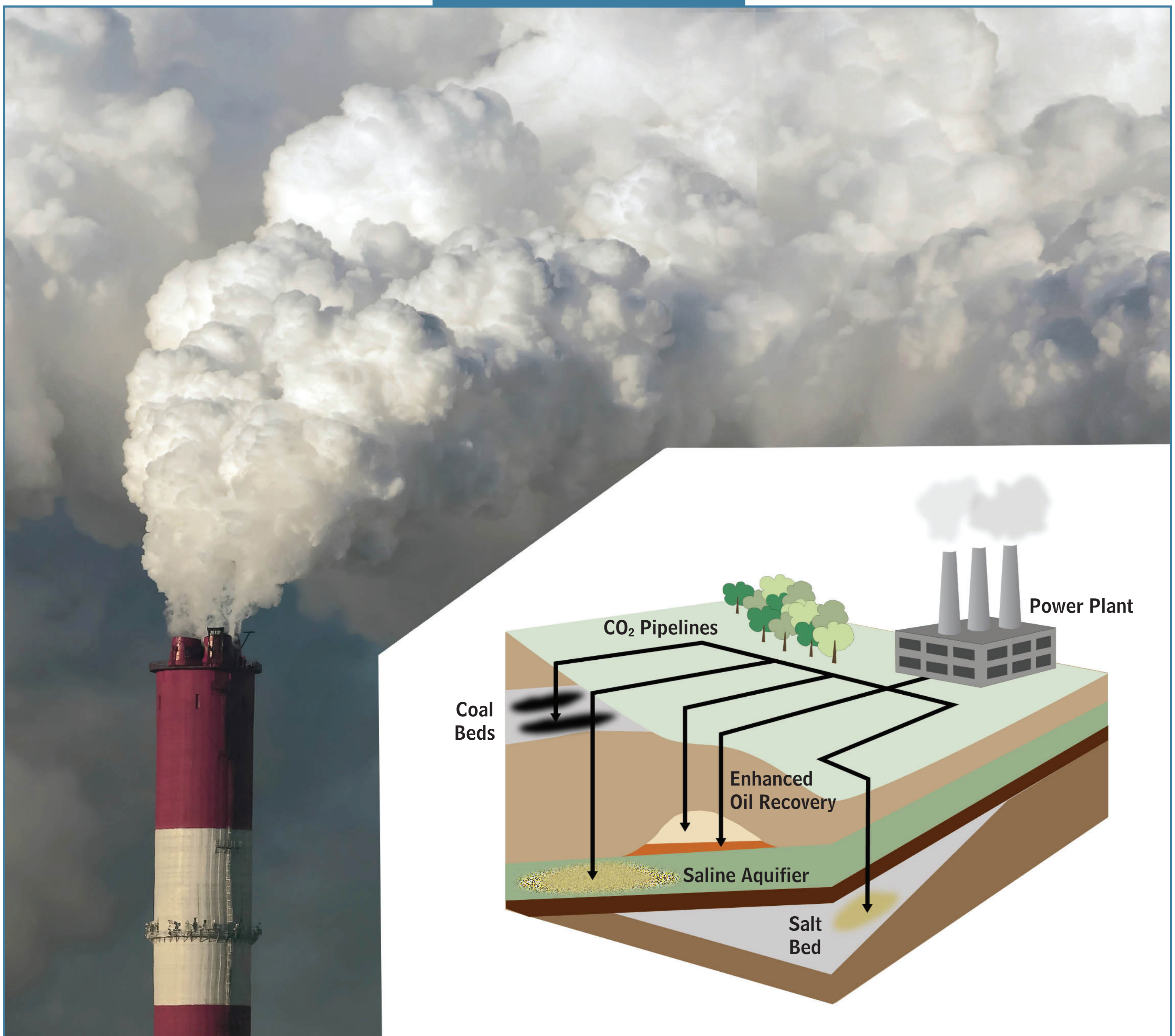
CONGRESS OF THE UNITED STATES
CONGRESSIONAL BUDGET OFFICE

CBO

Federal Efforts to Reduce the Cost of Capturing and Storing Carbon Dioxide



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Notes

Numbers in the text and tables may not add up to totals because of rounding.

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Summary

Electricity generation in the United States depends heavily on the use of coal: Coal-fired power plants produce 40 percent to 45 percent of the nation's electricity. At the same time, those facilities account for roughly a third of all U.S. emissions of carbon dioxide (CO_2), which together with other greenhouse gases has become increasingly concentrated in the atmosphere. Most climate scientists believe that the buildup of those gases could have costly consequences.

One much-discussed option for reducing the nation's greenhouse gas emissions while preserving its ability to produce electricity at coal-fired power plants is to capture the CO_2 that is emitted when the coal is burned, compress it into a fluid, and then store it deep underground. That process is commonly called carbon capture and storage (CCS). Although the process is in use in some industries, no CCS-equipped coal-fired power plants have been built on a commercial scale because any electricity generated by such plants would be much more expensive than electricity produced by conventional coal-burning plants. Utilities, rather than federal agencies, make most of the decisions about investments in the electricity industry, and today they have little incentive to equip their facilities with CCS technology to lessen their CO_2 emissions.

Since 2005, lawmakers have provided the Department of Energy (DOE) with about $6.9 billion to further develop CCS technology, demonstrate its commercial feasibility, and reduce the cost of electricity generated by CCS-equipped plants. But unless DOE's funding is substantially increased or other policies are adopted to encourage utilities to invest in CCS, federal support is likely to play only a minor role in deployment of the technology.

Engineers have estimated that, on average, electricity generated by the first CCS-equipped commercial-scale plants would initially be about 75 percent more costly than electricity generated by conventional coal-fired plants. (Most of that additional cost is attributable to the extra facilities and energy that would be needed to capture the CO_2.) That initial cost differential would probably shrink, however, as the technology became more widely applied and equipment manufacturers and construction companies became more familiar with it—a pattern of cost reduction called learning-by-doing.

DOE aims to bring down the additional costs for generating electricity with CCS technology to no more than 35 percent, or less than half the current cost premium. Such a cost differential, if combined with a tax on carbon or policies restricting CO_2 emissions, could allow coal-fired plants with CCS to be competitive with those without CCS.

Such a reduction in costs might be accomplished over time through learning-by-doing, which would require that a certain amount of new generating capacity be built—in the form of new coal-fired CCS-equipped generating plants. Using the historical pace of reductions in costs for earlier emission-control technologies, the Congressional Budget Office (CBO) estimates that more than 200 gigawatts (GW) of coal-fired generating capacity with CCS capabilities will have to be built to meet DOE's cost reduction goal. That estimate of new capacity, which is equivalent to about two-thirds of the total current capacity of U.S. coal-powered electricity generation plants, is subject to considerable uncertainty. Nevertheless, in the absence of a significant technological breakthrough, it seems clear that a large amount of new CCS capacity—installed either at new plants or, through retrofitting, at existing plants—would be needed to reduce costs by enough to achieve DOE's goal.

But the demand for electricity in the United States is growing slowly, and even if DOE's cost reduction target was attained, coal-fired power plants equipped with CCS technology would not be competitive with coal-fired plants that lacked it unless policies restricting CO_2 emissions or imposing a price on them were adopted. Consequently, under current laws and policies, utilities are unlikely to build that much new generating capacity—that is, more than 200 GW—or invest in adding CCS technology to much of their existing capacity for many decades. If, however, new policies restricted or imposed a price on CO_2 emissions, the domestic stock of electricity generation plants would turn over more rapidly, and CCS technology would become more competitive economically, increasing the potential for construction of CCS-equipped plants in the United States. Nevertheless, investors already have several options for generating electricity—nuclear power, wind, biomass, other renewables, and natural gas—that produce few, if any, CO_2 emissions. The amount of investment in CCS would depend on how costs for the different alternatives compared with costs for electricity generation without CCS.

Reductions in costs for CCS-equipped power plants could also come from experience outside the United States. Demand for electricity is growing rapidly in other parts of the world—for example, China and India—and those countries are increasing their capacity to satisfy it. If plants that were equipped with early versions of the CCS technology were built abroad or if some coal-fired power plants now in operation in other countries were retrofitted with CCS, the cost of generating electricity at plants that were subsequently built or retrofitted in the United States would be expected to be lower than the cost of generating electricity at the plants that were built initially. At present, however, foreign investment in CCS, like investment in the technology in the United States, centers not on building full-scale CCS-equipped commercial plants but on conducting research and development, carrying out small-scale demonstrations of the technology's feasibility, and building pilot plants.

Until now, most efforts to develop CCS have focused on coal-fired power plants. However, the price of natural gas has dropped substantially in recent years, and the share of electricity generated by natural gas-fired plants has expanded and is likely to continue to grow. The cost of producing electricity with a natural gas-fired plant equipped with CCS could be lower, depending on future prices for coal and natural gas, than the cost of producing electricity with a coal-fired CCS plant. At present, though, regulatory action to curb CO_2 emissions is more likely to shift electricity production from coal to natural gas (without CCS) and other low-emission fuels, such as biomass, rather than to CCS-capable plants.

CBO's analysis suggests that unless the federal government adopts policies that encourage or require utilities to generate electricity with fewer greenhouse gas emissions, the projected high cost of using CCS technology means that DOE's current program for developing CCS is unlikely to do much to support widespread use of the technology. A number of other policy approaches could be considered. For example, lawmakers could redirect resources that now fund technology demonstration projects toward research and development, for which the rationale for federal involvement is strongest and the record of success better. Alternatively, policymakers could impose costs on users of electricity whose generation releases greenhouse gases—for example, through a tax on carbon—thereby making CCS more competitive, or they could experiment with different types of electricity production subsidies that would provide more incentive for private-sector investments in CCS. As another option, lawmakers could reduce or eliminate future spending for CCS, leaving most of the potential for further development of CCS technology to countries with high rates of growth in the demand for electricity and in the need for new electricity-generating capacity.

