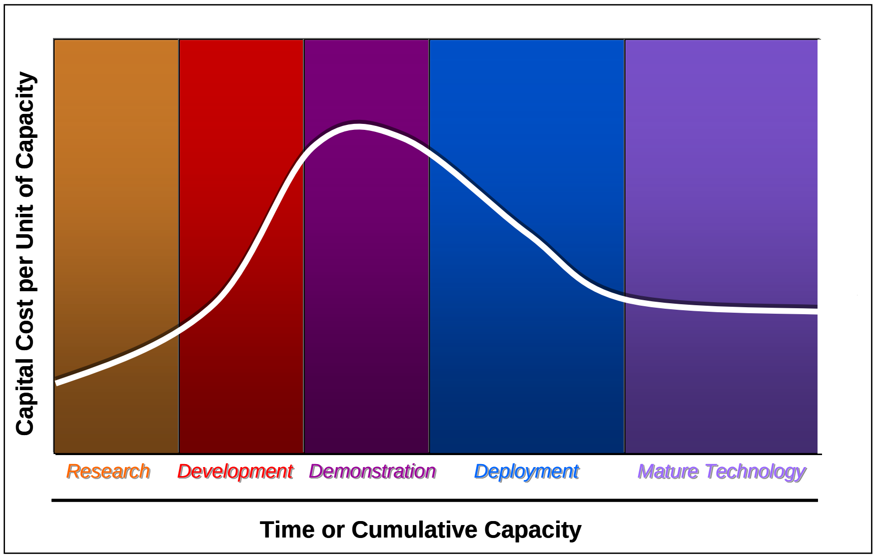
[29] Net power refers to the gross amount of power generated by the plant minus the electricity used to operate the plant. In this case, the electricity used to operate the plant includes the amount of electricity used for carbon capture.

[30] Gordon Hughes, *The Bottomless Pit: The Economics of Carbon Capture and Storage*, GWPF, GWPF Report 24, 2017, p. 55.

[31] Ian Austen, "Technology to Make Clean Energy from Coal Is Stumbling in Practice," *New York Times*, March 29, 2016, p. B1.

[32] Ibid.

Figure 1. Typical Trend in Cost for New Technology Development



Source: Adapted from S. Dalton, "CO_2 Capture at Coal Fired Power Plants—Status and Outlook," 9th International Conference on Greenhouse Gas Control Technologies, Washington, DC, November, 16-20, 2008.

In recent years, the DOE CCS program (discussed below) has emphasized commercial-scale demonstration projects to better estimate the future costs and technical challenges for CCS. Some CCS critics contend that the gap in time and cost between the "first of a kind" project, such as the three discussed above, and the "Nth of a kind" project—representing projects at the commercial deployment stage—could be decades away and require hundreds of billions of dollars in capital investment.[33] Such speculations, however, are highly uncertain, given the possible changes in U.S. and other countries' policies aimed at restricting carbon emissions, as well as technological development, the cost of competing fuels such as natural gas, and other factors. Nevertheless, with the recent suspension of the Kemper project, a near-term estimate of the economic viability of—or even interest in—new, commercial-scale electricity-generating plants with CCS in the United States remains uncertain.

CCS Legislation in the 115th Congress

The Senate and the House have seen bills introduced in the last several Congresses that would have tried to foster or shape CCS development in the United States. This trend has continued in the 115th Congress; several bills have been introduced that would address aspects of CCS. These bills are summarized briefly below.

S. 1535—The Furthering Carbon Capture, Utilization, Technology, Underground Storage, and Reduced Emissions Act

S. 1535 would amend Section 45(Q) of the Internal Revenue Code to increase the tax credit from $20 per ton to $50 per ton for capture and permanent storage of CO_2 and from $10 per ton to $35 per ton for capture and use of CO_2 for EOR. The tax credit amount would ramp up over a 12-year

[33] Gordon Hughes, *The Bottomless Pit: the Economics of Carbon Capture and Storage*, GWPF, GWPF Report 24, 2017, p. X.

period through 2025, increasing by an inflation factor after that. In addition to CO_2 captured from facilities such as power plants and oil refineries, the credit would be available for facilities that capture CO_2 directly from the atmosphere (direct air capture). The tax credit also would be available for *utilization* of CO_2, such as through bacteria or algae growth or the conversion of CO_2 into a solid material. Facilities and processes that use CO_2 to make materials or otherwise use CO_2 for any other purpose for which a commercial market exists (other than EOR) through utilization would be eligible for the tax credit.

