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Making Carbon Capture and Storage Work

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President Obama faces an old challenge of creating a national energy policy. That policy will be designed with multiple objectives in mind. After a year of record oil prices that added to U.S. economic troubles, some want an energy policy that will maintain lower energy prices. With nearly 150,000 troops still in Iraq and tensions raised with Russia over the Georgian invasion, some want an energy policy that will reduce American dependence on fossil fuel imports from these and other geopolitically sensitive regions. And with atmospheric carbon dioxide now more than 385 parts per million and rising, some want an energy policy that will reduce greenhouse gas emissions.

This chapter focuses on how the United States can accomplish the third objective, reducing carbon dioxide emissions from fossil fuels. I argue that demonstration and deployment of technologies to capture carbon dioxide from large stationary sources, storing the waste CO_2 in geological formations, is likely to be an essential component of any carbon reduction strategy, both for the United States and for the world, and is also consistent with economic and security concerns. It also reviews the major technical challenges involved with widespread deployment of carbon capture and storage, and discusses policies that would lead to the specific goal of capturing and storing the CO_2 from all large stationary sources by the middle of this century.

Several excellent reviews of carbon capture and storage have appeared in recent years, in particular the MIT report on *The Future of Coal* and the *IPCC*

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Special Report on Carbon Dioxide Capture and Storage.[1] Topics in this chapter are discussed in much greater detail in these reports and the references therein.

The Case for Carbon Capture and Storage

Strategies to lower CO_2 emissions to mitigate climate change can be grouped into three broad categories. The first category involves reducing CO_2 emissions by reducing energy consumption. This does not necessarily mean reducing energy use by reducing economic activity through conservation but also by investing in low-energy social adaptations, such as public transportation systems, or by adopting energy-efficient technologies in buildings, in automobiles, and throughout the economy. Huge discrepancies in energy efficiency exist today between countries, even within the developed world; in general, countries that have higher historical energy prices, including many in western Europe, are more efficient than those countries with inexpensive energy, although the differences can also be explained by historical investments in cities and suburbs, in highways and public transportation systems, government policies, and a variety of other factors. But whatever the cause of the current differences between countries, there is great potential across the developed and the developing world to dramatically lower energy use through smarter and better energy systems.[2]

The second category involves expansion of nonfossil energy systems including wind, solar, biomass, geothermal, and nuclear power. Wind is currently the most economical of these systems for electricity generation, at least in appropriate areas.[3] However, wind requires excess capacity because of intermittency in the wind resource, and so it is difficult to deploy as a source for base load power unless storage technologies become better and cheaper. Solar generated electricity has similar energy storage issues and is also expensive compared with wind or nuclear power, although solar thermal plants may be an interesting alternative to photovoltaic devices in addressing these concerns. Nuclear power can be used for base load power, unlike wind or solar photovoltaic power, but it has issues of safety and storage and handling of nuclear waste, and there are security concerns regarding nuclear weapons proliferation that must be addressed before widespread expansion is likely, at

[1] See Deutch and Moniz (2007) and Intergovernmental Panel on Climate Change (IPCC 2005), respectively.
[2] United Nations Foundation (2007).
[3] See, for example, Bird and Kaiser (2007).

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least in the United States and western Europe outside of France. Because of these factors, as well as other regulatory uncertainties, the economic cost of new nuclear power plants in the United States remains uncertain.[4]

Outside of the electric realm, biomass converted to transportation fuel may play a major role in reducing CO_2 emissions in the transportation sector, at least until powerful, inexpensive, and reliable battery technologies or some alternative transportation technologies are developed. For example, Brazil currently obtains most of its transportation fuel from sugarcane fermentation into ethanol, and programs around the world are following suit.[5] A more efficient technology may be the conversion of biomass into synthetic diesel and jet fuel via the Fischer-Tropsch process used by the Germans in World War II to make coal into liquid fuel. This process has the advantages of creating a more diverse range of fuel products, including jet fuel for air transport, and of being more efficient through use of all types of biomass, not just sugar (or cellulose for a cellulosic conversion process). Moreover, the Fischer-Tropsch process, which involves gasification of the biomass followed by conversion to liquid fuel via a cobalt or iron catalyst, requires removal of CO_2 to avoid poisoning the catalyst, making it easily adapted to capture and storage of CO_2, as discussed below.