Federal Efforts to Reduce the Cost of Capturing and Storing Carbon Dioxide

Concerns about global warming have raised questions about the United States' continued dependence on coal for producing electricity. About 1,400 coal-fired generating units located in roughly 600 power plants produce 40 percent to 45 percent of the electricity generated annually in this country and in so doing release about a third of the carbon dioxide attributable to human activities in the United States each year.[1] The consensus among scientific experts is that increasing concentrations of greenhouse gases in the atmosphere—including CO_2, which is the most common—are likely to have extensive, highly uncertain but potentially costly effects on regional climates throughout the world.[2]

The federal government, through the Department of Energy, is seeking ways to reduce greenhouse gas emissions while preserving the nation's ability to continue to rely on coal to produce electricity. A policy to reduce CO_2 emissions would benefit the United States by lessening the risk of costly changes to the climate. However, such a policy would also impose costs on the U.S. economy because it would limit activities that produce those emissions. Depending on the type of policy that lawmakers chose, electric utilities and their customers, coal producers, or certain areas of the country could bear increased costs or a considerable loss of income and jobs.[3] As a result, policymakers have sought options that would reduce CO_2 emissions but also limit the potential impact on the economy and allow the nation to continue to produce electricity from coal. Since 2005, lawmakers have provided DOE with about $6.9 billion to develop and demonstrate the commercial feasibility of technologies that would allow coal-burning power plants to generate electricity without emitting CO_2 into the atmosphere. Instead, the CO_2 would be removed from a plant's exhaust stream, compressed into a liquid, and stored underground indefinitely. Collectively, those processes are usually called carbon capture and storage.

This Congressional Budget Office study examines current federal policies that support the development, demonstration, and deployment of CCS technology and the policies' potential to reduce the future costs of generating electricity with power plants that capture and store carbon.

Carbon Capture and Storage Technology

Any industrial process that produces CO_2 can be modified to capture and store it. For example, CCS technology can be applied to coal-fired power plants—the primary focus of this report—as well as to generating facilities fueled by natural gas; it can also be used in manufacturing such products as cement, ethanol, and fertilizer. In coal-fired power plants, CCS requires facilities and processes that accomplish the following tasks:

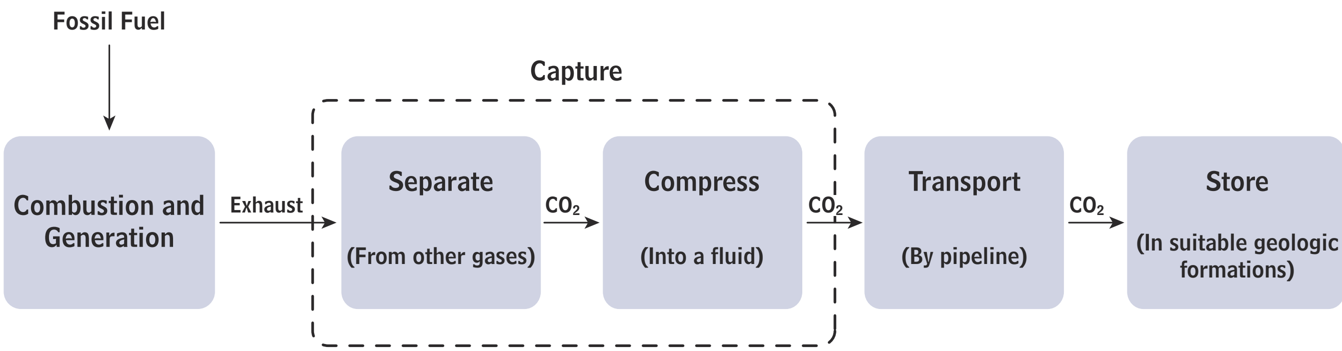
1. Electricity production and emission data are from, respectively, Department of Energy, Energy Information Administration, "Coal's Share of Total U.S. Electricity Generation Falls Below 40% in November and December," *Today in Energy* (March 9, 2012), www.eia.gov/todayinenergy/detail.cfm?id=5331&src=email, and *Annual Energy Review 2010,* DOE/EIA-0384(2010) (October 2011), Table 11.2, p. 317, www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.

2. For more information, see Congressional Budget Office, *The Economics of Climate Change: A Primer* (April 2003), and *Potential Impacts of Climate Change in the United States* (May 2009).

3. For additional discussion, see Congressional Budget Office, *How Policies to Reduce Greenhouse Gas Emissions Could Affect Employment* (May 2010).

Figure 1.

Steps in the Capture and Storage of Carbon Dioxide After Electricity Generation at a Coal-Fired Power Plant



Source: Congressional Budget Office based on CCSReg Project, *Carbon Capture and Sequestration: Framing the Issues for Regulation* (January 2009, updated March 2009), p. 10.

- Capture CO_2 at the plant and compress it into a liquid;
- Transport the compressed CO_2, usually through a pipeline, to a storage site; and
- Store CO_2 deep underground in a porous rock formation (see Figure 1).

The feasibility of using such facilities and processes in the generation of electricity has been explored on a small scale, but the technology has yet to be widely adopted.

Capturing Carbon Dioxide

When CCS technology is used in coal-fired power plants, exhaust gases that contain CO_2 are streamed through (or otherwise put into contact with) a specialized material that absorbs most of the CO_2 while allowing the rest of the exhaust to pass. Subsequently, the CO_2 that was absorbed is extracted, by heating or otherwise treating that material, and then compressed into a liquid. Because the approach applies CCS technology to exhaust gases, it is termed a postcombustion method. Two alternative approaches have been proposed and in some instances used in pilot plants or in fields unrelated to electricity generation—for example, in making glass. One alternative approach is to capture CO_2 through a precombustion method such as gasification. That process separates the CO_2 by transforming the coal into a gas (often referred to as syngas) before it is burned. The other alternative approach is oxy-fuel combustion, in which coal is burned in pure oxygen rather than air to produce exhaust gas that consists primarily of water and CO_2 and that is ready for drying, compression, and storage. However, CBO's analysis focuses on the postcombustion approach because that technology is the only one that is compatible with the most commonly used designs for electricity-generating plants.

The process of treating the absorbent material and compressing the CO_2 consumes a great deal of energy—so much so that the capture and compression of CO_2 reduce the net amount of energy that the power plant yields for customers by between 15 percent and 30 percent. Thus, a plant equipped with CCS technology must be larger than a traditionally equipped plant and must burn more coal to serve the same number of customers. Engineering studies suggest that the capture portion of the process will account for approximately 90 percent of the additional costs required to construct and operate a plant that uses CCS instead of conventional technology.

Transporting Carbon Dioxide

Once compressed, the captured CO_2 must be transported to an underground storage site. If CCS was widely adopted, it would be necessary to substantially expand the existing pipeline network to transport the gas to storage sites that might be hundreds of miles away. Such a network could use pipeline technology that has already been developed to transport carbon dioxide to oil fields, where it is injected into wells to boost their production—a process known as enhanced oil recovery. Currently, about 4,000 miles of pipeline is used for that purpose.

The market in CO_2 for enhanced oil recovery and the network of pipelines to transport compressed gas are expanding, a trend reflected in forecasts by DOE's Energy Information Administration (EIA) that enhanced oil recovery will increase significantly over the next 25 years.[4]

Storing Carbon Dioxide

After it has been transported, the CO_2 captured at power plants would be injected through deep wells, similar to oil or natural gas wells, into porous geologic formations roughly a kilometer or more underground. (That depth is considered to be enough to maintain the pressure required to keep CO_2 in its liquid state.) The types of underground formations typically discussed for storing CO_2 include depleted oil and natural gas reservoirs, porous formations filled with brine, and unminable coal seams. The technology for underground storage of CO_2 is well developed. Enhanced oil recovery efforts, together with some other storage projects, have already pumped more than 500 million tons of CO_2 underground, most of which has remained in place.[5]

Geologists believe that geologic formations in the United States have the potential to store enough CO_2 to permit widespread use of CCS technology in the country's electric power industry. Current estimates by DOE and the International Energy Agency suggest a theoretical storage potential of over 3,000 billion metric tons, or roughly 1,000 years' worth of the CO_2 emitted by U.S. coal-fired utilities.[6] The U.S. Geological Survey and DOE are trying to refine those estimates to determine how much of that potential could be developed.

Status of CCS Technology Development

The technology for separating and capturing CO_2 is already in use in several industries, although the conditions in which it is employed are less demanding than those that apply in utility-scale coal-fired power plants. CCS is used, for example, by producers of natural gas, which, as it comes out of the ground, routinely contains more CO_2 than conventional uses allow. To make natural gas fit for sale, refiners separate the CO_2 from the gas and simply vent it into the atmosphere. More recently, facilities that produce natural gas have shown that large-scale capture of CO_2 is technically and operationally feasible and that the captured gas can be compressed into a liquid, transported, and stored underground. The Sleipner natural gas plant in the North Sea off the coast of Norway and the Salah Gas plant in Algeria are the most prominent examples of that use of CCS technology. Both of those plants strip the CO_2 from natural gas and pump it into suitable geologic formations. Similarly, the Great Plains Synfuels Plant uses a precombustion CCS technology that turns coal into a gas. The plant, located near Beulah, North Dakota, is the largest CCS-equipped plant in the world; its early version of the technology has a CO_2 capture rate of 50 percent. (One of DOE's CCS-related goals is to have CCS-equipped plants capture 90 percent of the CO_2 emitted during the production of electricity.) The resulting liquid is piped to Canada, where it is used in enhanced oil recovery.

