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Capturing CO2 from Coal-Fired Power Plants: Challenges for a Comprehensive Strategy

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Summary

Any comprehensive approach to substantially reduce greenhouse gases must address the world's dependency on coal for one-quarter of its energy demand, including almost half of its electricity demand. To maintain coal in the world's energy mix in a carbon-constrained future would require development of a technology to capture and store its carbon dioxide emissions. This situation suggests to some that any greenhouse gas reduction program be delayed until such carbon capture technology has been demonstrated. However, technological innovation and the demands of a carbon control regime are interlinked; a technology policy is no substitute for environmental policy and should be developed in concert with it.

Much of the debate about developing and commercializing carbon capture technology has focused on the role of research, development, and deployment (technology-push mechanisms). However, for technology to be fully commercialized, it must also meet a market demand—a demand created either through a price mechanism or a regulatory requirement (demand-pull mechanisms). Any conceivable carbon capture technology for coal-fired power plants will increase the cost of electricity generation from affected plants because of efficiency losses. Therefore, few companies are likely to install such technology until they are required to, either by regulation or by a carbon price. Regulated industries may find their regulators reluctant to accept the risks and cost of installing technology that is not required.

The Department of Energy (DOE) has invested millions of dollars since 1997 in carbon capture technology research and development (R&D), and the question remains whether it has been too much, too little, or about the right amount. In addition to appropriating funds each year for the DOE program, Congress supported R&D investment through provisions for loan guarantees and tax credits. Congress also authorized a significant expansion of carbon capture and sequestration (CCS) spending at DOE in the Energy Independence and Security Act of 2007. Funding for carbon capture technology has increased substantially as a result of enactment of the American Recovery and Reinvestment Act of 2009.

Legislation introduced in the 111th and 110th Congresses invokes the symbolism of the Manhattan project of the 1940s and the Apollo program of the 1960s to frame proposals for large-scale energy policy initiatives that include developing CCS technology. However, commercialization of technology and integration of technology into the private market were not goals of either the Manhattan project or Apollo program.

Finally, it should be noted that the status quo for coal with respect to climate change legislation isn't necessarily the same as "business as usual." The financial markets and regulatory authorities appear to be hedging their bets on the outcomes of any federal legislation with respect to greenhouse gas reductions, and becoming increasingly unwilling to accept the risk of a coal-fired power plant with or without carbon capture capacity. The lack of a regulatory scheme presents numerous risks to any research and development effort designed to develop carbon capture technology. Ultimately, it also presents a risk to the future of coal.

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Introduction: Coal and Greenhouse Gas Emissions

The world meets 25% of its primary energy demand with coal, a number projected to increase steadily over the next 25 years. Overall, coal is responsible for about 20% of global greenhouse gas emissions.[1] With respect to carbon dioxide (CO_2), the most prevalent greenhouse gas, coal combustion was responsible for 41% of the world's CO_2 emissions in 2005 (11 billion metric tons).[2]

Coal is particularly important for electricity supply. In 2005, coal was responsible for about 46% of the world's power generation, including 50% of the electricity generated in the United States, 89% of the electricity generated in China, and 81% of the electricity generated in India.[3] Coal-fired power generation is estimated to increase 2.3% annually through 2030, with resulting CO_2 emissions estimated to increase from 7.9 billion metric tons per year to 13.9 billion metric tons per year. For example, during 2006, it is estimated that China added over 90 gigawatts (GW) of new coal-fired generating capacity, potentially adding an additional 500 million metric tons of CO_2 to the atmosphere annually.[4]

Developing a means to control coal-derived greenhouse gas emissions is an imperative if serious reductions in worldwide emissions are to occur in the foreseeable future. Developing technology to accomplish this task in an environmentally, economically, and operationally acceptable manner has been an ongoing interest of the federal government and energy companies for a decade, but no commercial system to capture and store these emissions is currently available for large-scale coal-fired power plants.

Arguably the most economic and technologically challenging part of the carbon capture and sequestration (CCS) equation is capturing the carbon and preparing it for transport and storage.[5] Depending on site-specific conditions, the capture component of a CCS system can be the dominant cost-variable, and the component that could be improved most dramatically by further technological advancement. As indicated in **Table 1**, capture costs could be 5-10 times the cost of storage. Breakthrough technologies that substantially reduce the cost of capturing CO_2 from existing or new power plants, for example by 50% or more, would immediately reshape the economics of CCS. Moreover, technological breakthroughs would change the economics of CCS irrespective of a regulatory framework that emerges and governs how CO_2 is transported away from the power plant and sequestered underground.

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[1] Pew Center on Global Climate Change, *Coal and Climate Change Facts*, (2008), available at http://www.pewclimate.org/global-warming-basics/coalfacts.cfm.

[2] International Energy Agency, *World Energy Outlook 2007: China and India Insights* (2007), pp. 593.

[3] World, China and India statistics from International Energy Agency, *World Energy Outlook 2007: China and India Insights*, (2007), pp. 592, 596, and 600; United States statistics from Energy Information Administration, *Annual Energy Review: 2005* (July 2006), p. 228.

[4] Pew Center on Global Climate Change, *Coal and Climate Change Facts* (2008), available at http://www.pewclimate.org/global-warming-basics/coalfacts.cfm. Capacity factor derived by CRS from data presented, assuming plants would operate in baseload mode with 70% capacity factors.

[5] For a general discussion of carbon capture and sequestration, see CRS Report RL33801, *Carbon Capture and Sequestration (CCS)*, by Peter Folger.

Table 1. Expected Costs of CCS Technology Elements

CCS Element	$/Metric Ton of CO_2
Capture	$40-$80
Storage	$3-$8
Monitoring and Verification	$0.2-$1.0

Source: S. Julio Friedmann, Carbon Capture and Sequestration As a Major Greenhouse Gas Abatement Option (November 2007), p. 11.

Note: Capture and storage costs are very site-specific. These estimates reflect the magnitude of difference between capture and storage costs; actual site-specific costs could vary substantially from these estimates. Estimates do not include any transportation costs.

In contrast, the cost of transporting CO_2 and sequestering it underground is likely less dependent on technological breakthroughs than on other factors, such as:

- the costs of construction materials and labor (in the case of pipelines for CO_2 transport);
- the degree of geologic characterization required to permit sequestration;
- the requirements for measuring, monitoring, and verifying permanent CO_2 storage;
- the costs of acquiring surface and subsurface rights to store CO_2;
- costs of insurance and long-term liability; and
- other variables driving the cost of transportation and sequestration.[6]

That is not to say that the transportation and storage components of CCS are independent of cost and timing. Depending on the degree of public acceptance of a large-scale CCS enterprise, the transportation and sequestration costs could be very large, and it may take years to reach agreement on the regulatory framework that would guide long-term CO_2 sequestration. But the variables driving cost and timing for the transportation and storage of CO_2 are less amenable to technological solution.

This report examines the current effort to develop technology that would capture CO_2. First, the report outlines the current status of carbon capture technology. Second, the report examines the role of government in developing that technology, both in terms of creating a market for carbon capture technology and encouraging development of the technology. Finally, the report concludes with a discussion of implications of capture technology for climate change legislation.

[6] For more information on policy issues related to the transportation of CO_2, see CRS Report RL33971, *Carbon Dioxide (CO2) Pipelines for Carbon Sequestration: Emerging Policy Issues*, and CRS Report RL34316, *Pipelines for Carbon Dioxide (CO2) Control: Network Needs and Cost Uncertainties*, both by Paul W. Parfomak and Peter Folger.

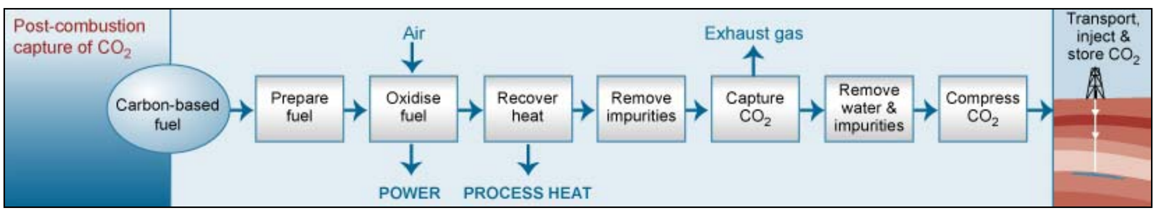
Background: What Is Carbon Capture Technology and What Is Its Status?

Major reductions in coal-fired CO_2 emissions would require either pre-combustion, combustion modification, or post-combustion devices to capture the CO_2. Because there is currently over 300 GW of coal-fired electric generating capacity in the United States and about 600 GW in China, a retrofittable post-combustion capture device could have a substantial market, depending on the specifics of any climate change program. The following discussion provides a brief summary of technology under development that may be available in the near term. It is not an exhaustive survey of the technological initiatives currently underway in this area, but illustrative of the range of activity. Funding for current government research and development activities to improve these technologies and move them to commercialization are discussed later.

Post-Combustion CO_2 Capture

Post-combustion CO_2 capture involves treating the burner exhaust gases immediately before they enter the stack. The advantage of this approach is that it would allow retrofit at existing facilities that can accommodate the necessary capturing hardware and ancillary equipment. In this sense, it is like retrofitting post-combustion sulfur dioxide (SO_2), nitrogen oxides (NOx), or particulate control on an existing facility. A simplified illustration of this process is provided in **Figure 1**.

Figure 1. Simplified Illustration of Post-Combustion CO_2 Capture



Source: Scottish Centre for Carbon Storage. Figure available at http://www.geos.ed.ac.uk/sccs/capture/postcombustion.html.

Post-combustion processes capture the CO_2 from the exhaust gas through the use of distillation, membranes, or absorption (physical or chemical). The most widely used capture technology is the chemical absorption process using amines (typically monoethanolamine (MEA)) available for industrial applications. Pilot-plant research on using ammonia (also an amine) as the chemical solvent is currently underway with demonstration plants announced. These approaches to carbon capture are discussed below. Numerous other solvent-based post-combustion processes are in the bench-scale stage.[7]

Monoethanolamine (MEA)

The MEA CO_2 carbon capture process is the most proven and tested capture process available. The basic design (common to most solvent-based processes) involves passing the exhaust gases

[7] For a useful summary of carbon capture technology, see Steve Blankinship, "The Evolution of Carbon Capture Technology Part 1," *Power Engineering* (March 2008).

through an absorber where the MEA interacts with the CO_2 and absorbs it. The now CO_2-rich MEA is then pumped to a stripper (also called a regenerator) which uses steam to separate the CO_2 from the MEA. Water is removed from the resulting CO_2, which is compressed while the regenerated MEA is purged of any contaminants (such as ammonium sulfate) and recirculated back to the absorber. The process can be optimized to remove 90-95% of the CO_2 from the flue gas.[8]

Although proven on an industrial scale, it has not been applied to the typically larger volumes of flue gas streams created by coal-fired power plants. The technology has three main drawbacks that would make current use on a coal-fired power plant quite costly. First is the need to divert steam away from its primary use—generating electricity—to be used instead for stripping CO_2 from MEA. A second related problem is the energy required to compress the CO_2 after it's captured—needed for transport through pipelines—which lowers overall power plant efficiency and increases generating costs. A study by the Massachusetts Institute of Technology (MIT) estimated the efficiency losses from the installation of MEA from 25%-28% for new construction and 36%-42% for retrofit on an existing plant.[9] This loss of efficiency comes in addition to the necessary capital and operations and maintenance cost of the equipment and reagents. For new construction, the increase in electricity generating cost on a levelized basis would be 60%-70%, depending on the boiler technology.[10] In the case of retrofit plants where the capital costs were fully amortized, the MEA capture process would increase generating costs on a levelized basis by about 220%-250%.[11]

A third drawback is degradation of the amine through either overheating (over 205 degrees Fahrenheit [F]) in the absorber or through oxidation from oxygen introduced in the wash water, chemical slurry, or flue gas that reacts with the MEA. For example, residual SO_2 in the flue gas will react with the MEA to form ammonium sulfate that must be purged from the system.[12] This could be a serious problem for existing plants that do not have highly efficient flue gas desulfurization (FGD) or selective catalytic reduction (SCR) devices (or none), requiring either upgrading of existing FGD and SCR equipment, or installation of them in addition to the MEA process.

MEA-Based Solvents (Fluor)

One approach to addressing the shortcomings of MEA identified above is to use an MEA-based formulation of different amines. The goal of the formulation is improve the reaction rates and CO_2 carrying capacity of the solvent under typical power plant conditions. One such proprietary amine-based technology has been developed by Fluor (called Economine FG Plus).[13] Fluor states

[8] Ryan M. Dailey and Donald S. Shattuck, "An Introduction to CO_2 Capture and Sequestration Technology, *Utility Engineering*" (May 2008), p. 3.