The third category involves CO_2 capture from emissions sources and then storage in geological repositories, often referred to as carbon capture and storage *(CCS). CCS* appears particularly attractive because it has the potential to allow some of the largest economies of the world to use their abundant and inexpensive coal resources without releasing vast amounts of CO_2 to the atmosphere. Coal produces the most CO_2 per unit energy of all fossil fuels, nearly twice as much as natural gas. And unlike petroleum and natural gas, which are predicted to decline in total production well before the middle of the century, there is enough coal to last for centuries, at least at current rates of use, and that makes it inexpensive relative to almost every other source of energy. Even with huge improvements in efficiency and increases in nuclear, solar, wind, and biomass power, the world is likely to depend heavily on coal, especially the five countries that hold 75 percent of world coal reserves: United States, Russia, China, India, and Australia. Domestic use of coal in the United States is also advantageous from a national security perspective, as the main alternative to coal for power generation is natural gas, which, in the future, may mean greater reliance on imports of liquefied natural gas from the Middle East and Russia.

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4. Deutch and Moniz (2003).
5. Gallagher and others (2006).

The vast majority of coal use is for electricity generation. In the United States, for example, 95 percent of coal in 2007 was used for power plants or for combined heat and power. Although coal-fired power plants make up only a third of the U.S. generating capacity, they account for 50 percent of total electricity generation and 40 percent of CO_2 emissions. This is due to the low price of electricity generated from coal plants and the operational difficulties of turning the plants on and off, making them the backbone of the U.S. power generating system. Incorporating CCS for these power plants could reduce their CO_2 emissions by at least 80 percent, enabling the United States to continue to use its vast coal reserves without harming the climate system.

Another reason why some have found CCS to be so compelling as part of a climate change strategy is that CCS, if cost effective, might allow the world to transition to a low-carbon economy without discarding capital investments that have been made in electricity infrastructure. In 2007 there were 2,211 power plants that emitted at least 1 million tons of CO_2 a year: 1,068 were in Asia (559 in China), 567 in North America (520 in the United States), 375 in Europe, and 157in Africa.[6] Together these power plants released 10billion tons of CO_2, or one-third of global emissions. To the extent that some of these plants can be retrofitted with capture technology and that appropriate storage locations can be identified, CCS would allow the world to continue to use these facilities for many decades but dramatically reduce their environmental impact.

Another consideration is the timescale over which it is possible to build new energy systems. Eliminating carbon emissions from electricity generation with new nuclear power plants, for example, would require building two large plants each week for the next 100 years. This rate of change seems improbable given current constraints on steel production, construction capacity, and education of operators, as well as many other practical considerations. Given the capital investment the world has already made in power generation, CCS appears to be one of the few ways to lower carbon emissions and still make use of those investments.

Although coal is the major motivation for the development of CCS, it is important to note that CCS need not apply exclusively to coal; any point source of CO_2 can be sequestered, including CO_2 from combusted biomass, which would result in negative emissions. Indeed, the oldest CCS installation, StatoilHydro's Sleipner project that started in 1996, sequesters CO_2 sep-

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[6] Carbon Monitoring for Action, "Power Plant Data" (http://carma.org/dig).

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arated from natural gas and injects it into a sandstone formation off the Norwegian coast. Even if one could imagine a U.S. energy system that did not rely heavily on coal for electricity (which is difficult), CCS would still be needed to achieve carbon reduction goals for large natural gas power plants, oil refineries, smelting and steel manufacturing facilities, fertilizer plants, and ethanol distilleries. Indeed, some of these non-coal stationary sources of CO_2 emissions are likely to be the first targets for CCS deployment as some of them already produce concentrated CO_2, eliminating most of the capture costs. Of course, limiting the amount of future coal use would greatly diminish the required scale of CCS, but CCS is likely to represent a large portion of any global strategy to lower CO_2 emissions, at least for the next century, even without new investments in coal-fired generating plants.