Technology for capturing CO_2 has been used in other industries, although not on a large scale. Some producers of ammonia, hydrogen, and ethanol may separate CO_2 from other gases as part of their production process. Also, in the electricity generation industry, a few facilities separate and capture a fraction of their CO_2 emissions for sale to nearby food-processing plants—to be used, for example, in carbonated products. Those facilities are relatively small, however, and the CCS technology they use is not of a sufficient scale to eliminate all or most of the CO_2 emissions from the exhaust of a commercial power plant.

Because CO_2 capture technologies are already in use to some extent, industrial engineers may have already taken advantage of the available opportunities to make the capture process more efficient and hence less costly. The additional advances necessary to markedly improve the technology's performance or reduce its costs are likely to require substantial investment in research and development (R&D) as well as experience in building and operating new plants. The area of research that is widely

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4. Department of Energy, Energy Information Administration, *Annual Energy Outlook 2012* (June 2012), p. 95, www.eia.gov/forecasts/aeo/.

5. For estimates of the quantities of CO_2 used for such efforts, see Department of Energy, Office of Fossil Energy, *Report of the Interagency Task Force on Carbon Capture and Storage* (August 2010), p. D-1, www.fe.doe.gov/programs/sequestration/ccs_task_force.html.

6. Ibid., p. 39. For more information, see Congressional Budget Office, *The Potential for Carbon Sequestration in the United States* (September 2007).

Table 1.

Large-Scale Projects to Install CCS Technology in Power Plants That Are Currently Planned or Under Construction in the United States

Project	Private-Sector Project Leader	Location	Size (Megawatts)	DOE Funding (Millions of dollars)	Planned Completion Date
FutureGen 2.0	FutureGen Industrial Alliance	Meredosia, Ill.	200	1,000	2015
Hydrogen Energy California	SCS Energy	Kern County, Calif.	390	308	2014
Kemper County	Mississippi Power/Southern Company	Kemper County, Miss.	582	270	2014
Tenaska Trailblazer Energy Center	Tenaska, Inc.	Sweetwater, Tex.	600	0	2014
Texas Clean Energy	Summit Power Group	Ector County, Tex.	400	450	2014–2015
W.A. Parish Plant	NRG Energy	Thompsons, Tex.	60	154	2017

Source: Congressional Budget Office based on Carbon Capture and Sequestration Technologies at MIT, CCS Project Database, "Power Plant Carbon Dioxide Capture and Storage Projects: Large-Scale Power Plant CCS Projects Worldwide" (March 15, 2012), http://sequestration.mit.edu/tools/projects/index_capture.html.

Note: CCS = carbon capture and storage (the set of processes and technologies that separate carbon dioxide, or CO_2, from other gases generated when a fossil fuel is burned; compress the CO_2 into a fluid; and then transport it to an underground location for storage); DOE = Department of Energy.

thought by experts to have the greatest potential to reduce costs and so move the technology toward more widespread use is to improve the absorbent materials used to extract the CO_2 and thereby reduce the energy required for the capture stage of the process.

However, integrating CCS technology into the production of electricity—and specifically into electricity generation at coal-fired power plants—appears to be more demanding technically than, for example, the use of CCS in the production of natural gas. That added technical complexity, which contributes to the greater cost of electricity generation at CCS-equipped versus conventional power plants, has limited the technology's use in existing coal-fired facilities. Until relatively recently, though, power companies worldwide were planning to undertake roughly 30 new large-scale coal-powered CCS projects—10 of them in the United States—to demonstrate the technology's commercial viability. The planned facilities ranged in capacity from 60 megawatts (MW) to more than 680 MW.[7] (The average coal-fired generating unit in the United States has a summer capacity of about 230 MW.)[8]

Plans for many of those "demonstration" projects have now changed, however, and in fact, a number of them (six in the European Union, Canada, and Norway, and four in the United States) have already been canceled or put on hold. Several projects in the United States were started when adoption of a cap-and-trade program or some other U.S. policy for reducing greenhouse gases seemed more likely to investors than it does today. As the prospect of a nationwide emission-reduction program has faded, so have plans for new CCS-equipped power plants, and now only six large-scale demonstration projects are still planned or under construction in the United States (see Table 1). Of those six projects, five have received federal funding. The private-sector organizers of the remaining project have discussed their hope of receiving federal funds, but as of this writing, the project has not received any federal support.

7. Massachusetts Institute of Technology, "Carbon Capture and Sequestration Project Database," http://sequestration.mit.edu/tools/projects/index.html, accessed June 18, 2012.

8. Department of Energy, Energy Information Administration, *Electric Power Annual 2010* (November 2011), Table 1.2, www.eia.gov/electricity/annual/pdf/table1.2.pdf. That capacity figure includes many older plants, which tend to be smaller than those being built today.

Table 2.

Funding for the Department of Energy's Coal Programs

(Billions of dollars of budget authority)

	2005	2006	2007	2008	2009	2010	2011	2012
Coal Program Funding	0.3	0.4	0.4	0.5	4.1	0.4	0.4	0.4

Source: Congressional Budget Office based on information from Department of Energy, Office of Fossil Energy, "Our Budget" (various years), www.fossil.energy.gov/aboutus/budget/index.html; and U.S. House of Representatives, *Conference Report to Accompany H.R. 1*, House Report 111-16 (February 12, 2009), p. 428.

Note: Budget authority is the authority provided by law to incur financial obligations that will result in immediate or future outlays of funds by the federal government.

Federal Policy to Demonstrate Current CCS Technology and Promote Its Future Technological Development

DOE encourages the advancement of CCS technologies through spending for projects to demonstrate the feasibility of using current CCS technology in commercial-scale power plants and by funding R&D activities to develop future generations of more advanced and more efficient equipment. In addition, the federal government encourages the use of CCS by providing tax credits for private utilities that choose to invest in and produce electricity from CCS-equipped plants.

The Department of Energy's CCS Programs

DOE's programs devoted to CCS have two overall goals: to reduce the added costs for electricity produced by CCS-equipped coal-fired power plants to no more than 35 percent and to improve the technology so that CCS-equipped plants capture 90 percent of the CO_2 emitted during the electricity generation process.[9] If the costs for CCS could be reduced to that extent, policies that imposed costs on emissions of carbon, such as a tax, might then make CCS-equipped plants competitive with conventional coal-fired facilities. Achieving those goals would allow for substantial reductions in CO_2 emissions while still permitting the extensive use of coal in the generation of power. The desired amount of cost reduction, DOE argues, would require "aggressive but feasible" development of the technology and would, in the end, reduce the cost of meeting targets for CO_2 emissions by billions of dollars.

The programs to develop and promote CCS technology—the CCS Demonstrations Program and the Carbon Capture and Storage and Power Systems Program—are overseen by DOE's Office of Fossil Energy. That office received about $0.4 billion for its coal programs in 2012 and similar amounts in most of the previous several years (see Table 2). It also received a large infusion of funds from the American Recovery and Reinvestment Act of 2009, which provided $3.4 billion for DOE's CCS efforts (bringing total funding in 2009 for that purpose to $4.1 billion). Much of the money appropriated for CCS remains unspent, however, in part because of the normal time lags in designing and building large projects but also because private investors have canceled several projects for which the federal government was planning to provide some funding.

Full-Scale Demonstration Projects. DOE is participating in five of the six full-scale CCS demonstration projects currently being planned and built in the United States (see Table 1). As of April 2012, DOE had committed $2.2 billion to the construction of those plants; private parties are contributing roughly $10 billion, although that amount does not take into account tax advantages and other considerations from state and local governments. The plants that DOE is helping fund generally embody new technology not only to capture and store CO_2 but also to advance the efficiency of coal-fired electricity production more broadly. Most of those projects include plans to use the captured CO_2 for enhanced oil

9. Department of Energy, National Energy Technology Laboratory, "Innovations for Existing Plants: CO_2 Emissions Control—Program Goals and Targets," www.netl.doe.gov/technologies/coalpower/ewr/co2/goals.html, which is based on *Research and Development Goals for CO_2 Capture Technology*, DOE/NETL-2009/1366 (December 2011).

recovery as a way to increase the projects' economic returns.

One DOE demonstration project that has evoked a great deal of public comment is the FutureGen project, to be located in Illinois. The FutureGen Industry Alliance, composed of several power companies, leads the project; its scope includes retrofitting an existing oil-fueled boiler with a coal-fueled boiler equipped with oxy-fuel combustion technology (for burning coal in pure oxygen) that could generate 200 MW of power. (The plans for the FutureGen project have been substantially modified since the program was first proposed in 2003, and the current project is now designated FutureGen 2.0.) In addition, the project calls for construction of a pipeline and storage facilities sufficient to accommodate an estimated 1.3 million tons per year of compressed carbon dioxide.

According to the FutureGen Industry Alliance, the project will cost approximately $1.3 billion, most of which will be covered by a $1 billion grant provided by DOE.[10] The alliance plans to spend approximately $730 million to retrofit the boiler and $550 million to build the pipeline and storage facilities. Construction is slated to begin in late 2012, and completion of the project is planned for 2015.

In addition to its support for the five plants currently under way, DOE had committed an additional $730 million to three of the four large-scale CCS projects that have been postponed or canceled. Much of that funding was intended for the Mountaineer power plant in New Haven, West Virginia. The large utility American Electric Power recently finished a CCS pilot project there and had planned to expand its CCS capabilities to encompass 20 percent of the plant's electricity generation. DOE was to have provided a grant of $335 million to pay for half the cost of the expansion. But the company has postponed construction indefinitely, citing uncertainty about federal policies for reducing greenhouse gases and prohibitions by local utility commissions on increases in rates (which would have prevented the utility from recouping its costs for the plant's construction).