S. 1068—The Clean Energy for America Act

S. 1068 would make available an investment tax credit for qualified CCS equipment that is installed at an electricity-producing facility and captures at least 50% of the CO_2 emissions at the facility that otherwise would have been emitted to the atmosphere. To qualify, the captured CO_2 would need to be disposed of in secure geological storage.[34]

H.R. 2011 and S. 843—The Carbon Capture Improvement Act of 2017

H.R. 2011 and S. 843 would make carbon capture facilities eligible for tax-exempt bonds by amending Section 142 of the Internal Revenue Code. The CCS facility components would be eligible for the tax-exempt bond if the facility captures and stores at least 65% of the CO_2 that otherwise would be emitted to the atmosphere. If the facility captures and stores less than 65% of the CO_2, the percentage of the cost of CCS components eligible for tax-exempt bonds could not be greater than the capture and storage percentage (i.e., if the facility captures and stores 50% of the CO_2, then 50% of the cost of the components would be eligible for the tax-exempt bond).

H.R. 2296—The Advancing CCUS Technology Act

H.R. 2296 would require the Secretary of Energy to conduct an annual evaluation of every CCS-related project that uses DOE funds for research, development, demonstration, or deployment of CCS technologies (including CO_2 utilization technologies).[35] The bill would require the Secretary to determine if the project—whether under contract, lease, cooperative agreement, or other similar transaction with a public agency, private organization, or person—has made significant progress in advancing a CCS technology. Based on the determination of whether progress has been made, the Secretary would make a recommendation to increase funding or would determine that the project has reached its full potential and recommend whether the project should continue. The Secretary would be required to report on the recommendations and make the report available to the public, the Senate Committee on Energy and Natural Resources, and the House Committee on Energy and Commerce's Subcommittee on Energy.

H.R. 2010—The CO_2 Regulatory Certainty Act

H.R. 2010 would amend Section 45Q(d) of the Internal Revenue Code to require that the Secretary of the Treasury, in consultation with the Secretaries of Energy and the Interior and the

[34] Geological storage refers to the permanent storage or sequestration of CO_2 in an underground formation. This is discussed further in the section "CO2 Sequestration."

[35] In this report, CCS and CCUS (carbon capture, utilization, and storage) are used interchangeably. Examples of utilization technologies would be the use of CO_2 to manufacture a product, such as cement, or its use to enhance oil recovery.

Administrator of the Environmental Protection Agency (EPA), establish regulations for the geological storage of CO_2. Those regulations would determine compliance for both CO_2 injected for EOR purposes and CO_2 injected for non-EOR purposes (i.e., permanent geological sequestration). For CO_2 injected for EOR purposes, the bill would consider the CO_2 disposed of (in secure geological storage) if it is stored in compliance with the rules promulgated by the EPA under subpart UU of 40 C.F.R. Part 98, under the Clean Air Act, and subpart C of 40 C.F.R. Part 146, under the Safe Drinking Water Act, to the extent the rules apply to Class II wells.[36]

As of July 2017, Congress has not acted on any of the bills introduced.

The DOE CCS Program

DOE has funded R&D of aspects of the three main steps leading to an integrated CCS system since 1997. Since FY2010, Congress has provided more than $4.3 billion in annual appropriations for CCS activities at DOE. The Recovery Act provided an additional $3.4 billion to that total.[37]

CCS-focused R&D has come to dominate the coal program area within DOE FER&D since 2010. The Trump Administration's FY2018 budget request, however, would cut the overall FER&D budget by more than half compared to FY2017. The budget request also would reduce CCS-related activities substantially and would refocus nearly the entire R&D portfolio toward "early-stage" research.[38] The Trump Administration's approach would be a reversal of Obama Administration and George W. Bush Administration DOE policies, which supported large carbon-capture demonstration projects and large injection and sequestration demonstration projects.

Table 1 shows the funding for DOE CCS programs under FER&D from FY2010 through FY2017 and includes the President's FY2018 budget request. Compared to the FY2017 total of $668 million for all FER&D, the Trump Administration's request of $280 million would be a reduction of approximately 58%. The CCS-focused activities, shown in **Table 1** under "Coal CCS and Power Systems," would receive $115 million under the Trump Administration's request, compared to $424 million for FY2017, a 73% reduction.