A final reason why CCS is so important for U.S. energy policy to achieve a dramatic reduction in global CO_2 emissions is that CCS is likely to be extremely important in China, India, and Russia as they all have large coal reserves. Widespread adoption of CCS in the United States over the next few decades will make it more likely that similar systems will be deployed overseas, especially in the rapidly growing economies with high present and future CO_2 emissions.

Scientific and Technological Challenges

The scientific and technological challenges associated with carbon capture are quite distinct from the challenges related to carbon storage. In the following sections, some of the most serious obstacles to CCS deployment for capture and for storage are discussed.

Capture

Geological storage of CO_2 requires a relatively pure gas stream; the energetic costs of compression prohibit sequestration of dilute mixtures. Some industrial processes release concentrated CO_2 and are therefore perfectly suited for storage. These include ammonia plants (Haber-Bosch process) and synthetic fuel plants (Fischer-Tropsch process) that capture CO_2 because it interferes with the main catalytic reactions. Some components of petroleum refineries, in particular CO_2 released from the production of hydrogen through steam methane reforming, are capable of producing pure CO_2 streams in a similar fashion. A range of capture technologies exists for such plants, most of which are based on chemical solutions (for example, Selexol) that absorb CO_2 at high pressure inside the reactor and release it at atmospheric pressure. This means that the only added cost for these facilities to make them ready for CO_2 storage, aside from the actual injection and storage costs, is compression for transport via pipelines. At smaller scales, many ethanol plants release concentrated CO_2 from the fermentation process that is similarly at low pressure and must be compressed before being transported to a storage site. All of these facilities are excellent prospects for early deployment of CCS because the compression, transportation, and injection costs are relatively minor and will likely be economical under a cap-and-trade system with only a modest price on CO_2 (less than $20 per ton).[7]

For power plants, which make up the largest class of CCS targets, the capture of CO_2 is very expensive, both in capital expenditures and in energy costs, in part because CO_2 capture is an additional cost and not built into the overall process. Conventional pulverized coal (PC) plants, whether critical, supercritical, or ultra-supercritical, burn coal in air, producing a low-pressure effluent composed of roughly 10 percent CO_2 in nitrogen. CO_2 can be scrubbed from the nitrogen using amine liquids, chilled ammonia, or other materials with high affinity for CO_2, These various CO_2 "scrubbers" must then be regenerated by heating them to release the CO_2, which can use a significant amount of energy. Overall, the energy penalty associated with capture and storage represents roughly 30 percent of the electricity from an average plant in the United States and may raise the generating cost of electricity from coal by 50 percent or more.[8] New plants designed with CCS in mind will likely be much more economical than retrofitting existing plants, as discussed below.[9]

If a PC plant, whether new or old, is outfitted with postcombustion capture technology, the energy to operate the scrubbing systems (primarily as heat to remove CO_2 from the amine or chilled ammonia scrubbers) as well as the electricity to run the gas compressors will reduce the total electrical output of the plant. Better scrubbing materials are being developed that are able to release CO_2 at lower temperatures, allowing the possibility that much of the energy used in the capture process can be waste heat from the coal combustion, minimizing the drop in electrical output. Such improvements in the ability to employ waste heat in the capture process will be critical in driving down the overall cost of CCS.

When one considers adding CCS to existing PC plants in the United States, the energy penalty entailed will constrain the extent to which CCS will be deployed as a retrofit. The average efficiency of coal-fired power plants in

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[7] McCoy and Rubin (2005).

[8] Anderson and Newell (2004); IPCC (2005).

[9] See also Rubin, Chen, and Rao (2007); Bohm and others (2007).