10. FutureGen Alliance, "FutureGen 2.0" (February 24, 2011), p. 1, http://futuregenalliance.org/pdf/FutureGenFacts.pdf.

Research and Development Programs. DOE's CCS-related R&D activities have focused mainly on capturing and storing CO_2. The department's analysts believe that the current technology for capturing CO_2 could never meet DOE's goal of reducing the cost of CCS-generated electricity. Consequently, DOE has been seeking to develop next-generation CCS equipment and processes that would capture CO_2 more quickly and more completely but use less energy than today's technology does. For example, some DOE-sponsored research involves basic and applied studies to identify better materials for absorbing CO_2 and reducing the amount of energy used by the process for capturing the gas. Those projects to develop new technologies are expected to begin to reach the pilot and demonstration stages over the next 10 to 15 years. DOE is also sponsoring research on reducing the cost and increasing the reliability and efficiency of CCS-equipped coal-gasification plants.

In the area of storing carbon dioxide, DOE is funding research to develop techniques to enhance firms' ability to predict the movement of CO_2 underground. Such techniques include the use of software that would enable analysts to better understand the capacity of underground formations for storing the compressed gas.

Federal Tax Preferences

Federal support for CCS extends beyond DOE's coal programs to provisions of law that reduce the amount of taxes paid by utilities that invest in the technology and use it to generate electricity. The Energy Policy Act of 2005 and the Energy Improvement and Extension Act of 2008 (Division B of Public Law 110-343) created several different tax credits for investment in plants that incorporate various types of "clean coal" technology. For operators of a plant to be eligible for those credits, the Secretary of the Treasury, in consultation with the Secretary of Energy, must certify that the plant will capture and store at least 65 percent to 75 percent of its total CO_2 emissions, depending on the specific technology and credit. Altogether, lawmakers authorized almost $3 billion in investment tax credits, which, the Joint Committee on Taxation forecasts, will cost roughly $0.2 billion per year in forgone revenues through 2015.[11]

11. Joint Committee on Taxation, *Estimates of Federal Tax Expenditures for Fiscal Years 2011–2015,* JCS-1-12 (January 17, 2012), p. 34.

Given the lack of new or proposed projects and the cancellation of projects already under way, a substantial portion of the authorized credits will probably never be used.

The Cost of Producing Electricity Using CCS Technology

CBO has compared the estimated costs of producing electricity at conventional coal-fired power plants with those that would be incurred at facilities equipped with CCS technology. Initially, the cost of generating electricity at a new coal-fired CCS-equipped plant would be substantially higher than the cost of generating it at a plant that produced the same net output of electricity but used conventional technology to do it. However, that premium could decline over time as electric utilities gained experience in installing and using CCS, a pattern seen with other new technologies. Even so, reducing the cost by enough to achieve DOE's goal of only a 35 percent premium could require a lengthy process of building a large amount of new electricity generation capacity.

Cost Differentials Associated with Current CCS Technology

Analysts have assessed what happens to the cost of generating electricity when CCS equipment is added to a power plant. However, because no full-sized CCS-equipped plants have been built, all of the estimates that analysts have produced derive from engineering designs for the construction of such a plant. On the basis of such designs, analysts predict that a plant equipped with CCS technology will cost more to build and to operate than will a conventionally equipped plant, for two main reasons:

- The equipment a CCS plant requires to capture and compress CO_2 is large, complex, and expensive; and

- Capturing and compressing CO_2 consumes a substantial fraction of the plant's total output. Consequently, to produce the same amount of electricity for customers, a plant with CCS capabilities has to be bigger than a plant without them.

According to CBO's analysis, average capital costs for a CCS-equipped plant would be 76 percent higher than those for a conventional plant: $3,070 per kilowatt of capacity compared with $1,740 per kilowatt. A CCS-equipped plant would also be more expensive to operate than a non-CCS-equipped plant would be because it would have to burn more fuel during the process of capturing and compressing the CO_2. Those higher capital and operating costs would in turn make the electricity generated by newly constructed CCS-equipped plants more expensive than that generated by conventional coal-fired plants.

CBO analyzed five engineering studies of the estimated costs for building and operating a new coal-fired power plant that would include technology for capturing, transporting, and storing carbon dioxide.[12] (The appendix discusses those studies more fully. Calculating the estimated costs for the construction of new plants, rather than the costs for retrofitting existing ones, is more useful for comparing the various studies' findings.) The studies provided cost estimates for two types of generating facilities whose costs would be fairly representative of the industry's experience: subcritical pulverized coal plants (which employ the most common coal-based generating technology in use in the United States) and supercritical pulverized coal plants (which use a newer technology that generates electricity more efficiently). CBO's calculations excluded gasification electricity-generating plants and oxy-fuel combustion plants because very few commercial power plants now use those technologies and estimates of construction costs for such plants will be less reliable than those for plants using postcombustion methods.[13]

Each of the five studies measured capital costs for building a CCS-equipped facility, expressed as the cost per kilowatt of generating capacity. Each one also calculated the average cost of producing electricity at such a plant over its lifetime, including the cost of transporting and

12. For a similar analysis of engineering studies, see Peter Folger, *Carbon Capture: A Technology Assessment*, CRS Report for Congress R41325 (Congressional Research Service, July 2010), pp. 17–19.

13. See Michael Hamilton, Howard J. Herzog, and John E. Parsons, "Cost and U.S. Public Policy for New Coal Power Plants with Carbon Capture and Sequestration," *Energy Procedia*, vol. 1, no. 1 (February 2009), p. 4489. For a discussion of the difference between subcritical and supercritical pulverized coal, see Massachusetts Institute of Technology, *The Future of Coal: Options for a Carbon-Constrained World* (Cambridge, Mass.: MIT, 2007), pp. 17–22, http://web.mit.edu/coal/.

storing the captured CO_2, expressed in dollars per megawatt-hour.[14] CBO converted all costs to 2010 dollars and adjusted several of the assumptions underlying the studies to provide a common basis for comparing their findings. Those adjustments involved the cost of a coal-fired plant's financing, the cost of coal, and the operating capacity of a plant, among others (see the appendix for details).

On average, the difference in the cost of electricity produced with and without CCS technology, as reported in the studies that CBO reviewed, was estimated to be $45 per megawatt-hour—that is, $104 with CCS versus $59 without it. That difference, like the cost premium for constructing a CCS-equipped plant versus a conventionally equipped one, is 76 percent.

Reducing Cost Differentials

Experience in applying new technologies to coal-fired power plants indicates that the cost of generating electricity with such a technology may decline over time. For example, one recent study examined reductions in the costs of seven technologies relevant to power plants equipped with machinery for capturing carbon dioxide. As the technologies became more widely applied and equipment manufacturers and construction companies became more familiar with them, costs fell—a pattern of cost reduction called learning-by-doing. The study used the historical average reduction in costs for each component technology, weighted by the technology's share of a plant's total costs, to estimate likely future declines in costs for carbon capture technology. That analysis indicated that if 100 gigawatts of new CCS capacity was installed—either in the United States or abroad—the cost of producing electricity in a CCS-equipped coal-fired plant would drop by between 10 percent and 18 percent.[15]

The potential for gradual reductions in CCS-related costs is borne out by experience with other types of emission-control technologies in the electricity generation industry, but the process of reducing costs can be slow and sometimes requires additional funding for R&D activities or a substantial period spent using the new approach. Starting in the 1970s, as required by the Clean Air Amendments of 1970 and increasingly stringent regulations that were subsequently adopted, utilities reduced sulfur dioxide emissions from their smokestacks. The 1990 amendments to the Clean Air Act added requirements for reducing emissions of nitrogen oxide. Yet despite power plants' long history of using technologies to capture sulfur dioxide emissions as well as funding from DOE for research, it took years to produce a technology that was efficient enough to meet the laws' more stringent requirements. As a result, costs dropped slowly. After 20 years of investment in such facilities, however, capital costs for the equipment had fallen by half, and the removal of sulfur dioxide from plants' emissions had become markedly more efficient.[16] To reduce costs by that much, the industry had put in place sulfur dioxide emission controls on power plants worldwide that together produced almost 200 GW of electricity.

Projections of the cost of CCS technology rest on engineering estimates and the learning-curve models, but two major sources of uncertainty characterize the findings from such analyses. First, the costs for building a CCS-equipped plant could be substantially greater than the initial estimates that the engineering studies present. The builders of a precombustion CCS plant in Mississippi, for example, recently announced that they expected an increase of $366 million in the project's previously estimated cost of $2.4 billion. Second, costs do not always decline as smoothly as learning curves suggest. In many cases, the first version of a new technology proves inadequate and requires redesigning, leading to costs for subsequent plants that are higher than those for the initial

14. A power plant's electricity-generating capacity is measured in kilowatts; the electrical power produced by that capacity is measured in megawatt-hours. During a full hour of operation, 1 kilowatt of capacity produces 1 kilowatt-hour of electricity. A megawatt-hour is 1,000 kilowatt-hours. The average cost of electricity over a plant's lifetime, sometimes called the levelized cost, takes into account such factors as the cost of building the plant, debt service, the return on equity investment, taxes, fuel costs, operating expenses, and the plant's electricity-generating capacity. For a discussion of methods used to estimate levelized costs, see Congressional Budget Office, "The Methodology Behind the Levelized Cost Analysis" (supplemental information for *Nuclear Power's Role in Generating Electricity*, May 2008).

15. Edward Rubin and others, "Use of Experience Curves to Estimate the Future Cost of Power Plants with CO_2 Capture," *International Journal of Greenhouse Gas Control*, vol. 1, no. 2 (2007), pp. 188–197.