[9] Massachusetts Institute of Technology, *The Future of Coal: An Interdisciplinary MIT Study* (2007), p. 147. Hereafter referred to as MIT, *The Future of Coal*.

[10] Levelized cost is the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments. Costs are levelized in real dollars (i.e., adjusted to remove the impact of inflation).

[11] MIT, *The Future of Coal*, pp. 27, 149.

[12] Ryan M. Dailey and Donald S. Shattuck, "An Introduction to CO_2 Capture and Sequestration Technology, *Utility Engineering*" (May 2008), p. 4.

[13] Satish Reddy, Dennis Johnson,, and John Gilmartin, *Fluror's Economine FG Plus[SM] Technology for CO_2 Capture at Coal-fired Power Plants*, presented at Power Plant Air Pollutant Control "Mega" Symposium, Baltimore (August 25-

(continued...)

that its MEA-based solvent is specially formulated to recover CO_2 from low pressure, oxygen-containing streams, such as boiler stack gases found in conventional coal-fired power plants. The treatment process is similar to generic gas treating processes, using simple, time-tested gas treating equipment. To address contamination of the solvent, the Fluor technology focuses on cleaning up impurities in the flue gas (e.g., SO_2, NOx, hydrochloric acid, and hydrofluoric acid) in order to inhibit the formulation of ammonium sulfate and other heat-stable salts.[14] Thus the process requires installation of modern SO_2 (with additional enhancements), NOx, Hg, and particulate controls upstream of the carbon capture technology to address the impurities. Solvent temperature issues are dealt with through the use of an intercooler system within the absorber. Finally, other enhancements in the process reduce the process energy consumption.

Fluor's technology has significant experience on a small commercial scale, including the only CO_2 recovery unit that has operated on the flue gas of a natural gas-fired turbine power plant under typical power plant conditions. Between 1991 and 2005, the Fluor facility at the Bellingham, MA, power plant captured 360 shorts tons of CO_2 daily for use in the food and beverage industry.[15] In September 2009, NRG Energy and Fluor announced that Economine FG Plus would be installed on a 60 megawatt (MW) slipstream[16] at NRG's WA Parish plant (Unit 7) in Texas, with a plan to be operational by 2013. The captured CO_2 would be sold or used for enhanced oil recovery (EOR). DOE will provide up to $154 million toward the project.

Mixed Amine Solvents (HTC Purenergy)

Other combinations of amines and other chemicals have been developed to increase the efficiency and reduce the energy requirements of capture processes. Using blends of water, amines, and other chemicals developed by the University of Regina's International Test Centre for CO_2 Capture, the Purenergy CCS Capture System is designed to be modular, shop-built, and transported to the site.[17] Currently a module is designed to handle the flow of a 50 MW facility with multi-unit train installation possible.

In December 2009, a commercial demonstration for Purenergy CCS was announced by Basin Electric and HTC Pure Energy, using a 20 MW slipstream at Basin Electric's Antelope Valley Station in North Dakota. Commercial operation is planned for 2012. The CO_2 produced will be transported via an existing CO_2 pipeline to Canada for use in EOR.

Chilled Ammonia (Alstom)

An approach to mitigating the oxidation problem identified above is to use an ammonia-based solvent rather than MEA. Ammonia is an amine that absorbs CO_2 at a slower rate than MEA. In a

(...continued)

28, 2008).

[14] Heat-stable salts are acid anions with a stronger acid strength than the acid gases that are removed from the process gas. These anions may bind to the usable amine and then therefore make it unavailable for acid gas absorption; hence the need to inhibit their formulation or to purge them from the system.

[15] Satish Reddy, Dennis Johnson,, and John Gilmartin, *Fluror's Economine FG Plus[SM] Technology for CO_2 Capture at Coal-fired Power Plants*, presented at Power Plant Air Pollutant Control "Mega" Symposium, Baltimore (August 25-28, 2008), pp. 3-5.

[16] Slipstream refers to pilot testing at an operating power plant using a portion of the flue gas stream.

[17] HTC Pureenergy, *CO_2—Source to Sink*, presentation (April 2008). Also see webite at http://www.htcenergy.com.

chilled ammonia process, the flue gas temperature is reduced from about 130 degrees F to about 35-60 degrees F. This lower temperature has two benefits: (1) it condenses the residual water in the flue gas, which minimizes the volume of flue gas entering the absorber; and (2) it causes pollutants in the flue gas, such as SO_2, to drop out, reducing the need for substantial upgrading of upstream control devices.[18] Using a slurry of ammonium carbonate and ammonium bicarbonate, the solvent absorbs more than 90% of the CO_2 in the flue gas. The resulting CO_2-rich ammonia is regenerated and the CO_2 is stripped from the ammonia mixture under pressure (300 pounds per square inch [psi] compared with 15 psi using MEA), reducing the energy necessary to compress the CO_2 for transportation (generally around 1,500 psi).[19]

The chilled ammonia process is a proprietary process, owned by Alstom. In collaboration with American Electric Power (AEP) and RWE AG (the largest electricity producer in Germany), Alstom began operating its technology on a 20 MW slipstream at AEP's Mountaineer plant in West Virginia in September 2009 and injecting the captured CO_2 into deep saline formations onsite in October 2009.[20] In March 2010, AEP received an award from DOE to cover as much as half the estimated $668 million cost required to scale up the Mountaineer project to capture and store CO_2 from a 235 MW slipstream (approximately 1.5 million tons annually). Once commercial viability is demonstrated at Mountaineer, AEP plans to install the technology at its 450 MW Northeastern Station in Oologah, OK, early in the next decade. The captured gas would be used for EOR. The target is for full commercialization in 2015.

Ammonia (Powerspan)

A second ammonia-based, regenerative process for CO_2 capture from existing coal-fired facilities does not involve chilling the flue gas before it enters the absorber. Using higher flue gas temperatures increases the CO_2 absorption rate in the absorber and, therefore, the CO_2 removal. However, the higher flue gas temperatures also mean that upgrades to existing FGD devices would be necessary.[21]

This process, called ECO_2, is being developed by Powerspan.[22] Powerspan announced test results for its 1 MW pilot unit, located at FirstEnergy Corp's R.E. Burger Plant, in December 2009. The pilot plant tests suggest that carbon capture and compression costs with ECO_2 are below $50 a ton at 90% reduction.[23]

Pre-Combustion CO_2 Capture

Currently, a requirement for the pre-combustion capture of CO_2 is the use of Integrated Gasification Combined-Cycle (IGCC) technology to generate electricity.[24] There are currently

[18] Ryan M. Dailey and Donald S. Shattuck, "An Introduction to CO_2 Capture and Sequestration Technology, *Utility Engineering*" (May 2008), p. 5.

[19] Steve Blankinship, "The Evolution of Carbon Capture Technology, Part 1," *Power Engineering* (March 2008), p. 30.

[20] AEP News Release, *RWE to Join AEP in Validation of Carbon Capture Technology*, (November 8, 2007).

[21] Ryan M Dailey and Donald S. Shattuck, "An Introduction to CO_2 Capture and Sequestration Technology, *Utility Engineering*" (May 2008), p. 7.

[22] Powerspan Corp., *Carbon Capture Technology for Existing and New Coal-Fired Power Plants* (April 15, 2008).

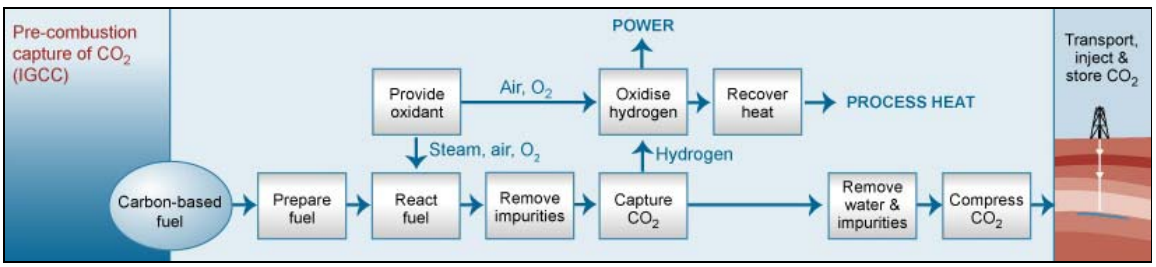
[23] Powerspan Corp., *Powerspan Announces CO2 Capture Technology Pilot Test Results* (December 22, 2009).

[24] IGCC is an electric generating technology in which pulverized coal is not burned directly but mixed with oxygen and (continued...)

four commercial IGCC plants worldwide (two in the United States) each with a capacity of about 250 MW. The technology has yet to make a major breakthrough in the U.S. market because its potential superior environmental performance is currently not required under the Clean Air Act, and as discussed above for carbon capture technology, its higher costs can not be justified (see the Virginia State Corporation Commission decision, discussed below).

Carbon capture in an IGCC facility would happen before combustion, under pressure using a physical solvent (e.g., Selexol and Rectisol processes), or a chemical solvent (e.g., methyl diethanolaimine (MDEA)). A simplified illustration of this process is provided in **Figure 2**. Basically, the IGCC unit pumps oxygen and a coal slurry into a gasifier to create a syngas consisting of carbon monoxide and hydrogen. The syngas is cleaned of conventional pollutants (SO_2, particulates) and sent to a shift reactor which uses steam and a catalyst to produce CO_2 and hydrogen. Because the gases are under substantial pressure with a high CO_2 content, a physical solvent can separate out the CO_2. The advantage of a physical solvent is that the CO_2 can be freed and the solvent regenerated by reducing the pressure—a process that is substantially less energy intensive than having to heat the gas as in an MEA stripper.

Figure 2. Simplified Illustration of Pre-Combustion CO_2 Capture



Source: Scottish Centre for Carbon Storage. Figure available at http://www.geos.ed.ac.uk/sccs/capture/precombustion.html.

From the capture process, the CO_2 is further compressed for transportation or storage, and the hydrogen is directed through gas and steam cycles to produce electricity. MIT estimates the efficiency loss from incorporating capture technology on an IGCC facility is about 19% (from 38.4% efficiency to 31.2%).[25] This loss of efficiency comes in addition to the necessary capital and operations and maintenance cost of the equipment and reagents. For new construction, the estimated increase in electricity generating cost on a levelized basis generally ranges from 22%-25%, with American Electric Power estimating the cost increase at 41%.[26]

There is a lot of activity surrounding the further commercialization of IGCC technology and in the demonstration of carbon capture methods on that technology. As illustrated in **Figure 3**, numerous projects are currently in the development pipeline. The FutureGen initiative—delayed by DOE's decision to restructure the program in early 2008 and subsequently revived in 2009

(...continued)

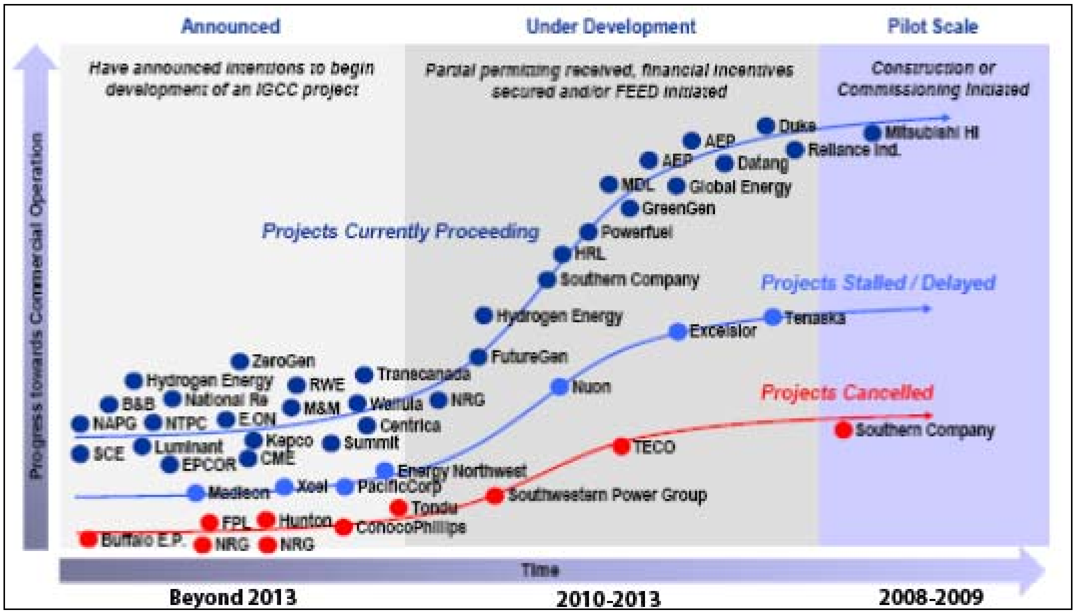
water in a high-pressure gasifier to make "syngas," a combustible fluid that is then burned in a conventional combined-cycle arrangement to generate power.