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the United States is 32 percent, but with a wide range between 20 and 40 percent. By definition, a plant with low efficiency will use more coal than a high efficiency plant to produce the same amount of power and therefore will produce more CO_2, This means that a PC plant with low efficiency will have to spend a much higher fraction of the electricity it produces on capture and compression than a higher-efficiency plant.[10] Indeed, for the least efficient quartile of PC plants in the United States, retrofitting with CCS equipment is unlikely to make economic sense under any foreseeable cap-and-trade regime since the energy penalty is simply too high. How to decommission these older, low-efficiency power plants will someday be a major challenge for U.S. energy policy, as discussed below.

Another way to capture CO_2 from a power plant is through what is commonly called precombustion technologies. One type of precombustion system uses an oxyfuel process, in which coal is combusted in pure oxygen instead of air. Separation of oxygen from air is energy intensive, and so the energy penalty is still significant. Modification of existing PC plants to use pure oxygen would be substantial as flame temperatures are higher, requiring replacement of many of the basic components of the plant, and so this is unlikely to be a useful strategy for retrofit applications. However, the few demonstration plants that exist today show some promise, largely due to their high thermal efficiency. Whether they will compete economically remains a question.[11]

Another precombustion process for carbon capture is integrated gasification combined cycle (IGCC) technology. Through a process called gasification, coal is heated and partially combusted in pure oxygen to make a mixture of carbon monoxide and hydrogen. The carbon monoxide is then converted to CO_2 through a "shift" reaction with steam, and the CO_2 is collected using separation technologies such as Selexol that use the change in CO_2 affinity from high pressure to low pressure-rather than a temperature change-to regenerate the CO_2 after separation. Much attention has been given to coal gasification as a means for promoting carbon sequestration since studies suggest that the overall costs and the energy penalty are lower for a new plant[12] However, experience with gasification plants is limited; there are only two such plants in the United States, and neither is equipped to capture carbon (that is, they do not have shift reaction or CO_2 separation capability). More encouragement of coal gasification technology is important to discover whether the promises of lower capture costs can be realized.

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10. House and others (2009).
11. Deutch and Moniz (2007).
12. Rubin, Chen, and Rao (2007); Deutch and Moniz (2007).

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Overall, there are advantages to each of the different approaches to CO_2 capture, and so each of them is likely to play some role in the U.S. energy system. For example, a power plant located near a petroleum refinery might prefer IGCC technology since the refinery could provide a market for excess hydrogen produced during off-peak hours when electricity prices are low. In addition, some state and local regulators may prefer IGCC technology because of concerns about other pollutants, including sulfur and mercury. In other situations, a new PC plant with postcombustion capture technology might be preferable because the capital costs may be lower. Postcombustion capture technology will likely be a major part of the overall CCS approach because it allows for the reduction of carbon emissions from existing PC plants, at least those with reasonable thermal efficiencies, as discussed above. Any policies that encourage deployment of capture technologies should be careful to remain neutral in selecting which specific capture technology is best, as competition at commercial scale will be essential to stimulate technological learning and lower costs. A challenge is that the small number of existing IGCC and oxyfuel plants around the world makes it difficult to confidently predict what these plants will cost, how reliable they will be, and whether they will live up to the expectation that their design will make CCS more efficient and less costly. Therefore, some special early incentives for launching these newer technologies will be important over the next decade.

Storage

The technological challenges associated with storage of carbon dioxide from large stationary sources for any individual project are relatively minor compared with those of capture systems, but the scale of the effort is daunting. To achieve the goal of using CCS for all coal combustion in the United States, at current levels of consumption, would require handling more than 2 billion tons of CO_2 a year, roughly double the volume of total U.S. oil consumption when compressed to a liquid state with a density near that of water. Just building the necessary pipeline infrastructure will be a major industrial undertaking, should CCS ever be deployed on such as scale.

The primary scientific question about carbon storage in geological formations concerns the reliability of this approach. Will the CO_2 escape? The good news is that repositories do not have to store CO_2 forever, just long enough to allow the natural carbon cycle to reduce the atmospheric CO_2 to near preindustrial levels. The ocean contains fifty times as much carbon as the atmosphere, mostly in the deep ocean, which has yet to equilibrate with the CO_2 from fossil fuel combustion. Over the timescale of deep ocean mix

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ing, roughly 1,000 to 2,000 years, natural uptake of CO_2 by the ocean combined with dissolution of marine carbonate will absorb 90 percent of the carbon released by human activities. Along as the geological storage of CO_2 can prevent significant leakage over the next few millennia, the natural carbon cycle can handle leakage on longer timescales.