16. Peter Folger, *Carbon Capture: A Technology Assessment*, CRS Report for Congress R41325 (Congressional Research Service, July 2010), pp. 76–88. The decline in costs refers only to costs for the components related to reducing sulfur emissions, which in many cases fall much more rapidly than costs for the entire plant.

Table 3.

CBO's Illustrative Calculations of the Estimated Reduction in the Cost of Electricity from CCS-Equipped Plants

(2010 dollars per megawatt-hour)

	Levelized Cost of Electricity[a]
	Costs When the First CCS Plant Goes into Operation
Initial CCS Plant	104
Coal-Fired Plant Without CCS	59
CCS Cost Differential (Percent)	76
	Costs After Investment in 210 Gigawatts of CCS Capacity Worldwide
CCS Plant After 210 Gigawatts of Worldwide Investment	74
Coal-Fired Plant Without CCS[b]	55
CCS Cost Differential (Percent)	35
Memorandum:	
Cost Reduction for CCS Plant per 100 Gigawatts of New Investment (Percent)	14

Source: Congressional Budget Office.

Notes: In this analysis, a power plant's electricity-generating capacity is measured in kilowatts; the electrical power generated by that capacity is measured in megawatt-hours. During a full hour of a plant's operation, 1 kilowatt of capacity produces 1 kilowatt-hour of electricity; 1,000 kilowatt-hours equals 1 megawatt-hour.

CCS = carbon capture and storage (the set of processes and technologies that separate carbon dioxide, or CO_2, from other gases generated when a fossil fuel is burned; compress the CO_2 into a fluid; and then transport it to an underground location for storage).

a. The levelized cost of electricity is the average cost over a plant's lifetime for producing a megawatt-hour of electricity, taking into account such factors as the cost of building the plant, debt service, the return on equity investment, tax rates, fuel costs, operating expenses, and the plant's electricity-generating capacity.

b. The cost of producing electricity at conventional coal-fired plants would also be expected to decline as more experience is gained in building such plants. However, the rate of that decline would probably be much slower than the decline in costs for CCS-equipped plants.

plant—although eventually, those higher costs decline as experience is gained. That pattern has characterized the introduction and adoption of some earlier technologies used to reduce emissions from coal-fired power plants; indeed, one study of electricity prices after the introduction of new emission-related equipment reported that initial costs increased in the majority of cases before such costs began to decline.[17]

How Much New Capacity Using CCS Technology Must Be Built to Reduce the Cost of Generating Electricity in a CCS-Equipped Plant?

According to CBO's estimates, roughly 210 GW of generation capacity in the form of new CCS-equipped coal-fired power plants would be required to achieve DOE's cost reduction goal for the technology (see Table 3). (That capacity is equal to about two-thirds of the total capacity—317 GW—of coal-fired generating plants operating in the United States.)[18] CBO based its calculations on the initial difference in costs that it derived from its review of engineering design studies for new CCS-equipped plants and its analysis of learning-curve studies of earlier emission-control technologies. Specifically, CBO used the following assumptions in its calculations:

- The average cost of electricity from a new coal-fired power plant without CCS capabilities is $59 per megawatt-hour, and the average cost of electricity

17. Edward Rubin and others, "Use of Experience Curves to Estimate the Future Cost of Power Plants with CO_2 Capture," *International Journal of Greenhouse Gas Control*, vol. 1, no. 2 (2007), pp. 188–190.

18. Based on data from Department of Energy, Energy Information Administration, *Electric Power Annual 2010* (November 2011), Table 1.2, www.eia.gov/electricity/annual/pdf/table1.2.pdf.

generated by early CCS-equipped plants is $104 per megawatt-hour, or 76 percent more (see the appendix for details).

- The cost of building and operating a CCS-equipped plant will fall by 14 percent for every 100 GW of additional capacity that is built. That assumption is the midpoint of the range of learning curves discussed earlier (10 percent to 18 percent).

- The cost of producing electricity in a new conventional coal-fired power plant will fall by 6 percent during the time required to add 210 GW of CCS-equipped capacity. According to EIA's forecasts, coal-fired generation capacity worldwide will increase by 66 percent between 2007 and 2035, an expansion that could provide opportunities for improvements in constructing and operating conventional as well as CCS-equipped plants.[19] If the development of CCS proceeds slowly, the reductions in the cost of the competing conventional capacity could be greater than CBO has assumed.

Because the amount of new CCS-equipped capacity needed to achieve DOE's cost reduction goal would vary under assumptions different from those above, CBO performed several analyses to explore those effects. Specific estimates of the amount of necessary additional capacity varied widely, but they were all substantial. For example, if the initial cost of a CCS-equipped plant turned out to be a third higher than the average of the estimates on which CBO based its analysis—so that such a plant cost twice as much as a new conventional coal-fired plant—310 GW of additional capacity (rather than 210 GW) would have to be built to meet DOE's goal. By contrast, if DOE's R&D program proved fruitful and reduced the cost of building a CCS-equipped plant to only 66 percent more than the cost of building a new conventional plant, then 170 GW of additional capacity would be sufficient to meet the goal. Overall, those estimates ranged from an amount at the low end roughly equal to half the United States' current coal-fired generating capacity to an amount at the high end roughly equal to all of the country's capacity.

Changing the pace of learning would also affect CBO's illustrative calculations. Those calculations used the midpoint (14 percent) of the learning-curve range of reductions in costs per 100 GW of new capacity (10 percent to 18 percent). If, instead, learning occurred more slowly and the cost of producing electricity at CCS-equipped plants fell by 10 percent for each 100 GW of new capacity, it would take 330 GW of additional capacity to reduce costs to the requisite level. Alternatively, if learning occurred more quickly and electricity production costs declined by 18 percent per 100 GW of new capacity, then 155 GW would be needed.

The cost of generating electricity at plants equipped with CCS technology would also be expected to decline over time if existing plants were retrofitted to capture CO_2 emissions. That is, the learning necessary to reduce costs would be similar regardless of whether the technology was installed in a new facility or an existing one. However, the cost of using CCS would generally be less at a new plant because the equipment and processes could be standardized, whereas at an existing plant, the technology would have to be adapted to the facilities that were already in place, which is usually a more expensive approach. Nevertheless, the higher costs of the CCS equipment at existing facilities might be more than offset by avoiding the array of construction costs that a new facility would entail. The decision about retrofitting existing plants rather than building new ones is complex and would be affected by many factors other than the cost of the CCS equipment.

How Much Construction of New Electricity-Generating Capacity Is Projected to Occur in the Near Future?

Given the economics of producing electricity with CCS technology, there seems to be little likelihood of substantial investment in that technology in the near future, either in the United States or elsewhere, particularly if no laws or agreements are in place to limit CO_2 emissions.

Current projections indicate that the United States is unlikely to need an additional 210 GW of coal-fired generating capacity in the near future. (One reason is that in recent years, natural gas has accounted for a greater share of electricity generation than it did in the past; see Box 1.) EIA has projected that the average annual growth in capacity in the entire electric power sector will be 0.4 percent per year through 2035, for a total addition

19. See Table H4 in Department of Energy, Energy Information Administration, *International Energy Outlook 2010*, DOE/EIA-0484 (July 27, 2010), www.eia.gov/forecasts/archive/ieo10/index.html.

of 187 GW of new capacity.[20] So even if all new generation capacity built by electric power companies in the United States through that year was devoted to CCS, it would probably be insufficient to meet DOE's cost reduction targets.

But currently, little incentive exists for investments in CCS capacity. That might change if the United States implemented policies to reduce CO_2 emissions; then, the domestic stock of electricity generation plants would turn over more rapidly, and the potential for new investment in CCS capacity in the United States—both in new plants and in existing plants that might be retrofitted—would be strengthened. If DOE met its goal of reducing the cost premium for CCS-generated electricity to no more than 35 percent while capturing 90 percent of the associated CO_2 emissions, utilities and others that might build CCS-equipped plants would still operate at a cost disadvantage of $19 per megawatt-hour ($74 versus $55; see Table 3 on page 9). However, if policymakers also imposed a price (say, as a tax or as part of a cap-and-trade system) of $20 per metric ton of CO_2 emissions, then, in CBO's estimation, that cost disadvantage would be eliminated.[21]

Investors and consumers that faced a price on CO_2 emissions could choose from among several approaches for reducing them: for example, coal-fired generation with CCS, conservation, or the use of other sources of energy, such as natural gas (with or without CCS), nuclear power, wind, biomass, or other renewables. Overall, investors would probably choose a mix of all of those types of investments, which would be determined in large part by the relative prices of the different options for reducing emissions. In one study that examined how the electricity industry could reduce its CO_2 emissions if policymakers imposed a price on them, the role played by CCS in the future varied widely—ranging from accounting for roughly half of all electricity generation to accounting for none—depending on the relative size of the cost premiums for CCS- and nuclear-generated power compared with power generated in conventional coal-fired plants.[22]

Another possibility is that the United States could benefit from knowledge about CCS gained through experience in other countries. In contrast to EIA's forecasts for the growth of capacity in the United States, its outlook for the rest of the world suggests that the needed investment of 210 GW in CCS-equipped capacity could be accommodated easily. By EIA's estimates, worldwide coal-fired generating capacity will grow by more than 940 GW during the 2007–2035 period, rising from 1,425 GW to 2,366 GW.[23] About 80 percent of that increase would occur in other countries, where, unlike projected demand in the United States, the demand for electricity is growing rapidly; China and India in particular are poised to experience increases. Thus, investments in CCS-equipped generation plants abroad could provide enough industry-wide learning to reduce costs for similar plants built in the United States. (In the same way, investments in plants in the United States would probably provide some experiential benefits to foreign generators.)