The June 29, 2017, draft Energy and Water Development and Related Agencies appropriations bill approved by the Energy and Water Subcommittee of the House Appropriations Committee would appropriate $634.6 million for FER&D for FY2018, about $33 million less than the FY2017 amount. The House bill is at odds with the Administration's request, as the bill likely would continue to fund the range of CCS-related activities within DOE and not just early-stage research.[39]

[36] Class II wells are used to inject fluids associated with oil and gas production, per the Underground Injection Control (UIC) program, authorized under the Safe Drinking Water Act. Class II wells include wells used for EOR.

[37] Authority to expend American Recovery and Reinvestment Act (Recovery Act; P.L. 111-5) funds expired in 2015. An analysis of Recovery Act funding for CCS activities at DOE is provided in CRS Report R44387, *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*, by Peter Folger.

[38] The FY2018 Trump Administration budget request indicates that early-stage research refers to fundamental research that has a significant degree of scientific or technical uncertainty, making it unlikely that industry will invest significant R&D on its own. See DOE, *FY2018 Congressional Budget Request*, p. 203, t https://energy.gov/sites/prod/files/2017/05/f34/FY2018BudgetVolume3_0.pdf.

[39] The amount of $634.6 million was unchanged in the July 18, 2017, House Rules Committee Print 115-30, at http://docs.house.gov/billsthisweek/20170724/BILLS%20-115HR3219HR3162HR2998HR3266-RCP115-30.pdf.

Table 1. Funding for DOE Fossil Energy Research, Development, and Demonstration Program Areas

(FY2010 through FY2017, including the Trump Administration's FY2018 budget request)

FER&D Coal Program Areas	Program/Activity	FY2010 ($1,000)	FY2011 ($1,000)	FY2012 ($1,000)	FY2013 ($1,000)	FY2014 ($1,000)	FY2015 ($1,000)	FY2016 ($1,000)	FY2017 ($1,000)	FY2018 Request ($1,000)
Coal CCS and Power Systems	**Carbon Capture**	—	58,703	66,986	63,725	92,000	88,000	101,000	101,000	16,000
	Carbon Storage	—	120,912	112,208	106,745	108,766	100,000	106,000	95,300	15,000
	Advanced Energy Systems	—	168,627	97,169	92,438	99,500	103,000	105,000	105,000	46,000
	Cross-Cutting Research	—	41,446	47,946	45,618	41,925	49,000	50,000	45,500	37,800
	Supercritical CO_2 Technology	—	—	—	—	—	10,000	15,000	24,000	0
	NETL Coal R&D	—	—	35,011	33,338	50,011	50,000	53,000	53,000	0
Subtotal Coal		**393,485**	**389,688**	**359,320**	**341,864**	**392,202**	**400,000**	**430,000**	**423,800**	**114,800**
Other FER&D	**Natural Gas Technologies**	17,364	0	14,575	13,865	20,600	25,121	43,000	43,000	5,500
	Unconventional Fossil	19,474	0	4,859	4,621	15,000	4,500	20,321	21,000	15,000
	Program Direction	158,000	164,725	119,929	114,201	120,000	119,000	114,202	60,000	58,478
	Plant and Capital	20,000	19,960	16,794	15,982	16,032	15,782	15,782	0	0
	Env. Restoration	10,000	9,980	7,897	7,515	5,897	5,897	7,995	0	0
	Special Recruitment	700	699	700	667	700	700	700	700	200
	NETL R&D	—	—	—	—	—	—	0	43,000	78,100
	NETL Inf. & Ops	—	—	—	—	—	—	0	40,500	63,100
	Coop R&D	4,868	—	—	—	—	—	—	—	—
	New Fossil Pilot	—	—	—	—	—	—	—	50,000	—
	Directed Projects	35,879	—	—	—	—	—	—	—	—

Subtotal Other FER&D	**266,285**	**195,364**	**164,754**	**156,851**	**178,229**	**171,000**	**202,000**	**258,200**	**220,378**
Rescissions/Use of Prior-Year Balances	—	(151,000)	(187,000)	—	—	—	—	(14,000)	(55,178)
Total FER&D	**659,770**	**434,052**	**337,074**	**498,715**	**570,431**	**571,000**	**632,000**	**668,000**	**280,000**
							FY2010-FY2017	**Grand Total**	**$4.4B**