[25] MIT, *The Future of Coal*, p. 35.

[26] MIT, *The Future of Coal*, p. 36.

with funding from P.L. 111-5—may influence how other IGCC projects develop (see box below).[27]

Figure 3. Status of Global IGCC Projects



Source: Emerging Energy Research (EER), "Global IGCC Power Markets and Strategies: 2007-2030" (December 2007). See http://www.emerging-energy.com/.

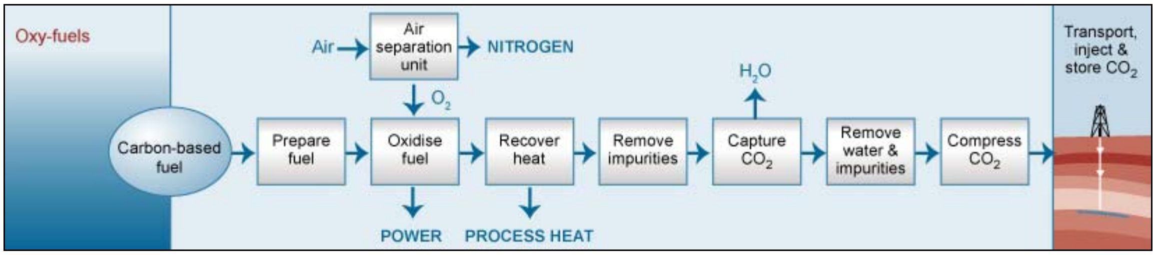
Combustion CO_2 Capture

Attempts to address CO_2 during the combustion stage of generation focus on increasing the CO_2 concentration of the flue gas exiting the boiler. The more concentrated the CO_2 is when it exits the boiler, the less energy (and cost) is required later to prepare it for transport or storage. The most developed approach involves combusting the coal with nearly pure oxygen (>95%) instead of air, resulting in a flue gas consisting mainly of highly concentrated CO_2 and water vapor. Using existing technology, the oxygen would be provided by an air-separation unit—an energy-intensive process that would be the primary source of reduced efficiency. The details of this "oxy-fuel" process are still being refined, but generally, from the boiler the exhaust gas is cleaned of conventional pollutants (SO_2, NOx, and particulates) and some of the gases recycled to the boiler to control the higher temperature resulting from coal combustion with pure oxygen. The rest of the gas stream is sent for further purification and compression in preparation for transport and/or storage.[28] Depending on site-specific conditions, oxy-fuel could be retrofitted onto existing boilers. A simplified illustration of this process is provided in **Figure 4**.

[27] Brad Kitchens and Greg Litra, "Restructuring FutureGen," *Electric Light & Power* (May/June 2008), pp. 46-47, 58.

[28] MIT, *The Future of Coal*, pp. 30-31.

Figure 4. Simplified Illustration of Oxy-fuels CO_2 Capture



Source: Scottish Centre for Carbon Storage. Figure available at http://www.geos.ed.ac.uk/sccs/capture/oxyfuel.html.

The largest oxy-fuel demonstration projects under development are the Vattenfall Project in Germany and the Callide Oxyfuel Project in Queensland, Australia. The Vattenfall project is a 30 MW pilot plant being constructed at Schwarze Pumpe, which began operation in September 2008. The captured CO_2 will be put in geological storage once siting and permitting processes are completed.[29] The Callide Project is being sponsored by CS Energy, who, with six partners, is retrofitting a 30 MW boiler at its Callide-A power station with an oxy-fuel process. Operation of the oxy-fuel process is scheduled for 2011, with transport and geological storage of the CO_2 planned for 2011.[30]

Numerous other bench- and pilot-plant scale initiatives are underway with specific work being conducted on improving the efficiency of the air-separation process. MIT estimates the efficiency losses from the installation of oxy-fuel at 23% for new construction and 31%-40% for retrofit on an existing plant (depending on boiler technology).[31] This loss of efficiency comes in addition to the necessary capital and operations and maintenance cost of the equipment and reagents. For new construction, the increase in electricity generating cost on a levelized basis would be about 46%. In the case of retrofit plants where the capital costs are fully amortized, the oxy-fuel capture process would increase generating costs on a levelized basis by about 170%-206%.[32]

DOE-Supported Technology Development

As summarized in **Table 2**, CO_2 capture technology is currently estimated to significantly increase the costs of electric generation from coal-fired power plants. Research is ongoing to improve the economics and operation of carbon capture technology. DOE's National Energy Technology Laboratory (NETL) is supporting a variety of carbon capture technology research and development (R&D) projects for pre-combustion, oxy-combustion, and post-combustion applications. A detailed description of all the NETL projects, and of carbon capture technology R&D efforts in the private sector, is beyond the scope of this report. However, funding from DOE (described later) is supporting approximately two dozen carbon capture research projects that range from bench-scale to pilot-scale testing.[33] The types of research explored in the NETL-

[29] For more information, see Vattenfall's website at http://www.vattenfall.com/www/co2_en/co2_en/879177tbd/879211pilot/index.jsp

[30] For more information, see Callide Project website at http://www.callideoxyfuel.com/What/CallideOxyfuelProject.aspx.

[31] MIT, *The Future of Coal*, p. 147.

[32] MIT, *The Future of Coal*, pp. 30, 149.

[33] Steve Blankinship, "The Evolution of Carbon Capture Technology, Part 2," *Power Engineering* (May 2008), pp. 62-(continued...)

supported projects include the use of membranes, physical solvents, oxy-combustion, chemical sorbents, and combinations of chemical and physical solvents. According to the NETL, these technologies will be ready for slipstream tests by 2014 and for large-scale field testing by 2018.[34] As discussed above, some projects pursued by the private sector are ready for pilot-scale testing (e.g., the AEP Mountaineer project in West Virginia).

Table 2. MIT Estimates of Additional Costs of Selected Carbon Capture Technology

(percent increase in electric generating costs on levelized basis)

	New Construction	Retrofit[a]
Post-combustion (MEA)	60%-70%	220%-250%
Pre-combustion (IGCC)	22%-25%	not applicable
Combustion (Oxy-fuel)	46%	170%-206%

Source: Massachusetts Institute of Technology, *The Future of Coal: An Interdisciplinary MIT Study* (2007), pp.27, 30, 36, 149. See text for discussion of technologies.

a. Assumes capital costs have been fully amortized.

Roles for Government

Generally, studies that indicate that emerging, less carbon-intensive new technologies are both available and cost-effective incorporate a price mechanism (such as a carbon tax) that provides the necessary long-term price signal to direct research, development, demonstration, and deployment efforts (called "demand-pull" or "market-pull" mechanisms).[35] Developing such a price signal involves variables such as the magnitude and nature of the market signal, and its timing, direction, and duration. In addition, studies indicate combining a sustained price signal with public support for research and development efforts is the most effective long-term strategy for encouraging development of new technology (called "technology-push" mechanisms).[36] As stated by Richard D. Morgenstern: "The key to a long term research and development strategy is both a rising carbon price, and some form of government supported research program to compensate for market imperfections."[37]

The various roles the government could take in encouraging development of environmental technologies are illustrated in **Figure 5**. The federal role in the innovation process is a complex one, reflecting the complexity of the innovation process itself. The inventive activity reflected by government and private research and development efforts overlap with demand pull mechanisms to promote or require adoption of technology, shaping the efforts. Likewise, these initiatives are

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34 DOE National Energy Technology Laboratory, Carbon Sequestration FAQ Information Portal, at http://www.netl.doe.gov/technologies/carbon_seq/FAQs/tech-status.html#.

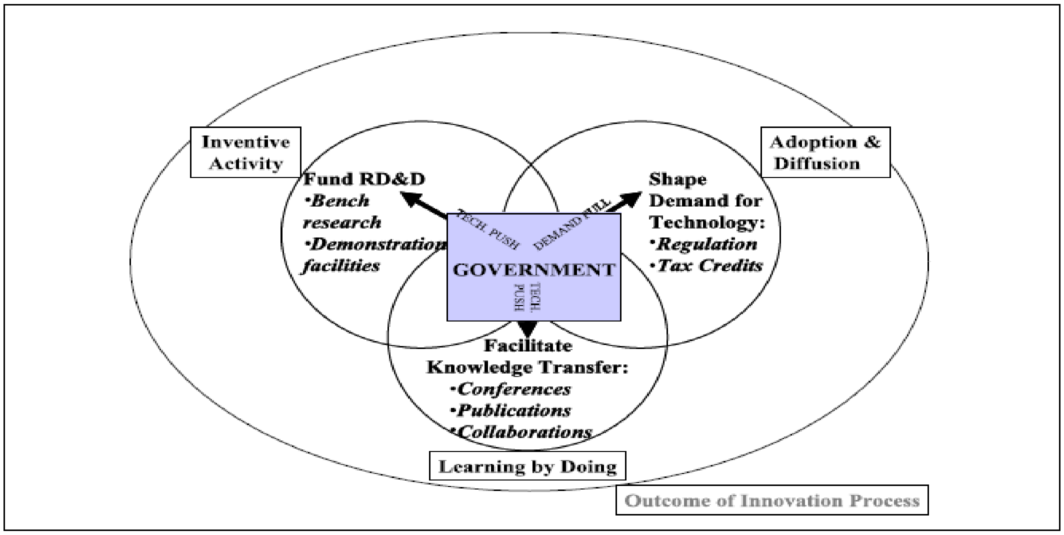
35 For example, see Interlaboratory Working Group, *Scenarios for a Clean Energy Future*, ORNL/CON-476 (November 2000).

36 For example, see *CERA Advisory Service, Design Issues for Market-based Greenhouse Gas Reduction Strategies; Special Report* (February 2006), p. 59; Congressional Budget Office, *Evaluating the Role of Prices and R&D in Reducing Carbon Dioxide Emissions* (September 2006).

37 Richard D. Morgenstern, *Climate Policy Instruments: The Case for the Safety Valve* (Council on Foreign Relations, September 20-21, 2004), p. 9.

facilitated by the government as a forum for feedback gained through both developed and demonstration efforts and practical application. The process is interlinked, overlapping, and dynamic, rather than linear. Attempting to implement one role in a vacuum can result in mis-directed funding or mis-timing of results.

Figure 5. The Federal Role in R&D



Source: Margaret R. Taylor, Edward S. Rubin and David A Hounshell, "Control of SO_2 Emissions from Power Plants: A Case of Induced Technological Innovation in the U.S.," *Technological Forecasting & Social Change* (July 2005), p. 699.

This section discusses these different roles with respect to encouraging development of carbon capture technology, including (1) the need for a demand-pull mechanism and possible options; (2) current technology-push efforts at the U.S. Department of Energy (DOE) and the questions they raise; and (3) comparison of current energy research and development efforts with past mission-oriented efforts.

The Need for a Demand-Pull Mechanism

> Economists note that the driving force behind the development of new and improved technologies is the profit motive.... However, market forces will provide insufficient incentives to develop climate-friendly technologies if the market prices of energy inputs do not fully reflect their social cost (inclusive of environmental consequences).... Even if energy prices reflect all production costs, without an explicit greenhouse gas policy firms have no incentive to reduce their greenhouse gas emissions per se beyond the motivation to economize on energy costs. For example, a utility would happily find a way to generate the same amount of electricity with less fuel, but without a policy that makes carbon dioxide emissions costly, it would not care specifically about the carbon content of its fuel mix in choosing between, say, coal and natural gas. For firms to have the desire to innovate cheaper and better ways to reduce emissions (and not merely inputs), they must bear additional financial costs for emissions.[38]

[38] Carolyn Fischer, *Climate change Policy Choices and Technical Innovation*, Resources for the Future Issue Brief #20 (June 2000), p. 2.