The potential for reciprocal technology transfer between the United States and other countries is limited in the short term, however, because of differences in the stages of various countries' development of the technology. China, for example, is currently focused on research and development, together with small-scale demonstration projects; funding for large-scale demonstration projects is limited.[24] Large-scale CCS projects are being built mainly in North America and Europe, where capacity is growing much more slowly.

Over the longer term, shifting growth in the world's coal-based electricity-generating capacity toward investment in CCS would require international agreements on substantial reductions in CO_2 emissions.

20. Department of Energy, Energy Information Administration, *Annual Energy Outlook 2012*, DOE/EIA-0383(2012) (June 2012), Table A9, www.eia.gov/forecasts/aeo/.

21. That differential falls within the commonly estimated range of damage caused by CO_2 emissions. One interagency federal analysis estimated that the average social costs of the damage from climate change associated with CO_2 emissions range from $5 to $37 per metric ton in 2010 dollars. See Interagency Working Group on Social Cost of Carbon, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (February 2010), pp. 1 and 33, www.epa.gov/otaq/climate/regulations/scc-tsd.pdf.

22. Sergey Paltsev and others, *The Cost of Climate Policy in the United States*, MIT Joint Program on the Science and Policy of Global Change, Report 173 (April 2009), http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt173.pdf.

23. Department of Energy, Energy Information Administration, *International Energy Outlook 2011,* DOE/EIA-0484(2011) (September 2011), Table F4, p. 254, www.eia.gov/forecasts/ieo/pdf/0484(2011).pdf.

24. See Global CCS Institute, *The Global Status of CCS: 2011* (Canberra, Australia, 2011), pp. 15–25.

Box 1.

Natural Gas-Fired Electricity Generation and the Development of Carbon Capture and Storage Technologies

Most public and private efforts to develop technologies for capturing, compressing, transporting, and storing carbon dioxide (CO_2) emitted during electricity generation have focused on coal-fired plants rather than on natural gas-fired plants. Until recently, natural gas has been more expensive than coal as a power source and thus has been used less; in addition, coal-fired power plants produce more electricity than their natural gas-fired counterparts, and coal combustion produces far more emissions of CO_2 per unit of electricity than does the burning of natural gas. But with lower prices for natural gas and its increasing use for electricity generation, carbon capture and storage (CCS) technology could also be developed for use in natural gas-fired power plants. Nevertheless, because demonstration and pilot projects to construct facilities equipped with CCS technology take years to plan and fund, and because the potential benefits of CCS are greater for coal-fired plants, the use of CCS at coal-fired facilities will probably remain at the forefront of the technology's development for at least the next few years.

Increased Use of Natural Gas in Electricity Generation

The role that natural gas plays in the production of electricity in the United States has been shaped by several factors. Capital costs for electricity-producing turbines powered by natural gas are lower than those for coal-fired or nuclear-powered generators; thus, by using natural gas, utilities can increase their capacity to generate electricity while incurring lower capital costs than would be necessary if those other power sources were used. However, because natural gas generators have, until the past few years, been more expensive to operate than coal-fired or nuclear-powered facilities, they have mainly been used at times of peak demand. Now, for several reasons, many analysts expect utilities to use natural gas more regularly to satisfy normal rather than just peak demand; those reasons include the fuel's relatively low price; the cost of addressing environmental effects other than the buildup of greenhouse gases, such as emissions of mercury; and uncertainty about the cost of complying with possible future regulation of greenhouse gas emissions.[1] A striking indication of that trend is that since 2000, the amount of electricity generated in coal-fired power plants has fallen by 7 percent and the amount of electricity generated in natural gas-fired plants has grown by 64 percent.[2]

1. Susan Tierney, *Why Coal Plants Retire: Power Market Fundamentals as of 2012* (Analysis Group, February 16, 2012), pp. 3–4.
2. Department of Energy, Energy Information Administration, *Electric Power Annual 2010* (November 2011), Table ES1, www.eia.gov/electricity/annual/.

Continued

Policy Options

In CBO's view, current policies are unlikely to achieve the goal of reducing the additional costs for producing electricity with CCS technology to 35 percent more than the cost of producing electricity without CCS. DOE's present funding for CCS would allow the United States to build only a small number of demonstration plants, which are unlikely to be sufficient to reduce costs through the learning process described earlier. If DOE adhered to its current plan, it would continue to support the R&D and demonstration programs for which the American Recovery and Reinvestment Act provided funding of $3.4 billion, and it would continue to seek annual appropriations of $300 million to $400 million for related efforts.

However, unless lawmakers substantially increased support for CCS, probably well beyond even those amounts, federal funding would be likely to contribute only a little to reducing the costs of CCS-equipped coal plants after

Box 1. **Continued**

Natural Gas-Fired Electricity Generation and the Development of Carbon Capture and Storage Technologies

That shift toward using natural gas in nonpeak times will undercut the possible need for coal-fired CCS plants to meet environmental goals. Natural gas facilities emit roughly half the CO_2 that a similarly sized coal-fired plant emits.[3] If natural gas prices remained low or the regulation of greenhouse gases became more stringent, natural gas-fired plants could prove an increasingly viable alternative to coal-fired plants. In fact, the Environmental Protection Agency (EPA) is considering regulations to limit emissions of CO_2 to a level below those produced by a typical coal-fired plant that is not equipped with CCS technology.

Carbon Capture and Storage Technology for Natural Gas-Fired Power Plants

CCS technology could be adopted at plants that use natural gas rather than coal for electricity generation. In fact, the cost of using CCS at natural gas-fired plants would probably be less than the cost of using it at coal-fired plants. In particular, although much of the capture and compression equipment integral to the CCS approach is the same for both types of plants (and the transportation and storage facilities are identical), natural gas-fired plants would require less equipment because they produce fewer CO_2 emissions. Similarly, developers of CCS-capable coal-fired facilities face additional challenges to ensure that the new emission-reduction technology is compatible with the plant's coal-handling and exhaust equipment, some of which limits the emissions of other pollutants.

However, firms today have no incentive to install CCS technology in natural gas-fired plants. It is not economically viable now, and no policies are in place to encourage utilities to purchase the additional equipment and incur the higher costs for producing electricity that CCS technology currently entails. If EPA adopted regulations for reducing greenhouse gases or lawmakers enacted policies to restrict emissions from power plants (such as imposing a price on CO_2 emissions or subsidizing the production of electricity at CCS-equipped electricity generation plants), then natural gas-fired facilities might have an incentive to use CCS to meet such requirements. At present, though, regulatory action to curb CO_2 emissions is more likely to shift electricity production from coal to natural gas (without CCS) and other low-emission fuels, such as biomass, rather than to CCS-capable plants.[4]

3. Utilities that generate electricity by burning natural gas also use that process as an inexpensive way to reduce emissions of mercury and other nongreenhouse gases.

4. Nathan Richardson, Art Fraas, and Dallas Burtraw, *Greenhouse Gas Regulation Under the Clean Air Act: Structure, Effects, and Implications of a Knowable Pathway*, RFF DP 10-23 (Resources for the Future, April 2010), pp. 43–45, www.rff.org/rff/Documents/RFF-DP-10-23.pdf.

the initial demonstration projects for the technology had ended. Most investment in electric utilities comes from the private sector. As CBO's illustrative calculations suggest, the amount of current federal spending is small relative to the magnitude of the investment necessary to make CCS-equipped plants economically competitive, and DOE's current activities are unlikely to provide the amount of learning that would drive down the technology's costs. Rather, reductions would have to be spurred by the activities of investors and the efforts of utilities and their customers.

To encourage investment and deployment, additional incentives would be needed, many analysts say; without them, the returns on investment in CCS plants beyond the demonstration stage would be too small to attract investors. Yet the history of other emission-control technologies suggests that the ability of widespread deployment alone to reduce costs is limited. Even with broad deployment, such earlier technologies as the removal of sulfur dioxide from utilities' emissions have required decades of experience and extensive research and development—as well as a substantial amount of investment—before costs were reduced.[25]

The decisions facing policymakers with regard to support for CCS center on whether current federal technology programs, which are mainly devoted to reducing the costs of the capture portion of the process, should continue as they are currently structured. Some alternatives include shifting the focus from demonstration projects to research and development, adopting policies that encourage private investment in CCS, or reducing or eliminating support for CCS.

Shift DOE's Focus from Demonstration Projects to Research and Development

One option for increasing the effectiveness of federal spending on CCS technology would be to limit that support to research and development and withdraw it from more-costly demonstration projects. Concentrating federal resources on R&D would focus DOE's efforts on activities for which the rationale for spending by the federal government is the strongest—that is, in bringing scientists and engineers together to perform research that is removed from specific commercial applications. R&D is also an area in which the federal record of success is long, compared with many failed federal attempts to commercialize earlier fossil energy technologies.[26]

One variation of that option would be for the federal government to collaborate with governments of other countries in developing CCS technology. DOE, sometimes in cooperation with the U.S. Agency for International Development, supports many activities through the United Nations, the International Energy Agency, and other multilateral groups to promote the transfer of CCS technology internationally. DOE is also promoting adoption of U.S.-developed environmental technology in China as well as the use of U.S.-developed clean coal technologies in other countries. In other areas—for example, research in particle physics and fusion energy—DOE collaborates with foreign partners to pay for large projects, which in many cases are not built on U.S. soil. Such collaboration might be a model that could be applied to CCS-equipped power plants. However, without international agreements on reducing CO_2 emissions, such new projects are likely to be developed only slowly, if at all.