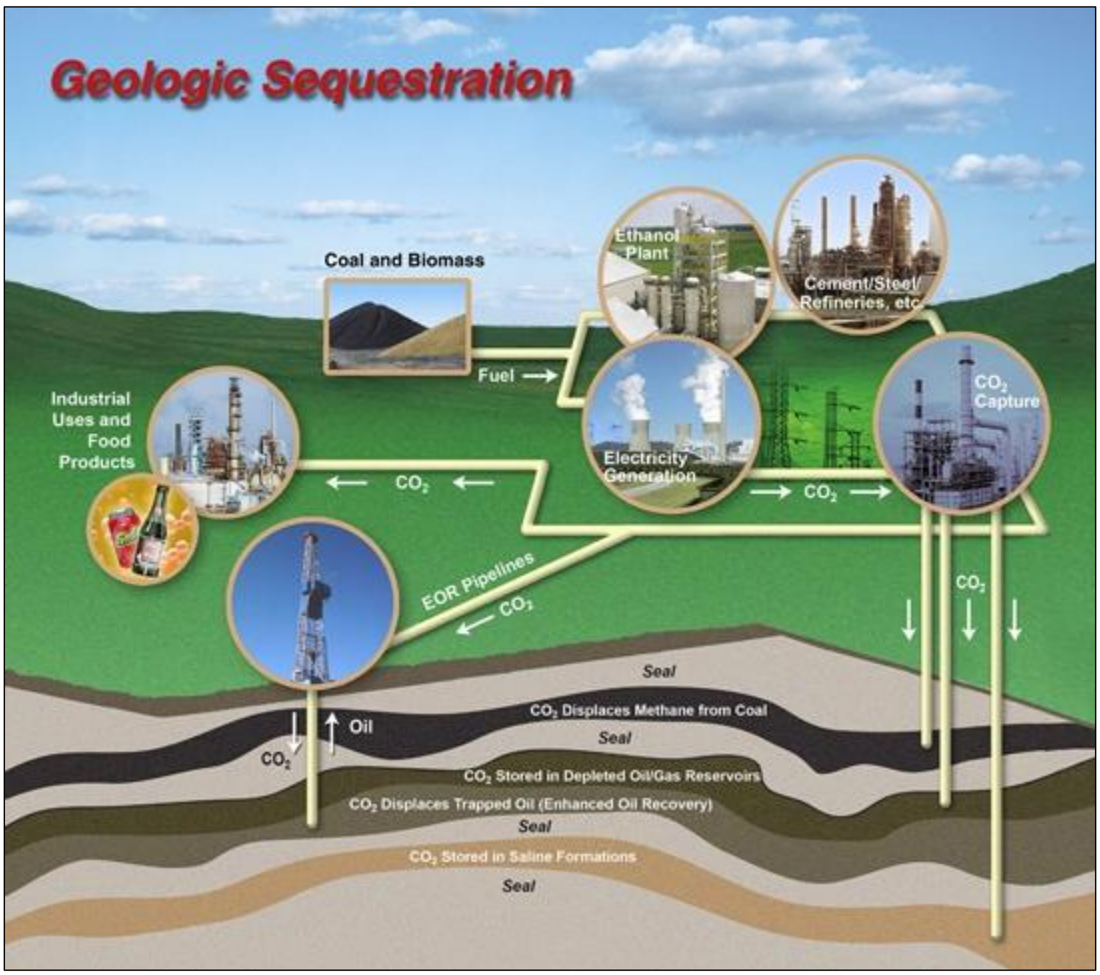
Sources: U.S. Department of Energy (DOE) annual budget justifications for FY2010 through FY2018; P.L. 115-31, Division D (Consolidated Appropriations Act, 2017).

Notes: CO_2 = Carbon dioxide; CCS = carbon capture and sequestration (or storage); FER&D = Fossil Energy Research and Development; NETL = National Energy Technology Laboratory; Inf. & Ops = Infrastructure and Operations; Coop = Cooperative; R&D = Research and development. Directed Projects refer to congressionally directed projects. Grand total for FY2010-FY2017 subject to rounding. Amounts provided by the American Recovery and Reinvestment Act of 2009 (P.L. 111-5) are not shown in the table or included in the grand total.