Much of the focus of debate on developing carbon capture technology has been on research, development, and demonstration (RD&D) needs. However, for technology to be fully commercialized, it must meet a market demand—a demand created either through a price mechanism or a regulatory requirement. As suggested by the previous discussion, any carbon capture technology for coal-fired power plants will increase the cost of electricity generation from affected plants with no increase in efficiency. Therefore, widespread commercialization of such technology is unlikely until it is required, either by regulation or by a carbon price. Indeed, regulated industries may find their regulators reluctant to accept the risks and cost of installing technology that is not required by legislation. This sentiment was reflected in a recent decision by the Virginia State Corporation Commission in denying an application by Appalachian Power Company (APCo) for a rate adjustment to construct an IGCC facility:

> The Company asserted that the value of this project is directly related to (1) potential future legal requirements for carbon capture and sequestration; and (2) the proposed IGCC Plant's potential ability to comply cost effectively with any such requirements. Both of these factors, however, are unknown at this time and do not overcome the other infirmities in the Application. The legal necessity of, and the capability of, cost-effective carbon capture and sequestration in this particular IGCC Plant, at this time, has not been sufficiently established to render APCo's Application reasonable or prudent under the Virginia Statute we must follow.[39]

At the same time, there is reluctance to invest in technology that is not required, and the unresolved nature of greenhouse gas regulation is affecting investment in any coal-fired generation.[40] The risk involved in investing in coal-fired generation absent anticipated greenhouse gas regulations is outlined in "The Carbon Principles" announced by three Wall Street banks—Citi, JP Morgan Chase, and Morgan Stanley—in February 2008. As stated in their paper:

> The absence of comprehensive federal action on climate change creates unknown financial risks for those building and financing new fossil fuel generation resources. The Financial Institutions that have signed the Principles recognize that federal CO_2 control legislation is being considered and is likely to be adopted during the service life of many new power plants. It is prudent to take concrete actions today that help developers, investors and financiers to identify, analyze, reduce and mitigate climate risks.[41]

Similarly, lack of a regulatory scheme presents numerous risks to any RD&D effort designed to develop carbon capture technology. Unlike a mission-oriented research effort, like the Manhattan Project to develop an atomic bomb, where the ultimate goal is victory and the cost virtually irrelevant, research efforts focused on developing a commercial device need to know what the market wants in a product and how much the product is worth. At the current time, the market value of a carbon capture device is zero in much of the country because there is no market for

[39] State Corporation Commission, *Application of Appalachian Power Company*, Case No. PUE-2007-00068 (Richmond, April 14, 2008), p. 16.

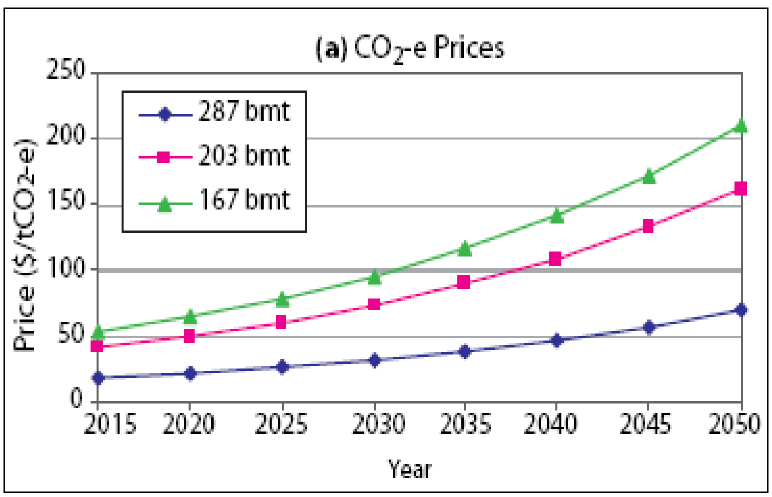
[40] As stated by DOE: "Regulatory uncertainty for GHG legislation is a key issue impacting technology selection and reliability of economic forecasts. Returns on investment for conventional plants, including supercritical, can be severely compromised by the need to subsequently address CO_2 mitigation. Higher capital costs incurred for IGCC may make such new plants less competitive unless their advantage in CO_2 mitigation is assured." DOE National Energy Technology Laboratory, *Tracking New Coal-fired Power Plants* (June 30, 2008), p. 14.

[41] Citi, Morgan Chase, and Morgan Stanley, *The Carbon Principles: Fossil Fuel Generation Financing Enhanced Environmental Diligence Process* (February 2008), p. 1.

carbon emissions or regulations requiring their reduction.[42] All estimates of value are hypothetical—dependent on a reduction program or regulatory regime that doesn't exist. With no market or regulatory signals determining appropriate performance standards and cost-effectiveness criteria, investment in carbon capture technology is a risky business that could easily result in the development of a "white elephant" or "gold-plated" technology that doesn't meet market demand.

While the "threat" of a carbon regime is stimulating RD&D efforts and influencing decisions about future energy (particularly electricity) supply, the current spread of greenhouse gas control regimes being proposed doesn't provide much guidance in suggesting appropriate performance and cost-effectiveness benchmarks for a solution with respect to coal-fired generation. For example, isolating just one variable in the future price of carbon under a cap-and-trade program—tonnage reduction requirement—the future value of carbon reductions can vary substantially.[43] As illustrated by **Figure 6**, three possible reduction targets in 2050—maintaining current 2008 levels (287 billion metric tons [bmt]), reducing emissions to 50% of 1990 levels (203 bmt), and reducing emissions to 20% of 1990 levels (167 bmt)—result in substantially different price tracks for CO_2.[44] Without a firm idea of the tonnage goal and reduction schedule, any deployment or commercialization strategy would be a high-risk venture, as suggested by the previously noted Virginia State Corporation Commission conclusion.

Figure 6. CO_2 Price Projections



Source: Segey Paltsev, et al., *Assessment of U.S. Cap-and-Trade Proposals*, MIT Joint Program on the Science and Policy of Global Change, Report 146 (April 2007), p. 16. For details on the analysis presented here, consult the report. Available at http://mit.edu/globalchange.

Note: CO_2e = carbon dioxide equivalent

[42] Exceptions to this would include areas where the carbon dioxide could be used for EOR, or where a state or region has enacted greenhouse gas controls, such as California and several northeastern states.

[43] For a fuller discussion of the uncertainties involved in estimating the cost of cap-and-trade programs, see CRS Report RL34489, *Climate Change: Costs and Benefits of S. 2191/S. 3036*, by Larry Parker and Brent D. Yacobucci.

[44] Segey Paltsev, et al., *Assessment of U.S. Cap-and-Trade Proposals*, MIT Joint Program on the Science and Policy of Global Change, Report 146 (April 2007), p. 16.

Approaches to a Demand-Pull Mechanism

There are two basic approaches to a demand-pull mechanism: (1) a regulatory requirement, and (2) a price signal via a market-based CO_2 reduction program. These approaches are not mutually exclusive and can serve different goals. For example, a regulation focused on new construction (such as the New Source Performance Standard under Section 111 of the Clean Air Act[45]) could be used to phase in deployment of carbon capture technology and prevent more coal-fired facilities from being constructed without carbon capture (or ensure they would be at least "ready" for carbon capture later). At the same time, a carbon tax or cap-and-trade program could be initiated to begin sending a market signal to companies that further controls will be necessary in the future if they decide to continue operating coal-fired facilities.

Creating Demand Through a Regulatory Requirement: An Example from the SO_2 New Source Performance Standards

> It is an understatement to say that the new source performance standards promulgated by the EPA were technology-forcing. Electric utilities went from having no scrubbers on their generating units to incorporating very complex chemical processes. Chemical plants and refineries had scrubbing systems that were a few feet in diameter, but not the 30- to 40-foot diameters required by the utility industry. Utilities had dealt with hot flue gases, but not with saturated flue gases that contained all sorts of contaminants. Industry, and the US EPA, has always looked upon new source performance standards as technology-forcing, because they force the development of new technologies in order to satisfy emissions requirements.[46]

The most direct method to encourage adoption of carbon capture technology would be to mandate it. Mandating a performance standard on coal-fired power plants is not a new idea; indeed, Section 111 of the Clean Air Act requires the Environmental Protection Agency (EPA) to develop New Source Performance Standards (NSPS) for any new and modified power plant (and other stationary sources) that in the Administrator's judgment "causes, or contributes significantly to, air pollution which may reasonably be anticipated to endanger public heath or welfare." NSPS can be issued for pollutants for which there is no National Ambient Air Quality Standard (NAAQS), like carbon dioxide.[47] In addition, NSPS is the floor for other stationary source standards such as Best Available Control Technology (BACT) determinations for Prevention of Significant Deterioration (PSD) areas and Lowest Achievable Emission Rate (LAER) determinations for non-attainment areas.[48]

The process of forcing the development of emission controls on coal-fired power plants is illustrated by the 1971 and 1978 SO_2 NSPS for coal-fired electric generating plants. The Clean Air Act states that NSPS should reflect "the degree of emission limitation achievable through the

[45] The Clean Air Act, Section 111 (42 U.S.C. 7411).

[46] Donald Shattuck, et al., *A History of Flue Gas Desulfurization (FGD)—The Early Years*, UE Technical Paper (June 2007), p. 3.

[47] For a fuller discussion of EPA authority to regulate greenhouse gases under the Clean Air Act, see Robert J. Meyer, Principal Deputy Assistant Administrator, Office of Air and Radiation, EPA Testimony before the Subcommittee on Energy and Air Quality, Committee on Energy and Commerce, U.S. House of Representation (April 10, 2008).

[48] For a discussion of the structure of the Clean Air Act, see CRS Report RL30853, *Clean Air Act: A Summary of the Act and Its Major Requirements*, by James E. McCarthy et al.

application of the best system of emission reduction which (taking into account the cost of achieving such reductions and any non-air quality health and environmental impact and energy requirements) the Administrator determines has been adequately demonstrated."[49] In promulgating its first utility SO_2 NSPS in 1971, EPA determined that a 1.2 pound of SO_2 per million Btu of heat input performance standard met the criteria of Sec. 111—a standard that required, on average, a 70% reduction in new power plant emissions, and could be met by low-sulfur coal that was available in both the eastern and western parts of the United States, or by the use of emerging flue gas desulfurization (FGD) devices.[50]

At the time the 1971 Utility SO_2 NSPS was promulgated, there was only one FGD vendor (Combustion Engineering) and only three commercial FGD units in operation—one of which would be retired by the end of the year.[51] This number would increase rapidly, not only because of the NSPS, but also because of the promulgation of the SO_2 NAAQS, the 1973 Supreme Court decision preventing significant deterioration of pristine areas,[52] and state requirements for stringent SO_2 controls, which opened up a market for retrofits of existing coal-fired facilities in addition to the NSPS focus on new facilities. Indeed, most of the growth in FGD installations during the early and mid-1970s was in retrofits—Taylor estimates that between 1973 and 1976, 72% of the FGD market was in retrofits.[53] By 1977, there were 14 vendors offering full-scale commercial FGD installation.[54]

Despite this growth, only 10% of the new coal-fired facilities constructed between 1973 and 1976 had FGD installations. In addition, the early performance of these devices was not brilliant.[55] In 1974, American Electric Power (AEP) spearheaded an ad campaign to have EPA reject FGD devices as "too unreliable, too impractical for electric utility use" in favor of tall stacks, supplementary controls, and low-sulfur western coal.[56] This effort was ultimately unsuccessful as the Congress chose to modify the NSPS requirements for coal-fired electric generators in 1977 by adding a "percentage reduction" requirement. As promulgated in 1979, the revised SO_2 NSPS retained the 1971 performance standard but added a requirement for a 70%-90% reduction in emissions, depending on the sulfur content of the coal.[57] At the time, this requirement could be met only through use of an FGD device. The effect of the "scrubber requirement" is clear from the data provided in **Figure 7**. Based on their analysis of FGD development, Taylor, Rubin, and Hounshell state the importance of demand-pull instruments:

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[49] 42 U.S.C. 7411, Clean Air Act, Sec. 111(a)(1)

[50] 40 CFR 60.40-46, Subpart D—Standards of Performance for Fossil-Fuel-Fired Steam Generator for Which Construction is Commenced After August 17, 1971.

[51] Margaret R. Taylor, *The Influence of Government Actions on Innovative Activities in the Development of Environmental Technologies to Control Sulfur Dioxide Emissions from Stationary Sources*, Thesis, Carnegie Institute of Technology (January 2001), p. 37, 40.

[52] Fri v. Sierra Club, 412 US 541 (l973). This decision resulted in EPA issuing "prevention of significant deterioration" regulations in 1974; regulations what were mostly codified in the 1977 Clean Air Amendment (Part C).

[53] Taylor, ibid., p. 37.

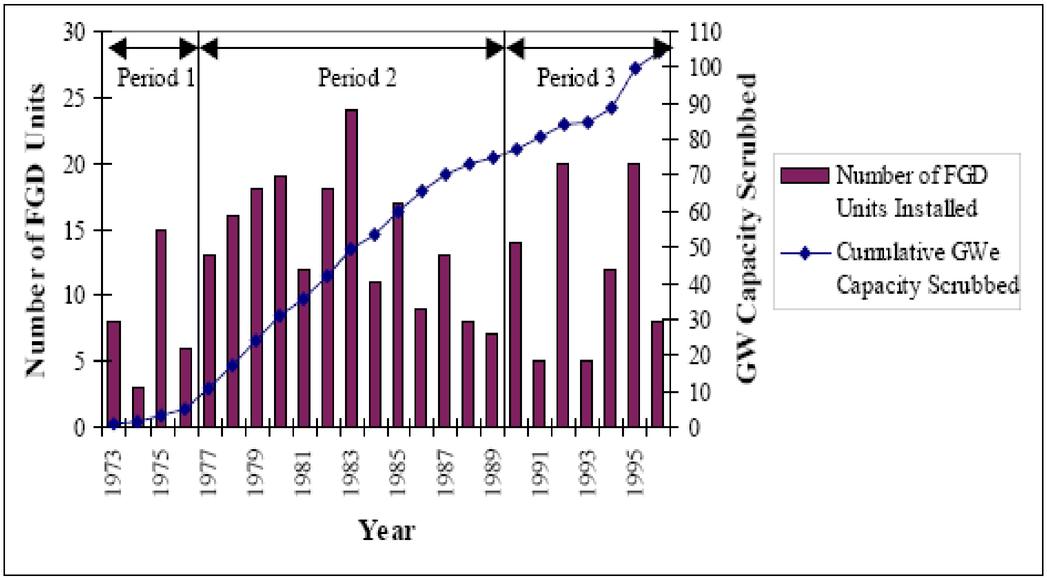
[54] Taylor, ibid., p. 39.