Adopt Policies That Encourage Private Investment in CCS-Equipped Plants

The private sector would have a greater incentive to invest in CCS technology if the federal government adopted policies that in some way offset the higher cost of generating electricity in coal-fired plants equipped with the technology. Currently, the price of electricity reflects the cost of producing it but not the cost of the damage that could be expected from climate change caused by emissions of greenhouse gases. The United States could adopt other policies that would incorporate the cost of that damage in the price of electricity. For example, imposing a tax on CO_2 emissions or adopting a cap-and-trade program that would limit emissions would cause the price of electricity from conventional coal-fired plants to increase. If it did, that rise would encourage investment in technologies like CCS that reduced emissions. However, even with such a policy in place, investors might choose other approaches for reducing CO_2 emissions because of the high cost of CCS.

Similarly, some analysts have suggested that instead of subsidizing the development and construction of CCS-equipped plants, the federal government could subsidize the electricity that the plants produce—for example, by offering to pay any utility using CCS technology a fixed amount for each ton of CO_2 that it captured and stored. Such a policy would avoid having DOE choose individual projects to support and could focus federal efforts on, for example, determining whether such plants were indeed producing electricity in a process that reduced emissions of CO_2. Currently, electric utilities can receive a tax credit for using CCS technology to generate electricity. However, the credit does not seem to have encouraged private investors to equip plants with CCS—either because the credit has been too small or because the credit does not provide an incentive for firms that do not pay taxes.

But subsidizing the electricity that CCS-equipped plants produce would be another form of federal investment in a technology that might never prove to be cost-effective. Moreover, lawmakers have already committed large amounts of money and many years to the construction of the next generation of CCS-equipped plants, and DOE

25. For more information, see Peter Folger, *Carbon Capture: A Technology Assessment*, CRS Report for Congress R41325 (Congressional Research Service, July 2010), pp. 76–88.

26. For more information, see Congressional Budget Office, *Federal Climate Change Programs: Funding History and Policy Issues* (March 2010).

has signed agreements to help fund the construction of several of them.

Reduce or Eliminate DOE's Support for CCS

Given the limits on DOE's ability to lower the costs of CCS through its currently planned activities, lawmakers could substantially reduce or discontinue funding for both developing and demonstrating the technology. If little coal-fired generation capacity was being built in the United States, lawmakers might decide that the development of technologies such as CCS would have little effect on either reducing CO_2 emissions or preserving the nation's ability to use coal-fired power plants in the future. Moreover, even if DOE's cost reduction target was attained, coal-fired plants with CCS would not be competitive with plants that lacked the technology unless policies were adopted that imposed costs on carbon emissions.

Scaling back or eliminating the CCS programs would reduce the need for future annual appropriations for those activities. Moreover, eliminating larger-scale technology demonstration projects would reduce DOE's involvement in fields in which the agency has a mixed track record and in which U.S. industry is generally not poised to follow up with subsequent investment.

An option that would reduce or discontinue support for CCS would not necessarily apply to the funding already provided for demonstration projects, however. Much of that money has been obligated (that is, legally committed for some purpose that will result in outlays) but not yet spent, and because of the CCS-equipped demonstration plants that have been canceled or put on hold, a great deal of it may never be spent. The eventual disposition of those obligated but unspent funds is currently unknown. Because DOE has signed agreements with several private investors to help pay for the five large-scale demonstration plants that are still being built or that are planned to be built, spending for CCS could not be eliminated immediately. In addition, because of existing agreements, DOE might bear some shutdown costs if its support of those plants was terminated or reduced.

Appendix:
Developing a Common Basis for Comparing Engineering Cost Estimates

The set of facilities and processes known as carbon capture and storage (CCS) technology would allow electric utilities that install the technology to capture emissions of carbon dioxide and store them as a liquid underground. The Congressional Budget Office (CBO) compared the costs for building and operating new coal-fired power plants with and without CCS technology. That comparison is based on estimates from five engineering studies, published from 2005 to 2010, of the cost of equipping new electricity-generating plants with CCS technology. Those studies consist of engineering designs and their associated costs for what are considered reasonable plans for constructing and operating such a plant. (No full-scale CCS-capable facility has as yet been built.) CBO used two principal measures of costs in its calculations:

- Total plant construction costs—the costs for building a new power plant per kilowatt of net electrical output that the plant can produce;[1] and
- The levelized cost of electricity—the average cost of producing a megawatt-hour of power over the lifetime of a plant, taking into account such factors as the costs of building, financing, and operating the facility.

On the basis of the studies' findings, CBO concluded that the added cost of constructing and operating a CCS-equipped coal-fired plant rather than a conventional coal-fired power plant would average about 76 percent for both total plant costs and for the levelized cost of electricity (see Table A-1).

For its analysis, CBO converted all costs to 2010 dollars and adjusted several of the assumptions underlying the studies to provide a common basis for comparing their findings. CBO's adjustments included the following:

- The engineering studies used a nominal *fixed-charge factor* to take into account the cost of financing for the plant's construction, calculated on an annual basis. The nominal fixed-charge factor includes the cost of funds used for construction plus payments toward the principal of any loans, calculated over the lifetime of the plant (which is assumed to be 30 years). The cost of funds represents a weighted cost of the debt and equity financing used in building the plant. (The cost of debt is the interest paid on any bonds that are issued, and the cost of the equity financing is the return to investors in a power plant; both costs are adjusted to take taxes into account.) The fixed-charge factors that the studies used ranged from 10.5 percent to 15.1 percent, a variation that reflects the general rise in interest rates leading up to 2008 and the subsequent drop in rates after 2009. To compare the studies on an equal basis, CBO used a nominal fixed-charge factor of 10.5 percent to reflect the lower interest rates in recent years.

1. A power plant's electricity-generating capacity is generally measured in megawatts (1 megawatt equals 1,000 kilowatts), and the electrical power generated by that capacity is measured in megawatt-hours. During a full hour of operation, 1 megawatt of capacity produces 1 megawatt-hour of electricity, which, according to statistics compiled by the Department of Energy's Energy Information Administration, can power roughly 800 average households.

   Total plant costs do not include preproduction costs, inventory capital costs, financing costs, or costs to pay off debt while the plant is being built. CBO used total plant costs rather than a more inclusive measure because many of the studies used the total costs metric.

Table A-1.

Estimates from Engineering Studies of Total Plant and Levelized Electricity Costs for New Coal-Fired Power Plants With and Without CCS Technology

	Total Plant Construction Costs[a] (Dollars)				Levelized Cost of Electricity[b] (Dollars)	
	Supercritical Pulverized Coal Plants[c]	Subcritical Pulverized Coal Plants[c]	Fixed-Charge Factor[d] (Percent)	Cost of Coal (Dollars per MMBtu)	Supercritical Pulverized Coal Plants[c]	Subcritical Pulverized Coal Plants[c]
			Carnegie Mellon University (2009 dollars)			
Without CCS	1,770	1,693	10.5	2.3	55.4	55.6
With CCS	3,205	3,202	10.5	2.3	96.2	99.9
Premium for CCS (Percent)	81	89	0	n.a.	74	80
			Electric Power Research Institute (2006 dollars)			
Without CCS	1,763	[e]	11.7	1.5	53.2	[e]
With CCS	2,930	[e]	11.7	1.5	92.8	[e]
Premium for CCS (Percent)	66	[e]	0	n.a.	74	[e]
			Global Carbon Capture and Storage Institute (2010 dollars)			
Without CCS	1,919	[e]	12.1	2.5	76.0	[e]
With CCS	3,464	[e]	12.1	2.5	131.0	[e]
Premium for CCS (Percent)	81	[e]	0	n.a.	72	[e]
			Massachusetts Institute of Technology (2005 dollars)			
Without CCS	1,330	1,280	15.1	1.5	47.8	48.4
With CCS	2,140	2,230	15.1	1.5	76.9 [f]	81.6 [f]
Premium for CCS (Percent)	61	74	0	n.a.	61	69
			National Energy Technology Laboratory (2007 dollars)			
Without CCS	1,647	1,622	13.4	1.6	74.7	75.3
With CCS	2,913	2,942	14.0	1.6	135.2	139.0
Premium for CCS (Percent)	77	81	4	n.a.	81	85

Continued

- Assumptions in the engineering studies about the *price of coal* over the 30-year lifetime of a plant ranged from $1.50 to $2.47 per million British thermal units (Btu) of heat produced. The price of coal assumed in CBO's analysis was $2.23 per million Btu. CBO derived that estimate by averaging forecasts for 2010 to 2035 of the price of coal used for electricity generation (developed by the Department of Energy's Energy Information Administration) and then converting that number to 2010 dollars.

- *Operating capacity factors* in the engineering studies ranged from 80 percent to 85 percent. (The capacity factor measures how much of a plant's total capacity for generating electricity is used over the course of a year.) A larger capacity factor will reduce the levelized cost of electricity because fixed costs can be spread over the production of more energy. Because four of the five studies used 85 percent as the capacity factor, CBO adjusted the capacity factor of the other study to equal 85 percent.

- To account for the *increase in power plant construction costs* from 2005 to 2010, CBO adjusted the studies' results to reflect costs in 2010. From 2005 to 2008, the nominal costs for building a new power plant rose by about 40 percent; between 2008 and 2010, however, costs fell by about 7 percent, making the estimates of costs for the beginning of the period quite different from those for the end.

Table A-1. **Continued**

Estimates from Engineering Studies of Total Plant and Levelized Electricity Costs for New Coal-Fired Power Plants With and Without CCS Technology

Source: Congressional Budget Office based on Massachusetts Institute of Technology, *The Future of Coal* (2007), web.mit.edu/coal/The_Future_of_Coal.pdf; Electric Power Research Institute, *Updated Cost and Performance Estimates for Clean Coal Technologies Including CO_2 Capture—2006*, EPRI Report 1013355 (March 2007), http://mydocs.epri.com/docs/public/000000000001013355.pdf; National Energy Technology Laboratory, *Cost and Performance Baseline for Fossil Energy Plants*, vol. 1, *Bituminous Coal and Natural Gas to Electricity*, DOE/NETL-2010/1397 (November 2010), www.netl.doe.gov/technologies/coalpower/ewr/co2/SystemsAnalysis.html; Carnegie Melon University, *Integrated Environmental Control Model*, version 6.24 (May 2010), www.cmu.edu/epp/iecm/iecm_dl.html; and Global CCS Institute, *Economic Assessment of Carbon Capture and Storage Technology: 2011 Update* (2011), www.globalccsinstitute.com/publications/economic-assessment-carbon-capture-and-storage-technologies-2011-update.