CCS Primer

An integrated CCS system would include three main steps: (1) capturing and separating CO_2 from other gases; (2) purifying, compressing, and transporting the captured CO_2 to the sequestration site; and (3) injecting the CO_2 in subsurface geological reservoirs. The most technologically challenging and costly step in the process is the capture step, which is capital-intensive to build and requires a considerable amount of energy to operate (the amount of energy a power plant uses to capture and compress CO_2 is that much less electricity the plant can deliver to its customers; this is sometimes referred to as the *energy penalty* or the *parasitic load*). **Figure 2** shows the CCS process schematically.

Figure 2. The CCS Process



Source: U.S. Department of Energy, Office of Fossil Energy, "Overview of Carbon Storage Research," at https://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/overview-carbon-storage-research.

The transport and injection/storage steps of the CCS process are not technologically challenging per se, as compared to the capture step. Carbon dioxide pipelines are in use for EOR in regions of the United States today, and large quantities of fluids have been injected into the deep subsurface for a variety of purposes for decades, such as disposal of wastewater from oil and gas operations or of municipal wastewater. However, the transport and capture steps still face challenges, including economic and regulatory issues, rights-of-way, and questions regarding the permanence of CO_2 sequestration in deep geological reservoirs, as well as ownership and liability for the stored CO_2, among others.

CO_2 Capture

The first step in CCS is to capture CO_2 at the source, compress it, and produce a concentrated stream for transport and storage. Currently, three main approaches are available to capture CO_2 from large-scale industrial facilities or power plants: (1) post-combustion capture, (2) precombustion capture, and (3) oxy-fuel combustion capture. For power plants, current commercial CO_2 capture systems could operate at 85%-95% capture efficiency.[40] In a worst-case scenario, the capture phase of the CCS process may increase the cost of electricity by 80% and reduce an electricity-generating plant's net capacity by 20%.[41] Further, as much as 70%-90% of the total cost for CCS is associated with the capture and compression phase of CCS.[42] Other estimates indicate that the energy penalty could be much lower, resulting in smaller impacts to subsequent electricity costs.[43] A detailed description and assessment of these capture technologies is provided in CRS Report R41325, *Carbon Capture: A Technology Assessment*, by Peter Folger.

Post-combustion Capture

The process of post-combustion capture involves extracting CO_2 from the flue gas following combustion of fossil fuels or biomass.[44] Several commercially available technologies, some involving absorption using chemical solvents, can in principle be used to capture large quantities of CO_2 from flue gases. Other than the Petra Nova plant, discussed above, no large U.S. commercial electricity-generating plants currently capture large volumes of CO_2. As the Petra Nova project indicates, the post-combustion capture process includes proven technologies that are commercially available today.

Precombustion Capture

The process of precombustion capture separates CO_2 from the fuel by combining the fuel with air and/or steam to produce hydrogen for combustion and a separate CO_2 stream that could be stored. The most common technologies today use steam reforming, in which steam is employed to extract hydrogen from natural gas.[45] One example of precombustion capture technology in operation today is at the Great Plains Synfuels Plant in Beulah, ND. The Great Plains plant produces synthetic natural gas from lignite coal through a gasification process, and the natural gas is shipped out of the facility for sale in the natural gas market. The process also produces a stream

[40] DOE, NETL, "Carbon Capture Program," fact sheet, June 2016, at https://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/Carbon-Capture-Factsheet-June-2016.pdf.

[41] Ibid.

[42] White House, *Report of Interagency Task Force on Carbon Capture and Storage*, August 2010, p. 9, at https://energy.gov/sites/prod/files/2013/04/f0/CCSTaskForceReport2010_0.pdf.

[43] See, for example, Howard J. Herzog, Edward S. Rubin, and Gary T. Rochelle, "Comment on 'Reassessing the Efficiency Penalty from Carbon Capture in Coal-Fired Power Plants,'" *Environmental Science and Technology*, vol. 50 (May 12, 2016), pp. 6112-6113.

[44] Flue gas refers to the emissions from combusting fossil fuels to generate steam at the plant. For post-combustion capture using air, the flue gas consists mostly of nitrogen, CO_2, and water vapor.