[55] For a discussion of challenges arising from the early development of FGD, see Donald Shattuck, et al., *A History of Flue Gas Desulfurization (FGD)—The Early Years*, UE Technical Paper (June 2007).

[56] Examples include full-page ads in the Washington Post entitled "Requiem for Scrubbers," "Scrubbers, Described, Examined and Rejected," and "Amen." For an example, see Washington Post, p. A32 (October 25, 1974).

[57] 40 CFR 60.40Da-52Da, Subpart Da—Standards of Performance for Electric Utility Stream Generating Units for Which Construction is Commenced After September 18, 1978.

Figure 7. Number of FGD Units and Cumulative GW Capacity of FGD Units: 1973-1996



Source: Adapted by Taylor from Soud (1994). See Margaret R. Taylor, op. cit., 74.

Note: Numbers are archival through June 1994, then projected for 1994-96.

> Results indicate that: regulation and the anticipation of regulation stimulate invention; technology-push instruments appear to be less effective at prompting invention than demand-pull instruments; and regulatory stringency focuses inventive activity along certain technology pathways.[58]

That government policy could force the development of a technology through creating a market should not suggest that the government was limited to that role, or that the process was smooth or seamless. On the latter point, Shattuck, et al., summarize the early years of FGD development as follows:

> The Standards of Performance for New Sources are technology-forcing, and for the utility industry they forced the development of a technology that had never been installed on facilities the size of utility plants. That technology had to be developed, and a number of installations completed in a short period of time. The US EPA continued to force technology through the promulgation of successive regulations. The development of the equipment was not an easy process. What may have appeared to be the simple application of an equipment item from one industry to another often turned out to be fraught with unforeseen challenges.[59]

The example indicates that technology-forcing regulations can be effective in pulling technology into the market—even when there remains some operational difficulties for that technology. The difference for carbon capture technology is that for long-term widespread development, a new infrastructure of pipelines and storage sites may be necessary in addition to effective carbon

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[58] Margaret R. Taylor, Edward S. Rubin, and David A. Hounshell, "Control of SO_2 Emissions from Power Plants: A Case of Induced Technological Innovation in the U.S.," *Technological Forecasting & Social Change* (July 2005), p. 697.

[59] Shattuck, et. al., p. 15.

capture technology. In the short-term, suitable alternatives, such as enhanced oil recovery needs and in-situ geologic storage, may be available to support early commercialization projects without the need for an integrated transport and storage system. Likewise, with economics more favorable for new facilities than for retrofits, concentrating on using new construction to introduce carbon capture technology might be one path to widespread commercialization. As an entry point to carbon capture deployment, a regulatory approach such as NSPS may represent a first step, as suggested by the SO_2 NSPS example above.

Creating Demand Through a Price Signal: Carbon Taxes, Allowance Pricing, and Auctions

Much of the current discussion of developing a market-pull mechanism for new carbon capture technology has focused on creating a price for carbon emissions. The literature suggests that this is an important component for developing new technology, perhaps more important even than research and development. As stated by the Congressional Budget Office (CBO):

> Analyses that consider the costs and benefits of both carbon pricing and R&D all come to the same qualitative conclusion: near-term pricing of carbon emissions is an element of a cost-effective policy approach. That result holds even though studies make different assumptions about the availability of alternative energy technologies, the amount of crowding out caused by federal subsidies, and the form of the policy target (maximizing net benefits versus minimizing the cost of reaching a target).[60]

Two basic approaches can be employed in the case of a market-based greenhouse gas control program: a carbon tax and a cap-and-trade program. The carbon tax would create a long-term price signal to stimulate innovation and development of new technology. This price signal could be strengthened if the carbon tax were escalated over the long run—either by a statutorily determined percentage or by an index (such as the producer price index). A carbon tax's basic approach to controlling greenhouse gas emissions is to supply the marketplace with a stable, consistent price signal—a signal that would also inform innovators as to the cost performance targets they should seek in developing alternative technologies. Designed appropriately, there would be little danger of the price spikes or market volatility that can occur in the early stages of a tradeable permit program.[61]

A cap-and-trade program creates a price signal for new technology through a market price for carbon permits (called allowances)—an allowance is a limited authorization to emit one metric ton of carbon dioxide equivalent (CO_2e). In a cap-and-trade system, these allowances are issued by the government and either allocated or auctioned to affected companies who may use them to comply with the cap, sell them to other companies on the market, or bank them for future use or sale. The resulting market transactions result in an allowance price. This price on carbon emissions, however, can be both uncertain and volatile.[62] In addition, a low allowance price may be insufficient to encourage technology development and refinement. For example, the 1990 acid

[60] Congressional Budget Office, *Evaluating the Roles of Prices and R&D in Reducing Carbon Dioxide Emissions* (September 2006), p. 17.

[61] In addition, some of the revenue generated by the tax could be used to fund research, development, demonstration, and deployment of new technology to encourage the long-term transition to a less-carbon-intensive economy.

[62] For a fuller discussion, see CRS Report RL30853, *Clean Air Act: A Summary of the Act and Its Major Requirements*, by James E. McCarthy et al.

rain control program effectively ended the development of FGD for retrofit purposes by setting an emission cap that resulted in low allowance prices and that could be met through the use of low-sulfur coal. Noting that only 10% of phase 1 facilities chose FGD to comply with its requirements, Taylor, et al., state:

> The 1990 CAAA, however, although initially predicted to increase demand for FGD systems, eroded the market potential for both dry and wet FGD system applications at existing power plants when the SO_2 allowance trading market returned low-sulfur coal to its importance in SO_2 control.... As a result, research in dry FGD technology declined significantly. In this case, the flexibility provided by the 1990 acid rain regulations discouraged inventive activity in technologies that might have had broader markets under the traditional command-and-control regimes in place prior to 1990.[63] [footnotes from original text omitted]

A cap-and-trade program need not have such a result. For example, to more effectively promote carbon capture technology, the price signal under a greenhouse gas reduction program could be strengthened by requiring the periodic auctioning of a substantial portion of available allowances rather than giving them away at no cost. The SO_2 program allocated virtually all of its allowance at no cost to affected companies. Auctioning a substantial portion of available allowances could create a powerful price signal and provide incentives for deploying new technology if structured properly.[64] The program could create a price floor to facilitate investment in new technology via a reserve price in the allowance auction process. In addition, the stability of that price signal could be strengthened by choosing to auction allowances on a frequent basis, ensuring availability of allowances close to the time of expected demand and making any potential short-squeezing of the secondary market more difficult.[65]

One positive aspect of the acid rain cap-and-trade experience for encouraging deployment of technology was the effectiveness of "bonus" allowances and deadline extensions as incentives to install FGD. Specifically, about 3.5 million of the allowances were earmarked for Phase 1 power plants choosing to install 90% control technology (such as FGD). Such units were allowed to delay Phase 1 compliance from 1995 to 1997 and receive two allowances for each ton of S02 reduced below a 1.2 lb. per mmBtu level during 1997-1999. The 3.5 million allowance reserve was fully subscribed, and was a major factor in what FGD was installed during Phase 1 of the program. This experience may bode well for proposed CCS "bonus allowance" provisions in several greenhouse gas reduction schemes currently introduced in the Congress.[66]

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[63] Margaret R. Taylor, Edward S. Rubin, and David A. Hounshell, "Effect of Government Actions on Technological Innovation for SO_2 Control," *Environmental Science & Technology* (October 15, 2003), p. 4531. In a more recent article, the authors state: "Finally, the case provides little evidence for the claim that cap-and-trade instruments induce innovation more effectively than other instruments." Margaret R. Taylor, Edward S. Rubin, and David A. Hounshell, "Control of SO_2 Emissions from Power Plants: A Case of Induced Technological Innovation in the U.S.," *Technological Forecasting & Social Change* (July 2005), p. 697-8.

[64] Like a carbon tax, the revenues received could be at least partly directed toward research, development, and demonstration programs.

[65] Karsten Neuhoff, *Auctions for CO_2 Allowances—A Straw Man Proposal*, University of Cambridge Electricity Policy Research Group (May 2007), pp. 3-6. A short-squeeze is a situation where the price of a stock or commodity rises and investors who sold short (believing the price was going to fall) rush to buy it to cover their short position and cut their losses.

[66] For more information on the emission allowance schemes for CCS in legislation, see CRS Report R40867, *Carbon Capture and Sequestration in H.R. 2454 and S. 1733*, by Peter Folger, Mary Tiemann, and Stan Mark Kaplan.

Current Technology-Push Mechanisms: DOE Investment in CCS R&D

The Department of Energy (DOE) is engaged in a variety of activities to push development and demonstration of carbon capture technologies. These activities include direct spending on research and development, and providing loan guarantees and tax credits to promote carbon capture projects. These technology-push incentives, and the issues they raise, are discussed below.

Direct Spending on R&D

The federal government has recognized the potential need for carbon capture technology—as part of broader efforts to address greenhouse-gas induced climate change—since at least 1997, when DOE spent approximately $1 million for the entire CCS program.[67] **Table 3** shows that DOE programs that provide funding for CCS-related activities totaled nearly $575 million for FY2009, a significant increase since 1997.[68] Funding for CCS R&D increased by nearly 58% from FY2008 to FY2009. **Table 3** also shows that funding appears to have decreased for CCS R&D in FY2010 as compared to FY2009, and the request for FY2011 is slightly lower than the FY2010 amounts. However, funding from P.L. 111-5, the American Recovery and Reinvestment Act of 2009 (ARRA, shown in the last column of the table), increases *overall* spending for CCS dramatically compared to previous years.

DOE indicated in its FY2011 budget request that its Office of Fossil Energy will propose a new budget structure for FY2012 to reflect the increased focus on CCS technologies within the DOE Clean Coal program. The FY2011 budget request further stated that research, development, and deployment of CCS is a major component of global activities needed if coal power plants with CCS are to be deployed "in a timeframe consistent with climate stabilization goals."[69] DOE indicated that these activities may lead to mass commercial deployment of CCS by 2020.[70]

Table 3. Funding for CCS-Related Activities at DOE

($ thousands)

	FY2008	FY2009	FY2010	FY2011 request	ARRA
Clean Coal Power Initiative (CCPI)[a]	67,444	288,174	0	0	800,000
FutureGen[b]	72,262	0	0	0	1,000,000
Innovation for Existing Plants (IEP)[c]	35,083	48,600	52,000	65,000	—
Advanced Integrated Gasification Combined Cycle[d]	52,029	63,409	63,000	55,000	—

[67] Personal communication, Timothy E. Fout, General Engineer, DOE National Energy Technology Laboratory, Morgantown, WV (July 16, 2008).

[68] Funding for FY2009 is according to U.S. Department of Energy, *FY2011 Congressional Budget Request*, volume 3, Fossil Energy Research and Development, at http://www.cfo.doe.gov/budget/11budget/Content/Volume%203.pdf.

[69] DOE FY2011 Congressional Budget Request, p. 649, at http://www.cfo.doe.gov/budget/11budget/Content/Volume%203.pdf.

[70] Ibid.

	FY2008	FY2009	FY2010	FY2011 request	ARRA
Advanced Turbines[e]	23,125	27,216	32,000	31,000	—
Industrial Carbon Capture Projects	—	—			1,520,000
Site Characterization, Training, Program Direction	—	—			80,000
Subtotal	249,943	427,399	147,000	151,000	3,400,000
Carbon Sequestration Greenhouse Gas Control	105,985	132,192	140,000	133,000	—
Carbon Sequestration Energy Innovation Hub	0	0	0		—
Carbon Sequestration Focus Area for Carbon Sequestration Science	9,635	13,608	14,000	10,000	—
Subtotal for Carbon Sequestration	115,620	145,800	154,000	143,000	—
Total	365,563	573,199	301,000	294,000	3,400,000

Source: CRS, from the U.S. Department of Energy, FY2011 *Congressional Budget Request*, volume 3, Fossil Energy Research and Development, at http://www.cfo.doe.gov/budget/11budget/Content/Volume%203.pdf; and U.S. Department of Energy, FY2010 *Congressional Budget Request*, volume 7, Fossil Energy Research and Development, at http://www.cfo.doe.gov/budget/10budget/Content/Volumes/Volume7.pdf.