Notes: In this analysis, a power plant's electricity-generating capacity is measured in kilowatts; the electrical power generated by that capacity is measured in megawatt-hours. During a full hour of a plant's operation, 1 kilowatt of capacity produces 1 kilowatt-hour of electricity; 1,000 kilowatt-hours equals 1 megawatt-hour.

All of the studies except the one conducted by the Electric Power Research Institute (EPRI) incorporated the assumption that over a year, a plant would operate 85 percent of the time. In contrast, the EPRI study incorporated an assumed annual rate of operation of 80 percent.

MMBtu = 1 million British thermal units (1 BBtu is the amount of energy required to raise the temperature of 1 pound of water by 1 degree Fahrenheit under certain controlled conditions); CCS = carbon capture and storage (the set of processes and technologies that separate carbon dioxide, or CO_2, from other gases generated when a fossil fuel is burned; compress the CO_2 into a liquid; and then transport it to an underground location for storage); n.a. = not applicable.

a. The costs for building a new power plant for each kilowatt of net electrical output that the plant can produce.

b. The levelized cost of electricity is the average cost over a power plant's lifetime for producing 1 megawatt-hour of electricity, taking into account such factors as the cost of building, financing, and operating the plant.

c. "Subcritical" and "supercritical" refer to the efficiency of electricity production from pulverized coal—that is, the percentage of the fuel's potential energy that is actually converted to electricity. The efficiency of electricity production using subcritical pulverized coal is about 37 percent; the efficiency of electricity production using supercritical pulverized coal, which uses higher steam temperatures and pressures during generation, is about 40 percent.

d. Broadly speaking, the cost of the funds required to build the plant, including the rate of interest on any debt and the rate of return on equity investment, adjusted to take federal, state, and property taxes into account.

e. EPRI and the Global Carbon Capture and Storage Institute did not estimate costs for a subcritical pulverized coal plant.

f. Does not include the cost of storing and transporting the captured CO_2.

- Similarly, to account for the increase in nominal *operating expenses*—that is, those not related to CCS operations—in the various years of the studies, CBO adjusted the studies' estimates of nonfuel operating expenses to reflect 2010 costs. The operating costs of a power plant increased by 20 percent from 2005 to 2008 before declining by about 9 percent in 2009.

- All of the studies except the one by the Massachusetts Institute of Technology (MIT) included a *cost for storing and transporting the captured carbon dioxide*. To account for such a cost and thus compare the MIT study with the others on an equal-cost basis, CBO added $10 for each short ton (2,000 pounds) of captured carbon dioxide to the MIT study's estimate of the levelized cost of electricity.[2]

The adjusted estimates of total plant costs for non-CCS-equipped plants ranged from about $1,600 to $1,900 per kilowatt of net electrical output (see Table A-2); the adjusted estimates for CCS-equipped plants ranged from about $2,800 to $3,500 per kilowatt. After the adjustments, the estimated cost premium for building a CCS plant ranged from 61 percent to 89 percent in the studies. The adjusted estimates of the levelized cost of electricity for non-CCS plants ranged from $53 to $66 per megawatt-hour, and the adjusted estimates for CCS-equipped plants ranged from $95 to $112 per megawatt-hour. The latter figures represent a premium of 70 percent to 89 percent in the levelized cost of electricity from a CCS plant.

2. The $10 cost per short ton for storage and transportation is taken from Jay Apt and others, *Incentives for Near-Term Carbon Dioxide Geological Sequestration* (Carnegie Mellon University, Carnegie Mellon Electricity Industry Center, October 2007), p. 4.

Table A-2.

CBO's Adjusted Estimates of Total Plant and Levelized Electricity Costs for New Coal-Fired Power Plants With and Without CCS Technology

(2010 dollars)

	Total Plant Construction Costs[a]		Levelized Cost of Electricity[b]	
	Supercritical Pulverized Coal Plants[c]	Subcritical Pulverized Coal Plants[c]	Supercritical Pulverized Coal Plants[c]	Subcritical Pulverized Coal Plants[c]
	Carnegie Mellon University			
Without CCS	1,788	1,710	55.9	56.0
With CCS	3,237	3,234	97.3	100.8
Premium for CCS (Percent)	81	89	74	80
	Electric Power Research Institute			
Without CCS	1,888	[d]	65.5	[d]
With CCS	3,138	[d]	111.5	[d]
Premium for CCS (Percent)	66	[d]	70	[d]
	Global Carbon Capture and Storage Institute			
Without CCS	1,919	[d]	57.4	[d]
With CCS	3,464	[d]	101.8	[d]
Premium for CCS (Percent)	81	[d]	77	[d]
	Massachusetts Institute of Technology			
Without CCS	1,734	1,669	53.1	54.6
With CCS	2,790	2,907	95.4	103.3
Premium for CCS (Percent)	61	74	79	89
	National Energy Technology Laboratory			
Without CCS	1,637	1,612	63.2	64.0
With CCS	2,895	2,924	107.7	111.3
Premium for CCS (Percent)	77	81	71	74

Continued

Table A-2. Continued

CBO's Adjusted Estimates of Total Plant and Levelized Electricity Costs for New Coal-Fired Power Plants With and Without CCS Technology

Source: Congressional Budget Office based on Massachusetts Institute of Technology, *The Future of Coal* (2007), web.mit.edu/coal/The_Future_of_Coal.pdf; Electric Power Research Institute, *Updated Cost and Performance Estimates for Clean Coal Technologies Including CO_2 Capture—2006*, EPRI Report 1013355 (March 2007), http://mydocs.epri.com/docs/public/000000000001013355.pdf; National Energy Technology Laboratory, *Cost and Performance Baseline for Fossil Energy Plants*, vol. 1, *Bituminous Coal and Natural Gas to Electricity*, DOE/NETL-2010/1397 (November 2010), www.netl.doe.gov/technologies/coalpower/ewr/co2/SystemsAnalysis.html; Carnegie Melon University, *Integrated Environmental Control Model*, version 6.24 (May 2010), www.cmu.edu/epp/iecm/iecm_dl.html; and Global CCS Institute, *Economic Assessment of Carbon Capture and Storage Technology: 2011 Update* (2011), www.globalccsinstitute.com/publications/economic-assessment-carbon-capture-and-storage-technologies-2011-update.

Notes: CBO adjusted the results of the studies to provide a basis for comparing them, using common assumptions about the price of coal, a fixed-charge factor, and capacity utilization—that is, how much of the time during a year a plant would be operating. (Broadly speaking, the fixed-charged factor is the cost of the funds required to build the plant, including the rate of interest on any debt and the rate of return on equity investment, adjusted to take federal, state, and property taxes into account.) In addition, CBO converted all costs into 2010 dollars.

In this analysis, a power plant's electricity-generating capacity is measured in kilowatts; the electrical power generated by that capacity is measured in megawatt-hours. During a full hour of a plant's operation, 1 kilowatt of capacity produces 1 kilowatt-hour of electricity; 1,000 kilowatt-hours equals 1 megawatt-hour.

CCS = carbon capture and storage (the set of processes and technologies that separate carbon dioxide, or CO_2, from other gases generated when a fossil fuel is burned; compress the CO_2 into a liquid; and then transport it to an underground location for storage).

a. The costs for building a new power plant for each kilowatt of net electrical output that the plant can produce.

b. The levelized cost of electricity is the average cost over a power plant's lifetime for producing 1 megawatt-hour of electricity, taking into account such factors as the cost of building, financing, and operating the plant.

c. "Subcritical" and "supercritical" refer to the efficiency of electricity production from the pulverized coal—that is, the percentage of the fuel's potential energy that is actually converted to electricity. The efficiency of electricity production using subcritical pulverized coal is about 37 percent; the efficiency of supercritical pulverized coal, which uses higher steam temperatures and pressures during generation, is greater, at about 40 percent.

d. The Electric Power Research Institute and the Global Carbon Capture and Storage Institute did not estimate costs for a subcritical pulverized coal plant.

Lists of Tables and Figures

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About This Document

This Congressional Budget Office (CBO) study was prepared at the request of the Chairman of the Senate Committee on Energy and Natural Resources. In keeping with CBO's mandate to provide objective, impartial analysis, the study makes no recommendations.

Philip Webre of CBO's Microeconomic Studies Division and Samuel Wice (formerly of CBO) prepared the study under the supervision of Joseph Kile and David Moore (formerly of CBO). Megan Carroll, Terry Dinan, and Robert Shackleton offered helpful comments, and Ashley Silberhorn provided research assistance.

Also reviewing the report were Jay Apt, Carnegie Mellon University; Alan Crane, National Research Council; Peter Folger, Congressional Research Service; Howard Herzog, Massachusetts Institute of Technology; Robert Hilton, Alstom (a producer of equipment for the electric power sector); David Mowery, University of California at Berkeley; Karen Palmer, Resources for the Future; and Chiara Trabucchi, Industrial Economics Inc. The assistance of external reviewers implies no responsibility for the final product, which rests solely with CBO.

Leah Mazade edited the report. Jeanine Rees prepared the study for publication, and Maureen Costantino designed the cover. The report is available on CBO's Web site (www.cbo.gov).

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