[45] See CRS Report R41325, *Carbon Capture: A Technology Assessment*, by Peter Folger.

of high-purity CO_2, which is piped northward into Canada for use in EOR at the Weyburn oil field.[46]

Oxy-Fuel Combustion Capture

The process of oxy-fuel combustion capture uses oxygen instead of air for combustion and produces a flue gas that is mostly CO_2 and water, which are easily separable, after which the CO_2 can be compressed, transported, and stored.

CO_2 Transport

Pipelines are the most common method for transporting CO_2 in the United States. Currently, approximately 4,500 miles of pipelines transport CO_2 in the United States, predominately to oil fields, where it is used for EOR.[47] Transporting CO_2 in pipelines is similar to transporting fuels such as natural gas and oil; it requires attention to design, monitoring for leaks, and protection against overpressure, especially in populated areas.[48] Typically, CO_2 would be compressed prior to transportation, making it dense like a liquid but fluid like a gas.[49]

Using ships may be feasible when CO_2 must be transported over large distances or overseas. Ships transport CO_2 today, but at a small scale because of limited demand. Liquefied natural gas, propane, and butane are routinely shipped by marine tankers on a large scale worldwide. Rail cars and trucks also can transport CO_2, but this mode probably would be uneconomical for large-scale CCS operations.

Costs for pipeline transport vary, depending on construction, operation and maintenance, and other factors, including right-of-way costs, regulatory fees, and more. The quantity and distance transported will mostly determine costs, which also will depend on whether the pipeline is onshore or offshore; the level of congestion along the route; and whether mountains, large rivers, or frozen ground are encountered. Shipping costs are unknown in any detail, because no large-scale CO_2 transport system via ship (in millions of tons of CO_2 per year, for example) is operating. Ship costs might be lower than pipeline transport for distances greater than 1,000 kilometers and for less than a few million tons of CO_2 transported per year.[50]

Even though regional CO_2 pipeline networks currently operate in the United States for EOR, developing a more expansive network for CCS could pose regulatory and economic challenges. Some observers note that development of a national CO_2 pipeline network that would address the broader issue of greenhouse gas reduction using CCS may require a concerted federal policy beyond the current joint federal-state regulatory policy.[51] One recommendation is for federal regulators to build on state experience for siting CO_2 pipelines, for example.

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[46] For a more detailed description of the Great Plains Synfuels plant, see DOE, NETL, "SNG From Coal: Process & Commercialization," at https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/great-plains.

[47] Mathew Wallace et al., *A Review of the CO2 Pipeline Infrastructure in the U.S.*, DOE, DOE/NETL-2014/1681, April 21, 2015, at https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20A%20Review%20of%20the%20CO2%20Pipeline%20Infrastructure%20in%20the%20U.S_0.pdf.

[48] Intergovernmental Panel on Climate Change (IPCC) Special Report, *Carbon Dioxide Capture and Storage*, 2005, p. 181, at https://www.ipcc.ch/report/srccs/. Hereinafter referred to as IPCC Special Report.

[49] Also, when injected underground to depths greater than 800 meters, the overlying pressure keeps CO_2 in a supercritical state, making it less likely to migrate out of the geological formation.

[50] IPCC Special Report, p. 31.

[51] Mathew Wallace et al., *A Review of the CO2 Pipeline Infrastructure in the U.S.*, DOE, April 21, 2015, p. 1.

CO_2 Sequestration

Three main types of geological formations are being considered for carbon sequestration: (1) depleted oil and gas reservoirs, (2) deep saline reservoirs, and (3) unmineable coal seams. In each case, CO_2 would be injected in a supercritical state—a relatively dense liquid—below ground into a porous rock formation that holds or previously held fluids. When CO_2 is injected at depths greater than 800 meters in a typical reservoir, the pressure keeps the injected CO_2 in a supercritical state (dense like a liquid, fluid like a gas), making the CO_2 less likely to migrate out of the geological formation. Injecting CO_2 into deep geological formations uses existing technologies that have been primarily developed and used by the oil and gas industry and that potentially could be adapted for long-term storage and monitoring of CO_2.

DOE's Regional Carbon Sequestration Partnership Initiative has been actively pursuing a three-phase approach to the sequestration step in the CCS process since 2003. It is currently in the development phase.[52] The development phase includes implementation of large-scale field testing of approximately 1 million tons of CO_2 per project to confirm the safety, permanence, and economics of industrial-scale CO_2 storage in seven different regions of the United States.[53] The development phase began in 2008 and is projected to last to 2018 or beyond.