Notes: Overall FY2010 Fossil Energy Research appropriations are included in CRS Report R40669, *Energy and Water Development: FY2010 Appropriations*.

a. The FY2011 budget request does not include any funds for CCPI demonstration projects because $800 million is already provided by ARRA (P.L. 111-5) for Phase III of the CCPI program.

b. Language in ARRA indicated that $1 billion would be allocated for Fossil Energy R&D. On June 12, 2009, Secretary Chu announced that the funds would be used to support FutureGen.

c. In its FY2011 budget request, DOE indicates that all the IEP activity is focused on the development of post-combustion CO_2 capture technology for new and existing plants.

d. According to DOE, the IGCC activity is focused on developing advanced gasification-based technologies to reduce the costs of near-zero emissions (including CO_2) coal-based IGCC plants. The program is also intended to improve the thermal efficiency of the plants, and to achieve near-zero atmospheric emissions for all pollutants, including CO_2, SO_2, NOx, and mercury.

e. The Advanced Turbines program is focused on creating the technology base for turbines that will permit the design of near-zero atmospheric emission IGCC plants (including CO_2).

Carbon Capture and Sequestration in the American Recovery and Reinvestment Act of 2009 (ARRA)

Funding for carbon capture and sequestration technology has increased substantially as a result of enactment of ARRA (P.L. 111-5). In the compromise legislation considered in conference on February 11, 2009, the conferees agreed to provide $3.4 billion through FY2010 for fossil energy research and development within the Department of Energy (DOE). Of that amount, $1.52 billion would be made available for a competitive solicitation for industrial carbon capture and energy efficiency improvement projects, according to the explanatory statement accompanying the legislation. This provision likely refers to a program for large scale demonstration projects that capture CO_2 from a range of industrial sources. A small portion of the $1.52 billion would be allocated for developing innovative concepts for reusing CO_2, according to the explanatory statement. Of the remaining $1.88 billion, $1 billion would be available for fossil energy research and development programs. The explanatory statement did not specify which program or programs would receive funding, however, or how the $1 billion would be allocated. However, on

June 12, 2009, Energy Secretary Chu announced that the $1 billion would be used to support a renewed FutureGen facility in Mattoon, IL. Of the remaining $880 million, the conferees agreed to allocate $800 million to the DOE Clean Coal Power Initiative Round III solicitations, which specifically target coal-based systems that capture and sequester, or reuse, CO_2 emissions. Lastly, $50 million would be allocated for site characterization activities in geologic formations (for the storage component of CCS activities), $20 million for geologic sequestration training and research, and $10 million for unspecified program activities.

With the announcement that $1 billion of the ARRA funds would be used to restart FutureGen, nearly all of the $3.4 billion agreed to by conferees will be used for CCS activities, which represents a substantial infusion of funding compared to current spending levels. This also amounts to a large and rapid increase in funding over what DOE has spent on CCS *cumulatively* since FY1997.[71] Moreover, the bulk of DOE's CCS program will shift to the capture component of CCS, unless funding for the storage component increases commensurately in annual appropriations. The large and rapid increase in funding, compared to the magnitude and pace of previous CCS spending, may raise questions about the efficacy of a "crash" CCS program as part of a long-term strategy to reduce CO_2 emissions. This issue is discussed further below.

Loan Guarantees and Tax Credits

Appropriations represent one mechanism for funding carbon capture technology R&D and deployment; others include loan guarantees and tax credits, both of which are available under current law.

Loan Guarantees

Loan guarantee incentives that could be applied to CCS were authorized under Title XVII of the Energy Policy Act of 2005 (EPAct2005, P.L. 109-58, 42 U.S.C. §§16511-16514), and were given indefinite authorization under the Omnibus Appropriations Act, 2009 (P.L. 111-8). Title XVII of EPAct2005 authorizes the Secretary of Energy to make loan guarantees for projects that, among other purposes, avoid, reduce, or sequester air pollutants or anthropogenic emissions of greenhouse gases. The Omnibus Appropriations Act for FY2009 restates the loan guarantee authority and provides $6 billion in loan guarantees for coal-based power generation and industrial gasification activities at retrofitted and new facilities that incorporate CCS or other beneficial uses of carbon. The act provides an additional $2 billion in loan guarantees for advanced coal gasification.[72]

Tax Credits

Title XIII of EPAct2005 provided for tax credits that could be used for Integrated Gasification Combined Cycle (IGCC) projects and for projects that use other advanced coal-based generation technologies (ACBGT). For these types of projects, the aggregate credits available under EPAct2005 totaled up to $1.3 billion: $800 million for IGCC projects, and $500 million for

[71] Approximately $1.4 billion through FY2009 (CRS estimate).

[72] U.S. Congress, House Committee on Appropriations, *Omnibus Appropriations Act, 2009, Division C—Energy and Water Development and Related Agencies Appropriations Act, 2009*, committee print, 111th Cong., 1st sess., March 11, 2009, p. 672.

ACBGT projects. Qualifying projects under Title XIII of EPAct2005 were not limited to technologies that employ carbon capture technologies, but the Secretary of the Treasury was directed to give high priority to projects that include greenhouse gas capture capability. An additional $350 million of tax credits were made available for coal gasification projects.

Sections 111 and 112 of P.L. 110-343, Division B, the Energy Improvement and Extension Act of 2008 (part of the Emergency Economic Stabilization Act of 2008), increased the aggregate tax credits available from $1.65 billion to $3.15 billion. Section 111 added an additional $1.25 billion to the existing tax credit authority for ACBGT projects. Section 112 added an additional $250 million to $350 million in existing authority for the coal gasification investment credit, for gasification projects that separate and sequester at least 75% of the project's total CO_2 emissions.

Section 115 of the act added a new tax credit for sequestering CO_2 and storing it underground. The section provides for a credit of $20 per metric ton of CO_2 captured at a qualified facility and disposed of in secure geological storage, and $10 per metric ton if the CO_2 is used as a tertiary injectant for the purposes of enhanced oil or natural gas recovery. To qualify for the tax credit, the facility must capture at least 500,000 metric tons of CO_2 per year. If CO_2 is used for enhanced oil or gas recovery, a tax credit would be available only for an initial injection; CO_2 subsequently recaptured, recycled, and re-injected would not be eligible for a tax credit.

Encouraging Technology Development in the Absence of a Market: Issues for Current Carbon Capture RD&D Policy

Each of the funding mechanisms described above—appropriations, loan guarantees, and tax credits—are examples of government "pushing" carbon capture technologies (the upper left arrow in **Figure 5**) via direct spending and through private sector incentives. Thus far, however, these activities are taking place in a vacuum with respect to a carbon market or a regulatory structure. Lacking a price signal or regulatory mandate, it is difficult to assess whether a government-push approach is sufficient for long-term technology development.[73] Some studies appear to discount the necessity of a price signal or regulatory mandate, at least initially, and place a higher priority on the successful demonstration of large-scale technological, economic, and environmental performance of technologies that comprise all of the components of an integrated CCS system: capture, transportation, and storage.[74] So far, however, the only federally sponsored, fully integrated, large-scale CCS demonstration project—called FutureGen (see box below)—failed in its original conception, which may have been due, in part, to the lack of a perceived market.

DOE announced it was restructuring the FutureGen program because of its rising costs, which are difficult to assess against the project's "benefits" without a monetary value attached to those benefits (i.e., the value of carbon extracted from the fuel and permanently sequestered). A carbon market would at least provide some way of comparing costs against benefits. One could argue

[73] See quote by Morgenstern above. In that analysis, government-supported research is needed to compensate for market imperfections. In the current situation, there is no market, and thus its imperfections are moot.

[74] MIT, *The Future of Coal*, p. xi.

that the benefits of CCS accrue to the amelioration of future costs of environmental degradation caused by greenhouse gas-induced global warming. Although it may be possible to identify overall environmental benefits to removing CO_2 that would otherwise be released to the atmosphere, assigning a monetary value to those benefits to compare against costs is extremely difficult.

Trying to Pick a Winner: FutureGen

On February 27, 2003, President Bush proposed a 10-year, $1 billion project to build a coal-fired power plant that integrates carbon sequestration and hydrogen production while generating 275 megawatts of electricity, enough to power about 150,000 average U.S. homes. As originally conceived, the plant would have been a coal-gasification facility and would have produced between 1 and 2 million metric tons of CO_2 annually. The plant was envisioned to be nearly emissions-free because most of the CO_2 produced would be captured and sequestered underground. On January 30, 2008, DOE announced that it was "restructuring" the FutureGen program away from a single, state-of-the-art "living laboratory" of integrated R&D technologies—a single plant—to instead pursue a new strategy of providing funding for the addition of CCS technology to multiple commercial-scale Integrated Gasification Combined Cycle (IGCC) power plants. In the restructured program, DOE would support up to two or three demonstration projects, each of at least 300 MW, and that would sequester at least 1 million metric tons of CO_2 per year. In its budget justification for FY2009, DOE cited "new market realities" for its decision, namely rising material and labor costs for new power plants and the need to demonstrate commercial viability of IGCC plants with CCS. A policy question that emerged following the DOE's decision to scrap the original FutureGen concept was whether such a concept can be viable without a long-term price signal for carbon. FutureGen supporters have indicated that the rise in FutureGen's projected costs were consistent with the rise in global energy infrastructure projects due to inflation, implying that rising costs are not unique to FutureGen. Nevertheless, the reasons given by DOE in its decision to cancel the original concept are *prima facie* evidence that lack of a price signal for carbon in the face of known and rising costs for plant construction created too much uncertainty for the agency to continue the project. It is unclear whether a long-term price signal would have supported the FutureGen concept anyway, given the project's other uncertainties, such as its choice of a capture technology and disagreements over the private cost-share agreement.

With the passage of ARRA, however, FutureGen was revived. On June 12, 2009, Secretary Chu announced that the $1 billion of funding from ARRA will be used to support FutureGen, and that the plant will be built in Mattoon, IL, the site selected by the FutureGen Alliance in 2007. According to DOE, its total anticipated contribution to FutureGen will be $1.073 billion, and the FutureGen Alliance will contribute between $400 and $600 million to the project. On July 14, 2009, DOE issued a National Environmental Policy Act record of decision to move forward on FutureGen. Some reports indicate that the newly revived plans for FutureGen call for an initial carbon capture goal of 60% for the facility, with the ultimate goal of achieving a 90% capture rate—the target set in the project's original conception. Some environmental groups have expressed views that the lower capture rate may put FutureGen in the same category as other CCS commercialization projects, calling into question the status of FutureGen as a "flagship facility to demonstrate carbon capture and storage at commercial scale."

Sources: DOE, http://www.fossil.energy.gov/news/techlines/2008/08003-DOE_Announces_Restructured_FutureG.htm; DOE FY2009 Budget request, p. 16; FutureGen Alliance press release (April 15, 2008), http://www.futuregenalliance.org/news/releases/pr_04-15-08.stm; Ben Geman, "Enviros Fault Scaled-Back FutureGen Carbon Goal," *Greenwire*, June 16, 2009; Secretary Chu's announcement on FutureGen at http://www.energy.gov/news2009/7454.htm; Michael T. Burr, "Death of a Turkey, DOE's Move to 'Restructure' FutureGen Clears the Way for a More Rational R&D," Public Utilities Fortnightly (March 2008); and David Goldston, "Demonstrably Wrong," *Nature*, vol. 453, no. 16 (April 30, 2008), p. 16.

What Should the Federal Government Spend on CCS Technology Development?

As discussed above, several studies underscore the value of a long-term price or regulatory signal to shape technological development and, presumably, to help determine a level of federal investment needed to encourage commercialization of an environmental technology such as carbon capture. As stated by Fischer:

> With respect to R&D for specific applications (such as particular manufacturing technologies or electricity generation), governments are notoriously bad at picking winners... [e.g., the breeder reactor]. The selection of these projects is best left to private markets while the government ensures those markets face the socially correct price signals.[75]

Despite the lack of regulatory incentives or price signals, DOE has invested millions of dollars since 1997 into capture technology R&D, and the question remains whether it has been too much, too little, or about the right amount. In addition to appropriating funds each year for the DOE program, Congress signaled its support for RD&D investment for CCS through provisions for tax credits available for carbon capture technology projects and through loan guarantees. Congress also authorized a significant expansion of CCS spending at DOE in the Energy Independence and Security Act of 2007 (EISA, P.L. 110-140), which would authorize appropriations for a total of $2.2 billion from FY2008 through FY2013. Although EISA places an increased emphasis on large-scale underground injection and storage experiments, the legislation authorizes $200 million per year for projects that demonstrate technologies for the large-scale capture of CO_2 from a range of industrial sources. Lastly, ARRA provides a dramatic infusion of funding for CCS RD&D over the next several years.