Experience with transport and injection of CO_2 into geological formations comes from decades of work on enhanced oil recovery (EOR) methods in older oil fields. For example, using pipelines built in the 1980s,Kinder Morgan transports CO_2 from natural CO_2 reservoirs in Colorado through a 36-inchdiameter pipe over 300 miles and then injects it into depleted oil reservoirs.

EOR demonstrates that CO_2 transport and injection is feasible.Moreover,CO_2 leakage from EOR locations appears to be relatively minor, although careful monitoring and modeling of the fate of CO_2 after injection has not been done in enough detail.[13] There are also some important differences between EOR and CO_2 storage, however, that call into question how useful the experience with EOR will be. First, EOR involves both injection of CO_2 and extraction of fluid-usually a mixture of water, CO_2, and oil (the CO_2 is usually reinjected). The pumping of fluid out of the formation increases the mobility of CO_2, resulting in higher saturation of pore spaces and more effective trapping. Injection of CO_2 into saline aquifers, for example, without concomitant extraction of saline water, may not be analogous to EOR practices in terms of increasing pore pressures and in terms of migration rates of CO_2 in the subsurface. Indeed, displacement of saline water may prove to be a very difficult challenge for terrestrial storage sites as the scale of CO_2 injections grows. Second, EOR may demonstrate that specific oil- and gas-bearing formations that have held hydrocarbons for millions of years can successfully store CO_2 for millennia, but there are not enough depleted oil and gas reservoirs to accommodate the vast volumes of CO_2 if long-term CCS goals are achieved. Overall, EOR does still provide great confidence that CO_2 storage at a massive scale can be accomplished. Moreover, as there is not yet a price on carbon, much less one that would cover the costs of CCS, EOR provides a market for CO_2 over the next decade that can accelerate the deployment of capture technologies.

Most discussion of CO_2 storage focuses on terrestrial injection into formations including deep saline aquifers and old oil and gas fields. In all terrestrial locations at the depth of injection, usually at least one kilometer below the surface, the geothermal gradient means that CO_2 exists as a supercritical fluid with roughly half the density of water. This means that CO_2 can

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[13] IPCC (2005).

escape if sedimentary formations are compromised by fractures, faults, or old drill holes. The handful of test sites around the world each inject roughly 1 million tons of CO_2 a year, a tiny amount compared to the need for as much as 10 billion tons a year by the middle of the century if most large stationary sources of CO_2 will use CCS to reduce emissions. An important question is whether leakage rates will rise as more and more CO_2 is injected and the reservoirs fill. It seems likely that many geological settings will provide adequate storage, but the data to demonstrate this do not yet exist. A more expansive program aimed at monitoring underground CO_2 injections in a wide variety of geological settings is essential.

Another approach to CO_2 storage is injection offshore into marine sediments, which avoids the hazards of direct ocean injection, including impacts on ocean ecology.[14] If the total depth (both water depth and depth below the sea floor) is greater than 800 meters, then the CO_2 will be in a liquid state with density within 20 percent of seawater (greater than seawater at depths exceeding 3,000 meters). In this case, the mobility of CO_2 would be greatly diminished, yielding essentially a leak-proof repository. This approach may be important for coastal locations, which are far from appropriate sedimentary basins, and may also reduce the extent of expensive monitoring efforts. In addition, offshore storage may be useful to avoid siting pipelines and storage facilities in heavily populated areas.