The storage capacity for CO_2 in geological formations is potentially huge if all the sedimentary basins in the world are considered.[54] In the United States alone, DOE has estimated the total storage capacity to range between about 2.6 trillion and 22 trillion metric tons of CO_2 (see **Table 2**). The suitability of any particular site, however, depends on many factors, including proximity to CO_2 sources and other reservoir-specific qualities such as porosity, permeability, and potential for leakage. For CCS to succeed, it is assumed that each reservoir type would permanently store the vast majority of injected CO_2, keeping the gas isolated from the atmosphere in perpetuity. That assumption is untested, although part of the DOE CCS R&D program has been devoted to testing and modeling the behavior of large quantities of injected CO_2. Theoretically—and without consideration of costs, regulatory issues, public acceptance, infrastructure needs, liability, ownership, and other issues—the United States could store its total greenhouse gas emissions (at the current rate) for centuries.

Table 2. Estimates of the U.S. Storage Capacity for CO_2

(in billions of metric tons)

	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**

Source: U.S. Department of Energy, National Energy Technology Laboratory, *Carbon Storage Atlas*, 5th ed., August 20, 2015, at https://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/atlasv/ATLAS-V-2015.pdf.

[52] DOE, NETL, "Regional Carbon Sequestration Partnership (RCSP) Initiative," at https://www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-infrastructure/rcsp.

[53] Ibid.

[54] Sedimentary basins refer to natural large-scale depressions in the Earth's surface that are filled with sediments and fluids and are therefore potential reservoirs for CO_2 storage.

Notes: Data current as of November 2014. The estimates represent only the physical restraints on storage (i.e., the pore volume in suitable sedimentary rocks) and do not consider economic or regulatory constraints. The low, medium, and high estimates correspond to a calculated probability of exceedance of 90%, 50%, and 10%, respectively, meaning that there is a 90% probability that the estimated storage volume will exceed the low estimate and a 10% probability that the estimated storage volume will exceed the high estimate.

Oil and Gas Reservoirs

Pumping CO_2 into oil and gas reservoirs to boost production (that is, enhanced oil recovery) is practiced in the petroleum industry today. The United States is a world leader in this technology, and oil and gas operators inject approximately 68 million tons of CO_2 underground each year to help recover oil and gas resources.[55] Most of the CO_2 used for EOR in the United States comes from naturally occurring geologic formations, however, not from industrial sources. Using CO_2 from industrial emitters has appeal because the costs of capture and transport from the facility could be partially offset by revenues from oil and gas production. Both of the currently operating large electricity-generating plants with CCS, Boundary Dam and Petra Nova, offset some of the costs of CCS by selling the captured CO_2 for EOR.

Carbon dioxide can be used for EOR onshore or offshore. To date, most CO_2 projects associated with EOR are onshore, with the bulk of U.S. activities in western Texas.[56] Carbon dioxide also can be injected into oil and gas reservoirs that are completely depleted, which would serve the purpose of long-term sequestration but without any offsetting benefit from oil and gas production.

Deep Saline Reservoirs

Some rocks in sedimentary basins contain saline fluids—brines or brackish water unsuitable for agriculture or drinking. As with oil and gas, deep saline reservoirs can be found onshore and offshore; they are often part of oil and gas reservoirs and share many characteristics. The oil industry routinely injects brines recovered during oil production into saline reservoirs for disposal.[57] As **Table 2** shows, deep saline reservoirs constitute the largest potential for storing CO_2 by far. However, unlike oil and gas reservoirs, storing CO_2 in deep saline reservoirs does not have the potential to enhance the production of oil and gas or to offset costs of CCS with revenues from the produced oil and gas.

Unmineable Coal Seams

U.S. coal resources that are not mineable with current technology are those in which the coal beds are not thick enough, are too deep, or lack structural integrity adequate for mining.[58] Even if they cannot be mined, coal beds are commonly permeable and can trap gases, such as methane, which can be extracted (a resource known as *coal-bed methane*, or CBM). Methane and other gases are physically bound (adsorbed) to the coal. Studies indicate that CO_2 binds to coal even more tightly than methane binds to coal.[59] CO_2 injected into permeable coal seams could displace methane,

[55] As of 2014. See Vello Kuuskraa and Matt Wallace, "CO2-EOR Set for Growth as New CO2 Supplies Emerge," *Oil and Gas Journal*, vol. 112, no. 4 (April 7, 2014), p. 66.