Legislation in the 110th and 111th Congresses

Legislation introduced in the 110th Congress would have authorized specific amounts of spending for CCS and capture technology development. Notably, the Carbon Capture and Storage Early Deployment Act (H.R. 6258) would have authorized distribution utilities[76] to collect an assessment on fossil-fuel based electricity delivered to retail customers. The assessment would total approximately $1 billion annually, and would be issued by a corporation—established by referendum among the distribution utilities—as grants or contracts to private, academic, or government entities to accelerate commercial demonstration or availability of CO_2 capture and storage technologies and methods. This legislation contained elements that resembled, in many respects, recommendations offered in the MIT report.[77] Hearings were held, but the measure was not reported out of committee.

Other bills introduced in the 110th Congress included incentives such as tax credits, debt financing, and regulations to promote CO_2 capture technology development. For example, S. 3132, the Accelerating Carbon Capture and Sequestration Act of 2008, would have provided a tax credit of $20 per metric ton of CO_2 captured and stored.[78] S. 3233, the 21st Century Energy Technology Deployment Act, would have established a corporation that could issue debt instruments (such as bonds) for financing technology development. A priority cited in S. 3233 was the deployment of commercial-scale CO_2 capture and storage technology that could capture 10 million short tons of CO_2 per year by 2015. A bill aimed at increasing the U.S. production of oil and natural gas while minimizing CO_2 emissions, the American Energy Production Act of 2008 (S. 2973), called for the promulgation of regulations for clean, coal-derived fuels. Facilities

[75] Carolyn Fischer, *Climate Change Policy Choices and Technical Innovation*, Resources for the Future Climate Issue Brief #20 (June 2000), p. 9

[76] A distribution utility is defined in the legislation as an electric utility that has a legal, regulatory, or contractual obligation to deliver electricity directly to retail customers.

[77] MIT, *The Future of Coal*, p. 102.

[78] S. 3132 would also provide a $10 per metric ton credit for CO_2 captured and used as a tertiary injectant in an enhanced oil and natural gas recovery project.

that process or refine such fuels would be required to capture 100% of the CO_2 that would otherwise be released at the facility. None of the bills were enacted into law.

In the 111th Congress, H.R. 2454, the American Clean Energy and Security Act of 2009, and S. 1733, the Clean Energy Jobs and American Power Act, are the two primary energy and climate change legislative proposals. H.R. 2454 passed the House on June 26, 2009, and S. 1733 was ordered to be reported by the Senate Environment and Public Works Committee on November 5, 2009. The CCS provisions in both bills are similar (some sections are identical), and both bills appear to share the goal of fostering the commercial development and deployment of CCS projects as an important component of mitigating greenhouse gas emissions. Both bills contain similar provisions that would create a program to accelerate the commercial availability of CO_2 capture and storage technologies and methods by awarding grants, contracts, and financial assistance to electric utilities, academic institutions, and other eligible entities (similar to H.R. 6258 of the 110th Congress, discussed above). Both bills would also create a second program that would distribute emission allowances from the cap-and-trade provisions to qualifying electric generating plants and industrial facilities.[79]

One bill introduced in the 111th Congress, the New Manhattan Project for Energy Independence (H.R. 513), calls for a system of grants and prizes for RD&D on the scale of the original Manhattan project, with a goal of attaining energy independence for the nation. Other legislation introduced in the 110th Congress invoked the symbolism of the Apollo program of the 1960s to frame proposals for large-scale energy policy initiatives that include developing CCS technology.[80] The relevance and utility of large-scale government projects, such as the Apollo program, or the Manhattan project, to developing carbon capture technology are explored in the following sections.

Should the Federal Government Embark on a "Crash" Research and Development Program?

Some policymakers have proposed that the United States invest in energy research, development, and demonstration activities at the same level of commitment as it invested in the past during the Manhattan project and the Apollo program.[81] As analogues to the development of technologies to reduce CO_2 emissions and thwart long-term climate change, the Manhattan project and Apollo program are imperfect at best. They both had short-term goals, their success or failure was easily measured, and perhaps most importantly, they did not depend on the successful commercialization of technology and its adoption by the private sector. Nevertheless, both projects provide a funding history for comparison against CO_2 capture technology cost projections, and as examples of large government-led projects initiated to achieve a national goal. The Manhattan project and Apollo program are discussed briefly below.

[79] For a comparison between both bills, see CRS Report R40867, *Carbon Capture and Sequestration in H.R. 2454 and S. 1733*, by Peter Folger, Mary Tiemann, and Stan Mark Kaplan.

[80] For example, H.R. 2809, the New Apollo Energy Act of 2007; and H.R. 6385, the Apollo Energy Independence Act of 2008.

[81] For more information on this topic, see CRS Report RL34645, *The Manhattan Project, the Apollo Program, and Federal Energy Technology R&D Programs: A Comparative Analysis*, by Deborah D. Stine.

The federal government's efforts to promote energy technology development in response to the energy crisis of the 1970s and early 1980s may be a richer analogy to CO_2 capture technology development than either the Manhattan project or Apollo program. After the first oil crisis in 1973, and with the second oil crisis in the late 1970s, the national priority was to reduce dependence on foreign supplies of energy, particularly crude oil, through a combination of new domestic supplies (e.g., oil shale), energy efficiency technologies, and alternative energy supplies such as solar, among others. The success of these efforts was to have been determined, in part, by the commercialization of energy technologies and alternative energy supplies and their incorporation into American society over the long term. Similarly, many analysts see the development of CCS technology as a necessary step needed over the next several decades or half-century to help alleviate human-induced climate change, which is itself viewed as a global problem for at least the next century or longer. As discussed more fully later, the outcome of the federal government's efforts to promote energy technologies in the 1970s and 1980s may be instructive to current approaches to develop CCS technology.

The Manhattan Project and Apollo Program

The Manhattan project took place from 1942 to 1946.[82] In July 1945, a bomb was successfully tested in New Mexico, and used against Japan at two locations in August 1945. In 1946, the civilian Atomic Energy Commission was established to manage the nation's future atomic activities, and the Manhattan project officially ended. According to one estimate, the Manhattan project cost $2.2 billion from 1942-1946 ($22 billion in 2008 dollars), greater than the original cost and time estimate of approximately $148 million for 1942 to 1944.[83]

The Apollo program encompassed 17 missions including six lunar landings that took place from FY1960 to FY1973.[84] Although preliminary discussions regarding the Apollo program began in 1960, Congress did not decide to fund it until 1961 after the Soviets became the first country to send a human into space. The peak cost for the Apollo program occurred in FY1966 when NASA's total budget was $4.5 billion and its funding for Apollo was $3.0 billion.[85] According to NASA, the total cost of the Apollo program for FY1960-FY1973 was $19.4 billion ($97.9 billion

[82] U.S. Department of Energy, Office of History and Heritage Resources, "The Manhattan Project: An Interactive History," webpage at http://www.cfo.doe.gov/me70/manhattan/1939-1942.htm. F.G. Gosling, *The Manhattan Project: Making the Atomic Bomb*, January 1999 edition (Oak Ridge, TN: Department of Energy).

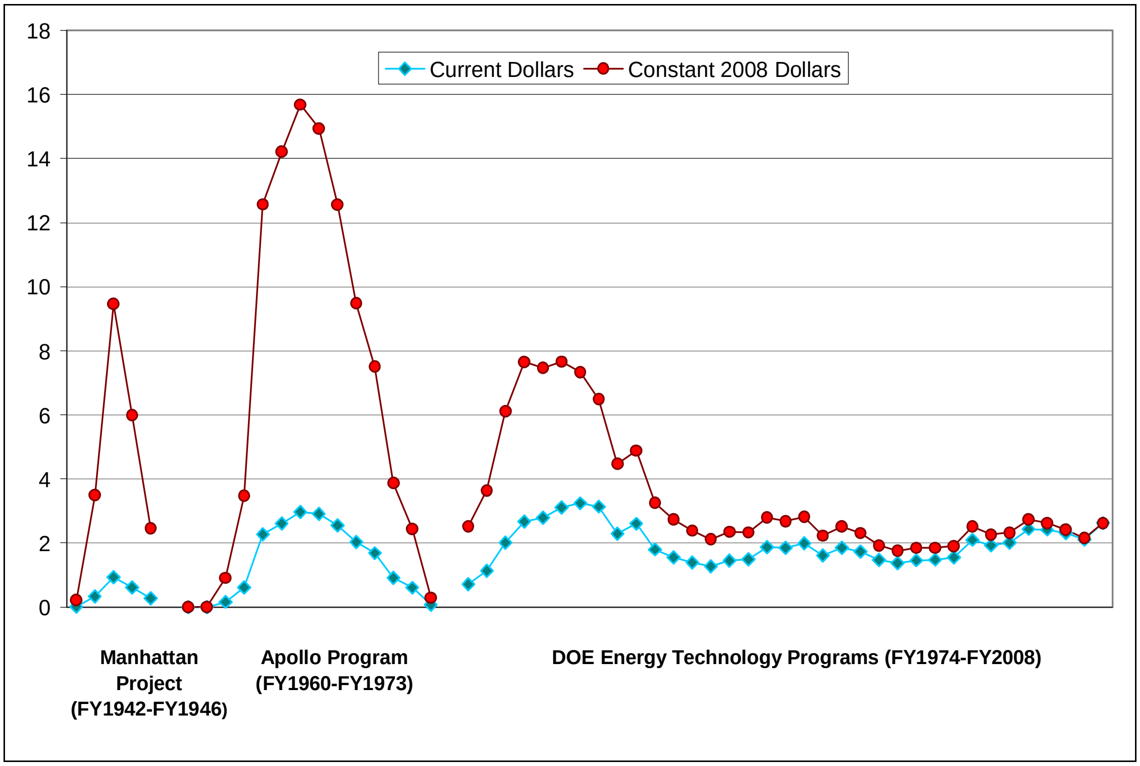
[83] Richard G. Hewlett and Oscar E. Anderson, Jr., A *History of the United States Atomic Energy Commission: The New World, 1939/1946 ,Volume I,* (University Park, PA: The Pennsylvania State University Press, 1962). Appendix 2 provides the annual Manhattan project expenditures. These costs were adjusted to 2007 dollars using the price index for gross domestic product (GDP), available from the Bureau of Economic Affairs, National Income and Product Accounts Table webpage, Table 1.1.4., at http://www.bea.gov/bea/dn/nipaweb/.

[84] There is some difference of opinion regarding what activities comprise the Apollo program, and thus when it begins and ends. Some include the first studies for Apollo, Skylab, and the use of Apollo spacecraft in the Apollo-Soyuz Test Project. This analysis is based on that provided by the National Aeronautics and Space Administration (NASA), which includes the first studies of Apollo, but not Skylab or Soyuz activities, in a 2004 web update by Richard Orloff of its publication entitled *Apollo By The Numbers: A Statistical Reference*, NASA SP-2000-4029, at http://history.nasa.gov/SP-4029/Apollo_00_Welcome.htm.

[85] The funding data is available at http://history.nasa.gov/SP-4214/app2.html#1965. It is based on information in NASA, *The Apollo Spacecraft - A Chronology*, NASA Special Publication-4009, at http://www.hq.nasa.gov/office/pao/History/SP-4009/contents.htm. This data is from Volume 4, Appendix 7 at http://www.hq.nasa.gov/office/pao/History/SP-4009/v4app7.htm.

in 2008 dollars).[86] The first lunar landing took place in July 1969. The last occurred in December 1972. **Figure 8** shows the funding history for both the Manhattan project and Apollo program.

Figure 8. Annual Funding for the Manhattan Project, Apollo Program, and DOE Energy Technology Programs



Source: Congressional Research Service. Manhattan Project data: Richard G. Hewlett and Oscar E. Anderson, Jr., A *History of the United States Atomic Energy Commission: The New World, 1939/1946, Volume I*. Apollo program data: Richard Orloff, *Apollo By The Numbers: A Statistical Reference*, NASA SP-2000-4029, 2004 web update. DOE data: CRS Report RS22858, *Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, and Energy Efficiency R&D*, by Fred Sissine.

DOE-Supported Energy Technology Development

The Department of Energy has its origins in the Manhattan project,[87] and became a Cabinet-level department in 1977,[88] partly in response to the first oil crisis of 1973, caused in part by the Arab oil embargo. Another oil crisis (the "second" oil crisis) took place from 1978-1981 as a result of political revolution in Iran. Funding for DOE energy R&D rose in the 1970s in concert with high oil prices and resultant Carter Administration priorities on conservation and development of

[86] Richard Orloff, *Apollo By The Numbers: A Statistical Reference*, NASA SP-2000-4029, 2004 web update, at http://history.nasa.gov/SP-4029/Apollo_00_Welcome.htm. The funding data is available at http://history.nasa.gov/SP-4029/Apollo_18-16_Apollo_Program_Budget_Appropriations.htm. It is based on information in NASA, *The Apollo Spacecraft - A Chronology*, NASA Special Publication-4009, at http://www.hq.nasa.gov/office/pao/History/SP-4009/contents.htm.