In terms of capacity, the requirements are vast if most stationary sources will use CCS to reduce emissions. Conservative estimates of reservoir needs over the century are more than 1 trillion tons of CO_2 and might exceed twice that amount. Fortunately, the capacity of deep saline aquifers and marine sediments is more than enough to handle centuries of world CO_2 emissions from burning coal. Matching existing stationary sources of CO_2 with appropriate storage facilities to avoid having to build long pipelines is premature, given that there still is not a single coal-fired power plant in the world that uses CCS technologies, and that the prospects for retrofitting existing plants remain uncertain. However, it appears that the main types of geological storage offer enough options to allow CCS to be deployed in most parts of the United States, either in sedimentary basins on land or in offshore reservoirs in coastal areas in a manner similar to the Sleipner project in the North Sea.

Other forms of CO_2 storage have been proposed, but none has yet shown the promise of simple injection into geological formations, either on land or offshore. Mineralization strategies that would convert CO_2 into carbonate

[14] House and others (2006).

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minerals appear to be very expensive relative to simple injection, and they have additional challenges associated with moving vast quantities of rock.[15] However, continued research on these and other new approaches is important as CCS goals are likely to require a spectrum of storage strategies for different parts of the country with different geology, state and local regulatory regimes, and levels of public concern.

Moving Forward with CCS Demonstration and Deployment

From the discussion above, it appears that CCS has great potential to reduce CO_2 emissions from stationary sources in the United States (as well as in China and other large emitters); to provide relatively low-cost, low-carbon power; to make use of abundant coal resources in a more environmentally benign fashion; and to make use of some of the existing power plant infrastructure with significant modification but not total reconstruction. The incremental cost of CCS may still be modest when compared to the cost of new nuclear power, new renewable power with storage, or natural gas. So why are any policy interventions or subsidies needed for CCS projects if CCS is likely to be the most cost-effective way to have low-carbon power? Ultimately, they will not be needed, at least beyond an initial demonstration period, if CCS lives up to its promise. But in the short term, the scientific and technological challenges discussed above must be explored, and enough CCS projects must be operating at a commercial scale so that power developers and investors will have confidence in the technology and in the costs, including those related to liability issues. Through a series of policy recommendations, I discuss the obstacles that must be overcome before there can be widespread adoption of CCS throughout the U.S. energy system. The goals should be to surmount the obstacles to demonstration and initial commercial deployment of CCS systems to learn whether CCS is feasible at a large scale, whether the cost is indeed much lower than alternatives, and whether a proper regulatory framework can be developed using the experience of the initial commercial installations.

Recommendation 1: *Provide Federal Subsidies for Commercial-Scale CCS*
The U.S. government should provide federal subsidies for ten to twenty commercial-scale CCS projects. These should include different capture technologies (if appropriate) and different strategies for geological storage, and should

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[15] IPCC (2005).

be spread across different regions of the United States to have the biggest impact, both on knowledge gained and also on public perception.

Although CCS should be profitable at some point given a sufficient price on carbon, government assistance is needed in the short term to demonstrate the technology at commercial scale. The price that would be imposed by any of the cap-and-trade legislation currently under discussion in Congress is still well below the level that would cover the cost of sequestration. This may not be a fatal obstacle as investors will anticipate higher prices in the future. But without an adequate price, it is likely that new plants would be built "capture ready" (that is, designed to capture CO_2) but would not actually capture CO_2 and store it in geological repositories. Another problem is that the price of CO_2 could be volatile under a cap-and-trade regime, and this may discourage investment in large capital projects like CCS that depend on a high carbon price.

It should be noted that in several parts of the country, including the Northeast, California, and even parts of the Midwest, it is extremely difficult, if not impossible, to obtain a permit to build a new coal-fired power plant, not because of a price on carbon but simply because local regulators are unlikely to allow any new power plant with high CO_2 emissions. In these markets, a new coal-fired power plant with CCS may actually be profitable today, particularly in the regions dominated by natural gas-generated electricity that have very high prices. But even where CCS is commercially viable today, it is difficult to get investors to assume the technology risks, as well as the risks associated with legal and regulatory issues, including postinjection liability. A simple way around these concerns is to encourage ten to twenty CCS projects at commercial scales through a variety of government policies and programs. This would allow for demonstration of CCS at enough locations that we would learn whether leakage was a significant problem in certain places, determine which capture technologies were most efficient, and identify any unforeseen problems or challenges. To accomplish this, grants could be awarded on a competitive basis that would pay for some of the incremental capital costs of building a new power plant with CCS.A competitive bidding program might be an efficient way to distribute such subsidies as long as cost was only one of the factors considered when making awards. The Department of Energy, in its restructured FutureGen program, is essentially doing just that at a smaller scale, although sufficient funding has not yet been allocated to the program.