[56] As of 2014, nearly two-thirds of oil production using CO_2 for EOR came from the Permian Basin, located in western Texas and southeastern New Mexico. Ibid., p. 67.

[57] The U.S. Environmental Protection Agency (EPA) regulates this practice under authority of the Safe Drinking Water Act, Underground Injection Control (UIC) program. See the EPA UIC program at https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells.

[58] *Coal bed* and *coal seam* are interchangeable terms.

[59] IPCC Special Report, p. 217.

which could be recovered by wells and brought to the surface, providing a source of revenue to offset the costs of CO_2 injection. Unlike EOR, injecting CO_2 and displacing, capturing, and selling CBM (a process known as *enhanced coal bed methane recovery*) to offset the costs of CCS is not yet part of commercial production. Currently, nearly all CBM is produced by removing the water trapped in the coal seam, which reduces the pressure and enables the release of the methane gas from the coal.

Discussion

Many CCS proponents hailed the start-up of the first U.S. coal-fired power plant with CCS—Petra Nova—as a major step in the advancement of CCS deployment across the electricity sector and a milestone for CCS as a viable technology for reducing greenhouse gas emissions.[60] The enthusiasm for Petra Nova may have been tempered somewhat by the June 28, 2017, announcement that Mississippi Power was suspending the CCS portion of its Kemper County Energy Facility. Kemper is a long-anticipated project with combined coal gasification and CCS using technology developed with assistance from DOE. Unlike Petra Nova and the Boundary Dam CCS plant in Canada—both retrofits of older plants—Kemper was built with the intention to integrate CCS technology into the plant design from the outset. All three plants received subsidies from the federal government, but other factors were at play in determining the success or failure of each venture.

In some aspects, the Kemper plant resembled the original design for the FutureGen plant during the George W. Bush Administration: a power plant built from scratch to be largely emissions free using CCS.[61] Cost issues and schedule delays also hampered FutureGen, even though it was slated to receive nearly $1 billion in federal funds, far more than the amount provided to Kemper.

Costs and schedule delays for nearly first-of-a-kind large, capital-intensive projects are not unanticipated, as demonstration phase projects commonly fall along the most expensive part of a cost curve from inception to commercial deployment. Nevertheless, the mixed success in 2017 of the Petra Nova and Kemper plants puts the further development of CCS somewhat at a crossroads, particularly with the apparent lack of interest in further support for such projects signaled by the Trump Administration. President Trump's FY2018 budget request would severely reduce DOE funding for CCS overall. In addition, the Administration has expressed interest in supporting early-stage research within its FER&D portfolio but not in supporting large demonstration-scale projects such as Petra Nova or Kemper.

The Obama Administration commissioned a CCS task force, which concluded that the largest barrier to long-term demonstration and deployment of CCS technology is the absence of a federal policy to reduce greenhouse gas emissions.[62] The task force further concluded that widespread deployment of CCS will occur only if the technology is commercially available at economically competitive prices. None of those factors appear to be in place currently, which may indicate that demonstration and deployment of industrial-scale CCS will be delayed compared to earlier projections, pending future policy, technological, and economic developments.

[60] Edward Klump and Nathanial Gronewald, "After Petra Nova, What's Next for NRG and Carbon Capture?," *EnergyWire*, April 14, 2017, at https://www.eenews.net/energywire/stories/1060053094.

[61] For a brief discussion of FutureGen, see CRS Report R44387, *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*, by Peter Folger.

[62] White House, *Report of Interagency Task Force on Carbon Capture and Storage*, August 2010, p. 14.

Even with the current uncertainty over the future of CCS, some in Congress have signaled continued support for DOE's R&D efforts with respect to CCS. The House Energy and Water Development appropriations draft legislation would support CCS R&D at a level comparable to FY2017, for example.[63] In addition, some Senators and Members of Congress have continued to introduce legislation in the 115th Congress intended to advance and shape CCS.

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[63] The amount of $634.6 million was unchanged in the July 18, 2017, House Rules Committee Print 115-30, referencing FY2018 Energy and Water appropriations.