[87] Department of Energy, "Origins & Evolution of the Department of Energy," webpage at http://www.doe.gov/about/origins.htm.

[88] The Department of Energy Organization Act of 1977 (P.L. 95-91).

alternative energy supplies. Crude oil prices fell during the 1980s and the Reagan Administration eliminated many energy R&D programs that began during the oil crisis years. **Figure 8** shows the rise and fall of funding for DOE energy technology programs from 1974 to 2008.

Comparisons to CO_2 Capture R&D at DOE

Current DOE spending on CCS technology development (discussed above) is far below levels of funding for the Manhattan project and Apollo program and for the energy technology R&D programs at their peak spending in the late 1970s and early 1980s. The development of CO_2 capture technology is, of course, only one component of all federal spending on global climate change mitigation. However, the total annual federal expenditures on climate change, including basic research, are still far less than the Manhattan project and Apollo program, although similar to DOE energy technology development programs during their peak spending period.[89] For comparison, the FY2008 budget and FY2009 budget request for DOE's energy technology R&D is approximately $3 billion per year. (See **Figure 8**.)

Even if spending on CO_2 capture technology were increased dramatically to Manhattan project or Apollo program levels, it is not clear whether the goal of developing a commercially deployable technology would be realized. As mentioned above, commercialization of technology and integration of technology into the private market were not goals of either the Manhattan project or Apollo program. For the Manhattan project, it did not matter what the cost was, in one sense, if a consequence of failing to build a nuclear weapon was to lose the war. For CO_2 capture, the *primary* goal is to develop a technology that would be widely deployed and thus effective at removing a substantial amount of CO_2 over the next half century or more, which necessarily requires its commercialization and widespread use throughout the utility sector.

The Possibility of Failure: The Synthetic Fuels Corporation

A careful study of one of the federal projects initiated in response to the energy crisis of the 1970s and early 1980s—the Synthetic Fuels Corporation (SFC)—may provide a valuable comparison to current thinking about the federal role in CO_2 capture technology development:

> The government's attempt to develop a synthetic fuels industry in the late 1970s and early 1980s is a case study of unsuccessful federal involvement in technology development. In 1980, Congress established the Synthetic Fuels Corporation (SFC), a quasi-independent corporation, to develop large-scale projects in coal and shale liquefaction and gasification. Most of the projects centered on basic and conceptual work that would contribute to demonstration programs in later stages, although funds were expended on several prototype and full-scale demonstration experiments. Formed in response to the 1970s energy crisis, the SFC was intended to support projects that industry was unable to support because of technical, environmental, or financial uncertainties. Federal loans, loan guarantees, price guarantees, and other financial incentives totaling $20 billion were authorized to spur industry action. Although SFC was designed to continue operating until at least 1992, the collapse in energy prices, environmental concerns, lack of support from the Reagan

[89] CRS estimates that federal funding to address global climate change was $6.37 billion in FY2008. See CRS Report RL33817, *Climate Change: Federal Program Funding and Tax Incentives,* by Jane A. Leggett.

> Administration, and administrative problems ended the synthetic fuels program in 1986.[90] [citations from original text omitted]

One of the primary reasons commonly cited for the failure of the SFC was the collapse of crude oil prices during the 1980s, although other factors contributed.[91] Without a stable and predictable price for the commodity that the SFC was attempting to produce in specific, mandated quantities, the structure of the SFC was unable to cope with market changes:

> The failure of the federal government's effort to create a synthetic fuels industry yields valuable lessons about the role of government in technology innovation. The synthetic fuels program was established without sufficient flexibility to meet changes in market conditions, such as the price of fuel. Public unwillingness to endure the environmental costs of some of the large-scale projects was an added complication. An emphasis on production targets was an added complication. An emphasis on production targets reduced research and program flexibility. Rapid turnover among SFC's high-level officials slowed administrative actions. The synthetic fuels program did demonstrate, however, that large-scale synthetic energy projects could be build and operated within specified technical parameters.[92] [citations from original text omitted]

It may be argued that DOE's initial decision to "restructure" the FutureGen program (as originally conceived, see box above) was partly attributable to the project's inflexibility in dealing with changing market conditions, in this case the rise in materials and construction costs and the doubling of FutureGen's original price estimate. However, the analogy between FutureGen and the SFC is limited. Although the SFC failed in part because of collapsing oil prices (the costs of the SFC program could be measured against the benefits of producing oil), for FutureGen the value of CO_2 *avoided* (i.e., the benefit provided by the technology) is not even calculable for comparison to the costs of building the plant, because there is no real global price for CO_2.

The market conditions that contributed to the downfall of the SFC, however, could be very different from the market conditions that would arise following the creation of a price for CO_2 emissions. The stability and predictability of the price signal would depend on the mechanism: carbon tax, allowance pricing, or auctions. A mechanism that allowed for a long-term price signal for carbon would likely benefit CO_2 capture technology R&D programs.

Implications for Climate Change Legislation

Any comprehensive approach to reducing greenhouse gases substantially must address the world's dependency on coal for one-quarter of its energy demand, including almost half of its electricity demand. To maintain coal as a key component in the world's energy mix in a carbon-constrained future would require developing a technology to capture and store its CO_2 emissions. This situation suggests to some that any greenhouse gas reduction program be delayed until such

[90] The National Academy of Sciences, "The Government Role in Civilian Technology: Building a New Alliance" (National Academy Press, Washington, DC, 1992), pp. 58-59.

[91] For a variety of reasons, Canada's experience with producing synthetic fuels, specifically oil sands development, has differed from the U.S. experience. For more information, see CRS Report RL34258, *North American Oil Sands: History of Development, Prospects for the Future*, by Marc Humphries.

[92] The National Academy of Sciences, "The Government Role in Civilian Technology: Building a New Alliance," p. 59.

carbon capture technology has been demonstrated. However, technological innovation and the demands of a carbon control regime are interlinked; therefore, a technology policy is no substitute for environmental policy and must be developed in concert with it.[93]

This linkage raises issues for legislators attempting to craft greenhouse gas reduction legislation. For the demand-pull side of the equation, the issue revolves around how to create the appropriate market for emerging carbon capture technologies. **Table 4** compares four different "price" signals across five different criteria that influence their effectiveness in promoting technology:

- **Magnitude**: What size of price signal or stringency of the regulation is imposed initially?
- **Direction**: What influences the direction (up or down) of the price signal or stringency of the regulation over time?
- **Timing**: How quickly is the price or regulation imposed and strengthened?
- **Stability**: How stable is the price or regulation over time?
- **Duration**: How long is the price or regulation imposed on affected companies?

In general, the criteria suggest that regulation is the surest method of forcing the development of technology—price is not necessarily a direct consideration in decision-making. However, regulation is also the most limiting; technologies more or less stringent than the standard would have a limited domestic market (although foreign opportunities may be available), and development could be frozen if the standards are not reviewed and strengthened periodically. In contrast, allowance prices would provide the most equivocal signal, particularly if they are allocated free to participants. Experience has shown allowance prices to be subject to volatility with swings both up and down. The experience with the SO_2 cap-and-trade program suggests the incentive can be improved with "bonus" allowances; however, the eligibility criteria used could be perceived as the government attempting to pick a winner.

In contrast, carbon taxes and allowance auctions (particularly 100% auctions with a reserve price) provide strong market-based price signals. A carbon tax is the most stable price signal, providing a clear and transparent signal of the value of any method of greenhouse gas reductions. Substantial auctioning of allowances also places a price on carbon emissions, a price that can be strengthened by incorporating a reserve price into the structure of the auction.

However, each of these signals ultimately depends on the environmental goal envisioned and the specifics of the control program: (1) the stringency of the reduction requirement; (2) the timing of desired reductions; (3) the techniques allowed to achieve compliance. The interplay of these factors informs the technology community about the urgency of the need for carbon capture technology; the price signal informs the community what cost-performance parameters are appropriate for the emerging carbon market. The nature of that price signal (regulatory, market, stability) informs the community of the confidence it can have that it is not wasting capital on a "white elephant" or on a project that the market does not want or need.

[93] Carolyn Fischer, *Climate Change Policy Choices and Technical Innovation*, Resources for the Future Climate Issue Brief #20 (June 2000), p. 9.

Table 4. Comparison of Various Demand-Pull Mechanisms

Mechanism	Magnitude	Direction	Timing	Stability	Duration
Regulation	Depends on available technology or performance standard	Subject to periodic review by regulatory authorities based on technological progress	Depends on frequency of regulatory review and pace of technological progress	Very stable—can become stagnant if discourages further innovation or regulators rarely review standard	Depends on the regulatory procedures for reassessment
Allowance Prices	Depends on stringency of emissions cap and other provisions of the cap-and-trade program	Market-driven based on the supply and demand for allowances	Depends on environmental goal and specified schedule of emission reductions	Can be quite volatile	Depends on environmental goal and specified schedule of emission reductions
Carbon Tax	Depends on level of tax	Generally specified by legislation	Depends on escalator provisions in legislation	Stable	Depends on the specified schedule of the carbon tax
Allowance Auctions	Same dynamics as allowance prices; can be strengthened by 100% auctioning of allowances and specifying a reserve price	Same dynamics as allowance prices unless legislation specifies a reserve price	Same dynamics as allowance prices unless legislation includes a reserve price—then it depends on any escalator clause	Allowance price volatility can be tempered by a reserve price and the specifics of the auctioning process	Same as for allowance prices, but includes the details of the auctioning procedures

Source: Congressional Research Service.

The issues for technology-push mechanisms are broader, and include not only the specifics of any reduction program and resulting price signal, but also international considerations and the interplay between carbon capture technology, storage, and the potential need for CO_2 transport. Groups as diverse as The Pew Center, the Electric Power Research Institute, DOE, and MIT have suggested "roadmaps" and other schemes for preparing carbon capture technology for a pending greenhouse gas reduction program.[94] Generally, all of these approaches agree on the need for demonstration-size (200-300 MW) projects to sort out technical performance and cost effectiveness, and identify potential environmental and safety concerns. The Energy Independence and Security Act of 2007 (P.L. 110-140) reflected Congress's desire for more integrated demonstration projects, and ARRA provides a dramatic step increase in funding for CCS technology over a relatively short period.

Finally, it should be noted that the status quo for coal with respect to climate change legislation isn't necessarily the same as "business as usual." The financial markets and regulatory authorities appear to be hedging their bets on the outcomes of any federal legislation with respect to greenhouse gas reductions, and are becoming increasingly unwilling to accept the risk of a coal-fired power plant with or without carbon capture capacity. This sort of limbo for coal-fired power plants is reinforced by the MIT study, which makes a strong case against subsidizing new construction (allowed for IGCC under the EPAct2005) without carbon capture because of the unattractive costs of retrofits:

> *Coal plants will not be cheap to retrofit for CO_2 capture*. Our analysis confirms that the costs to retrofit an air-driven SCPC [supercritical pulverized coal] plant for significant CO_2 capture, say 90%, will be greater than the costs to retrofit an IGCC plant. However, ... the modifications needed to retrofit an IGCC plant for appreciable CCS are extensive and not a matter of simply adding a single simple and inexpensive process step to an existing IGCC plant.... Consequently, IGCC plants without CCS that receive assistance under the 2005 Energy Act will be more costly to retrofit and less likely to do so.
>
> *The concept of a "capture ready" IGCC or pulverized coal plant is as yet unproven and unlikely to be fruitful*. The Energy Act envisions "capture ready" to apply to gasification technology. [citation omitted] Retrofitting IGCC plants, or for that matter pulverized coal plants, to incorporate CCS technology involves substantial additional investments and a significant penalty to the efficiency and net electricity output of the plant. As a result, we are unconvinced that such financial assistance to conventional IGCC plants without CCS is wise.[95] [*emphasis in original*]

As noted earlier, lack of a regulatory scheme (or carbon price) presents numerous risks to any research and development effort designed to develop carbon capture technology. Ultimately, it also presents a risk to the future of coal.

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[94] For example, see Pew Center on Global Climate Change, *Coal and Climate Change Facts*, (2008), available at http://www.pewclimate.org/global-warming-basics/coalfacts.cfm; Coal Utilization Research Council and Electric Power Research Institute technology roadmap at http://www.coal.org/roadmap/; DOE Energy, National Energy Technology Laboratory, *Carbon Sequestration Technology Roadmap and Program Plan 2007* available at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf; and, MIT, *The Future of Coal*, pp. xi-xv.

[95] MIT, *The Future of Coal*, pp. 98-99.

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