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It is essential that government support for commercial demonstration of CCS would also cover the costs of independent monitoring for these projects, at least during the first several years of operation, because knowledge of how the capture technologies operate and what happens to the CO_2 after injection will be important in setting and revising CCS regulations in the future.

Within these projects, it would be important to have a range of technologies and storage strategies included. Some of these grants should support retrofit of existing PC plants with postcombustion capture systems, which may require slightly greater funding. Because the intent of these government investments would be to launch true CCS projects and increase our understanding of how such systems would operate at commercial scales, projects that involve storing the CO_2 through EOR should be ineligible for funding.

The size of the grants would vary between regions because of differences in the local cost of electricity as well as the existence in some states of subsidy programs for low-carbon electricity that would apply to CCS. Grants would likely need to be higher in coal-intensive regions that currently have very low electricity prices. Awards would not necessarily have to cover the entire additional cost of CCS as these projects may have additional factors that make them more economical, such as accelerated permitting and state subsidies for low-carbon energy. Additional support could come in the form of tax credits that would depend on some minimum fraction of CO_2 captured and stored (for example, 80 percent), or loan guarantees that would reduce the risk to investors in newer technologies including IGCC. All these forms of support could be tied to a carbon price so that the subsidies would diminish if a cap-and-trade bill were passed and these projects were able to benefit from a national carbon price.

Recommendation 2: *Create New Federal Laws and Regulations*

New federal laws and regulatory policies should be created that would make it easier for operators of power plants and CO_2 storage facilities to understand their liability and to know what environmental regulations will be applied to CCS projects.

The scientific and technical issues discussed above will be confronted over the next decade as the first commercial-scale CCS installations are constructed. However, none of the technical concerns is significant enough to suggest that carbon sequestration cannot be done. But to do it safely and effectively, and to give investors confidence in the approach, a new regulatory regime will be required to address key issues concerning the operation of storage facilities and postinjection liability. These issues are not the focus of this chapter, but they are crucial in moving forward with widespread adoption of CCS technology. Key questions include: Who will certify a storage site as appropriate? How will the capacity be determined? Who will be responsible if CO_2 leaks? Who will safeguard against cheating and how? It is clear that state and federal governments need to play some role in CO_2 storage, just as they do in other forms of waste disposal, but the exact operational details remain murky, which discourages industry from investing in sequestration efforts. However, some agencies have taken a rather narrow view of the CCS challenge. For example, the recent draft of a U.S. Environmental Protection Agency (EPA) rule on CCS only considers possible impacts on drinking water and not the myriad other issues associated with leakage, migration of CO_2 in the subsurface across property lines, or impacts on subsurface processes including earthquake hazards. The EPA rule gives no indication whether the EPA will inspect storage facilities or what the permitting process will be. A broader discussion of a new regulatory regime for disposing ofCO_2 is urgently needed.

One key issue that may be decided in the courts is whether CO_2 will be classified as waste, which would make CO_2 disposal subject to many preexisting environmental regulations that were never intended to regulate CO_2 emissions. If the courts rule that CO_2 in CCS applications is indeed waste, then new legislation will be required to specify which rules and regulations apply to CO_2 disposal.

Recommendation 3: *Accelerate Permitting and Support Pipeline Installation*

The U.S. government should use its authority to encourage state and local governments to accelerate permitting processes for CCS projects. In addition, governments may need to consider supporting pipeline installations for CO_2 transport through grants, tax credits, and rules that will make it easier to site such essential infrastructure.

One of the major obstacles for any new power plant or large industrial construction project is the permitting process, which may involve federal, state, and local regulators. These processes may take several years, which can drive up the price of the projects and may scare away investors. In order to accelerate construction of the first generation of CCS projects in the United States, streamlining of the permitting process will be extremely important and may also drive down the costs. Another local regulatory challenge is the high cost of building pipelines, especially in heavily settled areas where power demand is high. In this case, federal subsidies for CO_2 pipeline construction can encourage CCS, particularly for retrofit of higher-efficiency PC plants (supercritical and ultra-supercritical) with postcombustion capture systems that may be distant from appropriate storage facilities. Siting of pipelines may need to be encouraged via legislation similar to that which allows the Department of Energy to permit transmission lines without consent of state regulators by declaring them in the "national interest."

Recommendation 4: *Plan and Provide Assistance for Decommissioning and Retrofitting*

If the initial commercialization of CCS is effective, the long-term goal for U.S. energy policy should be the adoption of CCS for all large stationary sources of CO_2 (for example, those emitting more than 1 million tons per year) by the middle of the century or sooner. To accomplish this will require a strategy for shutting down older, low-efficiency plants for which CCS is not a good option. Retrofitting existing plants-not just coal plants-where CCS does make sense may require additional federal assistance beyond the support for demonstration projects as discussed above.

The average age of U.S. electricity-generating plants greater than 500MW is thirty-two years, and the average age of coal plants is even greater, so most of the capital costs for these plants have been paid for. For these plants, the cost of electricity is primarily a function of the operating costs, including labor, and the cost of the fuel. This is one of the reasons why electricity is so inexpensive in states that have large numbers of older coal plants. This is not true for new power plants, especially PC plants for which capital can contribute as much as half of the total cost of generation. Older plants are also more likely to have low thermal efficiencies and are therefore less likely to be good targets for CCS retrofits, as mentioned earlier. The challenge is that, depending on the cost of construction of new power plants, it may remain profitable to operate these older coal-fired power plants, even with a moderate price on carbon established through a cap-and-trade regime. Rather than simply allowing the price of carbon to rise until such plants are no longer profitable, which may lead to a higher price than what the political system will tolerate, it may be more efficient to encourage the deployment of CCS for plants for which the energy penalty is not too high, and force the decommission of older plants that are incapable of CCS retrofit because of too high an energy penalty, inappropriate design, or a location that is too difficult to match with a storage facility. This will be a political challenge as there are specific regions, such as the Ohio River Valley, that will be affected the most by such policies. Federal funding to subsidize new power projects in these regions may be important to gain support for an overall carbon reduction strategy.

Summary

Carbon capture from stationary sources of fossil fuel combustion and storage in geological formations is an essential component of any comprehensive plan to reduce carbon dioxide emissions in the United States. Scientific and engineering challenges remain, in particular, how to capture and store carbon dioxide from existing power plants that were not designed with this in mind, but none is serious enough to suggest that CCS will not work at the scale required to offset billions of tons of carbon dioxide emissions per year. Widespread commercial deployment of such technologies will require new policies and public investments beyond a price on carbon in order to establish this technology and gain the confidence of investors and regulators. As part of a new national energy policy, a high priority should be placed on accelerating the installation of CCS systems for ten to twenty commercial-scale power plants around the country with different capture technologies, different storage strategies, and extensive monitoring efforts in order to learn what works and what does not, and to gain experience regarding different aspects of CCS systems. If such efforts are successful, and if there is a price on carbon as well as regulatory pressures on carbon emissions, it is reasonable to expect that CCS would become standard for all new coal-fired power plants and many other large stationary sources of CO_2 without additional public funding in the medium term. Additional government policies or subsidies will be needed to add CCS systems to many existing stationary sources, as it is unlikely that a price on carbon alone will be sufficient. For many existing power plants, CCS will not be feasible, either due to engineering restrictions or to the low efficiency of older power plants. In the end, achieving carbon reduction goals will require that these plants be shut down. The ultimate goal of a national CCS policy, if the initial deployment is successful, should be a requirement that such technologies be used for all stationary sources of CO_2 emitting more than 1 million tons per year.

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